GEOLOGICAL SURVEY
of
WESTERN AUSTRALIA

ANNUAL REPORT 1980

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ANNUAL REPORT

FOR THE YEAR

1980

EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

Minister: The Hon. P. V. Jones, M.L.A.

Under Secretary: D. R. Kelly

Director, Geological Survey: A. F. Trendall

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1981

DIVISION IV

Annual Report of the Geological Survey Division of the Mines Department for the Year 1980

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REPORTS

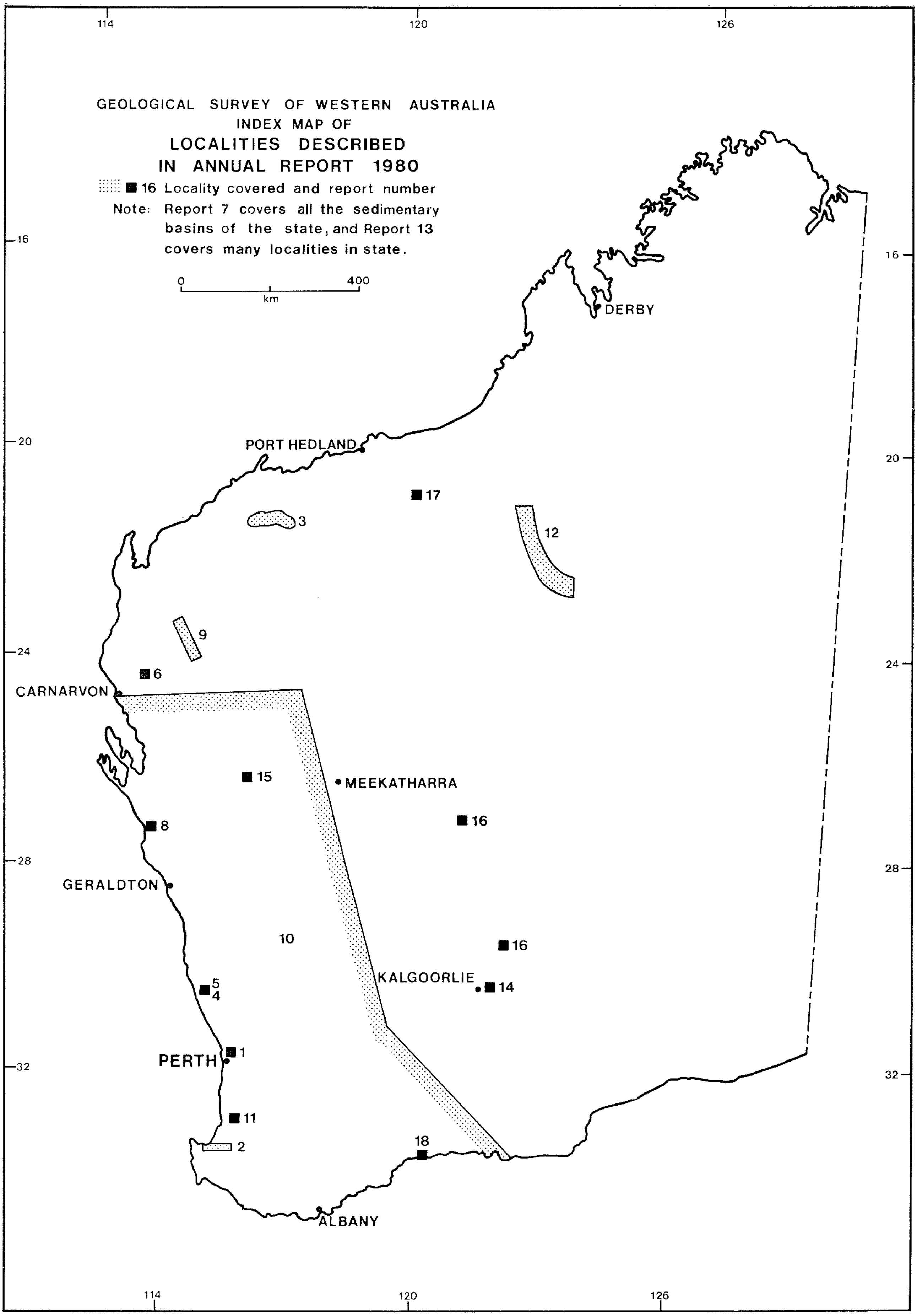

Figure 1 Index map showing areas and localities described in the Annual Report 1980.

DIVISION IV

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Annual Report of the Geological Survey Division of the Mines Department for the Year 1980

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Under Secretary for Mines:

My report on the activities and progress of the Geological Survey of Western Australia during 1980 is herewith forwarded for the information of the Honourable Minister for Mines. As is customary, the report is accompanied by a selection of technical papers which present the results of representative investigations and studies carried out in accordance with the objectives of the Department during that year.

INTRODUCTION

The activities of the Geological Survey of Western Australia during 1980 were generally subject to three factors which combined to make it a year of transition, rather than one in which any major programme was either completed or initiated. These factors were a change of Director, a massive increase in the work load of some sections owing to the exploration boom which began in 1978 and gained momentum during 1979, and finally the loss of many geologists to private industry as a further response to the same boom. As in the "nickel boom" of 10 years ago, it is paradoxical that at times when the greatest demands for the services of the Survey are made, it is least able to satisfy them. In general, what should have been a year of finalization of many long-standing projects and active preparation for new programmes in 1981, became instead a year in which much planned work had to be curtailed or postponed to maintain essential ongoing responsibilities. A more optimistic note at the end of the year was that the prospect of filling vacancies appeared hopeful; the accomplishment of all the work listed in the programme for 1981 below is dependent on the early achievement of a full professional staff establishment.

The consolidation of the exploration boom through 1980 was marked by a continued high level of interest in uranium, gold, and diamond, and a marked increase of interest in coal and oil shale. The demand for Temporary Reserves is a useful indicator of mineral exploration activity, and the following Table uses this to illustrate growth during recent years.

Temporary Reserves

Year	New applications approved during year	Total in force at year end
1976	117	439
1977	92	411
1978	228	528
1979	290	818
1980	747	1 169

At the end of 1980, 320 Temporary Reserves were held for gold, 229 for coal and 134 for iron ore. Of the Temporary Reserves held for other minerals, diamond figured among the chief commodities under search together with uranium, which has been the subject of a high level of exploration for many years.

Diamond was sought in many parts of the State. The Kimberley remains the main scene of activity though exploration continues in the Carnarvon Basin and new ground was acquired under Temporary Reserves for diamond in the Fraser Range some 200 km southeast of Kalgoorlie by Stockdale Prospecting Limited.

In the Kimberley, the Ashton Syndicate with Conzinc Riotinto of Australia (CRA) as operator, began evaluation of their important prospect on Smoke Creek at Lake Argyle near Kununurra. To date the Syndicate has discovered some eighty kimberlites in the Kimberley but only three, Smoke Creek and Ellendale pipes A and B (some 150 km southeast of Derby) are considered potentially economic. At Smoke Creek, the prospect consists of an elongate kimberlite pipe (AK1) some 45 ha in surface area. From the pipe, diamondiferous alluvial gravels extend downstream for 32 km to Lake Argyle. These gravels are subdivided into an upper terrace about a kilometre in length near the head of Smoke Creek and a lower terrace extending over the remainder of the total length. Very high diamond contents are present in the alluvials of the upper terrace. However, the proportion of gemstones (less than 20 per cent) at Smoke Creek is lower than at Ellendale and the average value per carat is correspondingly less. Mining the Smoke Creek alluvials may commence in 1981.

Gold maintained the high prices reached during 1979 and stimulated interest in old gold workings in many former notable producing areas. The major producers, Telfer, Mount Charlotte and Central Norseman mines were joined by the Marvel Loch mine, which Kia Ora Gold Corporation re-opened in August. Other important developments included Western Mining Corporation's move to include a cyanide circuit to treat gold ore encountered in their nickel operations at Kambalda, the decision of Kalgoorlie Mining Associates to re-open the Fimiston leases, and the dewatering of the Morning Star gold mine at Mount Magnet, which was closed down in 1976.

Exploration for uranium continued in many parts of the State with more attention being paid to the possibility of uranium occurring in sandstones within Phanerozoic sedimentary basins. Preparations for the development of the Yeelirrie deposit continued, and the possibility of mining the Lake Way deposit near Wiluna was renewed.

Iron ore in the Hamersley Basin was the subject of continuing steady exploration throughout 1980.

A feature of exploration in 1980 was a significant increase of interest in coal, and particularly in the possible occurrence of low-grade but extensive resources of Tertiary lignite in incised drainage channels cut into the southern areas of the Yilgarn Block and elsewhere. Several Permits granted under the Petroleum Act to explore for oil shale were granted to seek hydrocarbon-richer facies of essentially the same strata, and it may be necessary to rationalize existing legislation to adequately provide for the exploitation of this material if economically significant deposits are located. No results had been reported by the end of the year.

In the area of conventional petroleum exploration, drilling activity onshore increased in 1980 with 33 exploration wells drilled in the Perth, Carnarvon, Officer and Canning Basins. These include 11 new-pool wildcats in Barrow Island. Attention has been focussed on the onshore Perth Basin where the Woodada 1 and 2 wells flowed significant quantities of gas on initial tests. These wells indicate that previously unsuspected reservoirs exist in the Permian sequence in the Perth Basin. All the other exploration wells drilled onshore during the year were abandoned as dry holes. Offshore drilling activity maintained a steady pace with 12 wells being drilled. One of these was in the far north of the state in the Bonaparte Gulf Basin, and another was off the south coast—offshore in the Eucla Basin. All of the others were on the North West Shelf, Browse Basin, or Exmouth Plateau. One of these Phoenix 1, had the first significant gas shows encountered to date in the offshore Canning Basin.

Seismic activity increased in 1980 when compared to the downturn in 1979. Offshore, one marine seismic crew was occupied on the northwest and western coasts from mid-March to the end of the year with a break to carry out about one month's work in Northern Territory waters. A second crew was similarly occupied in Western Australian and Northern Territory waters between early June and the end of December.

Onshore, there was a considerable increase in seismic activity. One land crew began a 2½ month survey in the Perth Basin late in January, and, during the northern dry season, up to five crews were working at any one time. From August through to the year end, four crews were working continuously. A land gravity survey was also conducted in the Bonaparte Gulf Basin for one month.

One unforeseen and unwelcome result of this exploration boom has been the resignation of some professional staff before they were able to complete the writing up of the intensive field work carried out in order to complete the 1:250 000 geological mapping of the State. It will be necessary to re-examine some sheets in order to maintain the uniformly high standard of previously published sheets. The finalization of this work will free staff for the urgent task of re-mapping early sheets, and for attending to the many problems which this reconnaissance-scale mapping has revealed, and whose solution is vital to an understanding of the factors controlling the distribution and occurrence of the State's mineral deposits.

Field excursion: A public excursion was organized to the Gascoyne Province. Two well-attended lectures were presented at the Gascoyne Junction Shire Hall on the evening of September 22. This was followed by a three day safari-type field excursion to parts of the Glenburgh and Mount Phillips 1:250 000 Sheets.

Public lectures: Following the practice initiated in 1977, public lectures were presented at Mineral House on 10 April and the morning of 11 April 1980. There was an average attendance of 43 at the 11 talks delivered by staff geologists.

Regional Offices: The first Regional Office of the Geological Survey was established at Kalgoorlie in mid-1979 with three geologists. The resignations of two of these towards the end of 1979 adversely affected operations during the first part of 1980, but from May onwards two geologists maintained services at Kalgoorlie. The two main functions of the office, to provide a regional focus for public and industry assistance, and to serve as a basis for local geological studies, were maintained during 1980, but it is clear that at least three geologists are desirable to maintain an efficient service and working unit, and further experience is essential to determine whether the maintenance of a Regional Office at Kalgoorlie is justifiable in strict cost-benefit terms. Office accommodation is now available at Karratha for the second Regional Office, but housing will not be available until 1981.

Study tour: In June and July Dr R. D. Gee, Supervising Geologist of the Regional Geology Branch, spent three weeks in South Africa and three weeks in Canada in an intensive study tour of areas of Precambrian geology and associated mines. Dr Gee had become widely recognized as having made a major contribution to Precambrian geology in Western Australia, and the experience of comparable more intensively studied areas overseas will be invaluable to the ongoing work of the Survey. Five officers attended the 26th International Geological Congress in Paris in July at their own expense, and two of these presented papers; the value of the experience so gained to the State should be recognized and noted.

STAFF

An important staff change during 1980 was the retirement in February of Mr J. H. (Joe) Lord, who on his promotion to the position of Government Geologist in May 1961 was the fifth and last person to bear that formal title, and the first to hold the formal title of Director, since the foundation of the Geological Survey in 1896. In all Mr Lord had spent 25 years on the staff of the Survey (1947–53 and 1961–80) and for nearly the last 19 of these he had been in administrative charge. In this latter period, during which the Geological Survey expanded significantly in both size and in the scope of its activities, his strong guidance and deep professional commitment to the Survey and its work earned the respect of all staff and of a wide range of others both in the mineral and petroleum industries and elsewhere. His decision to take early retirement was characteristic of his adherence in personal practice to all the principles in which he believed—and in this case the belief that guided him was that all organizations periodically benefit from a fresh appraisal of traditional practices. He made a major contribution not only to the Geological Survey and the Mines Department but to the geological profession in the State.

In addition to the retirement of Mr Lord there were 13 resignations from the professional staff, reflecting the continuation and intensification of the exploration boom whose initiation was noted in 1979 and which has already been referred to in this report. A disturbing feature of these resignations is the number of more experienced geologists who left to join industry: between them those who resigned had 77 man years of experience with the Survey, disregarding experience already possessed at the time of joining, and their departure represents a substantial loss of irreplaceable experience and expertise. There is an urgent need for a review of the wide discrepancies between the rewards presently available to geologists in industry and those in Government services, and also of the overall scope for experienced geologists to achieve satisfactory career levels within the Geological Survey by comparison with both other professions within the public service and with professional opportunities outside it. While it is in the best interest of the State that there should be a degree of professional interchange between the Survey and industry the gross imbalance in this interchange during 1980 will certainly be harmful if it remains unchecked.

PROFESSIONAL

Name	Position	Effective Date
Appointments		
Barley, M. Ph.D.	Geologist L1	2/1/80
Beere, G. B.Sc. (Hons)	Geologist L1	6/2/80
Mory, A. J. B.Sc. (Hons)	Geologist L1	4/3/80
Griffin, T. B.Sc. Ph.D.	Geologist L1	9/4/80
Seymour, D. B.Sc. (Hons)	Geologist L1	11/4/80
Thorne, A. B.Sc., Ph.D.	Geologist L1	10/9/80
Kevi, L. B.Sc., D.I.C.	Geologist L2	2/12/80
Promotions		
Trendall, A. F.	Director	25/2/80
Playford, P. E.	Deputy Director	15/5/80
Gee, R. D.	Assistant Director	24/7/80
Resignations		
Brakel, A.	Geologist L2	29/2/80
Muhling, P. C.	Geologist L2	26/3/80
Archer, R. H.	Geologist L2	18/4/80
Denman, P. D.	Geologist L3	9/5/80
Morrison, J. R.	Geologist L2	21/5/80
Nowak, I. R.	Geologist L2	23/5/80
Daetwyler, N. A.	Geologist L1	23/5/80
Lewis, I. H.	Geologist L2	30/5/80
Thom, R.	Geologist L2	4/7/80
Tuckson, M.	Geologist L1	21/11/80
Barnett, J. C.	Geologist L2	28/11/80
Marston, R. J.	Geologist L3	17/12/80
Barley, M.	Geologist L1	19/12/80

CLERICAL AND GENERAL

Name	Position	Effective Date
Appointments		
Martin, S.	Laboratory Assistant	26/2/80
Walker, R. M.	Typist	6/5/80
Sadgrove, G.	Geological Assistant	8/5/80
Eddy, A.	Geological Assistant	12/5/80
Bicknell, D.	Technical Assistant	10/7/80
Crossley, L.	Laboratory Assistant	15/9/80
Giles, K.	Technical Assistant	22/10/80
Promotions		
Thomas, H.	Technical Officer	21/2/80
Transfer Out		
McKenzie, J.	Clerk	11/1/80
Toohey, J.	Technical Assistant	29/4/80
Mountier, A.	Typist	5/5/80
Resignations		
Walker, I.	Geological Assistant	1/2/80
Bryce, A.	Laboratory Assistant	9/4/80
Wall (Kirov), H.	Technical Assistant	4/7/80
Evans, D.	Technical Assistant	10/9/80

ACCOMMODATION

No changes to available accommodation took place during 1980. The location of the Hydrogeology and Engineering Geology Branches at 196 Adelaide Terrace continued to inconvenience the most effective operation of those groups, and there is an urgent need for additional construction on the Mineral House site so that the operations of the geological survey as a whole can be more efficiently integrated.

OPERATIONS

HYDROGEOLOGY BRANCH

T. T. Bestow (Supervising Geologist), A. D. Allen, A. T. Laws (Senior Geologists), J. C. Barnett, D. P. Commander, W. A. Davidson, K-J. B. Hirschberg, L. J. Furness, J. Hall, M. Martin, J. S. Moncrieff, R. Smith, M. Tuckson, P. H. Wharton.

The amount of drilling undertaken by the Mines Department for water resources investigations fell sharply from an aggregate depth of about 6 300 m in 1979 to less than 3 000 m in 1980. It was necessary to suspend further work on the highly successful Perth Basin deep drilling programme for 12 months. This unfortunate decline in an important aspect of the work of the Department resulted from the effects of cost inflation and a reduced budgetary provision for drilling.

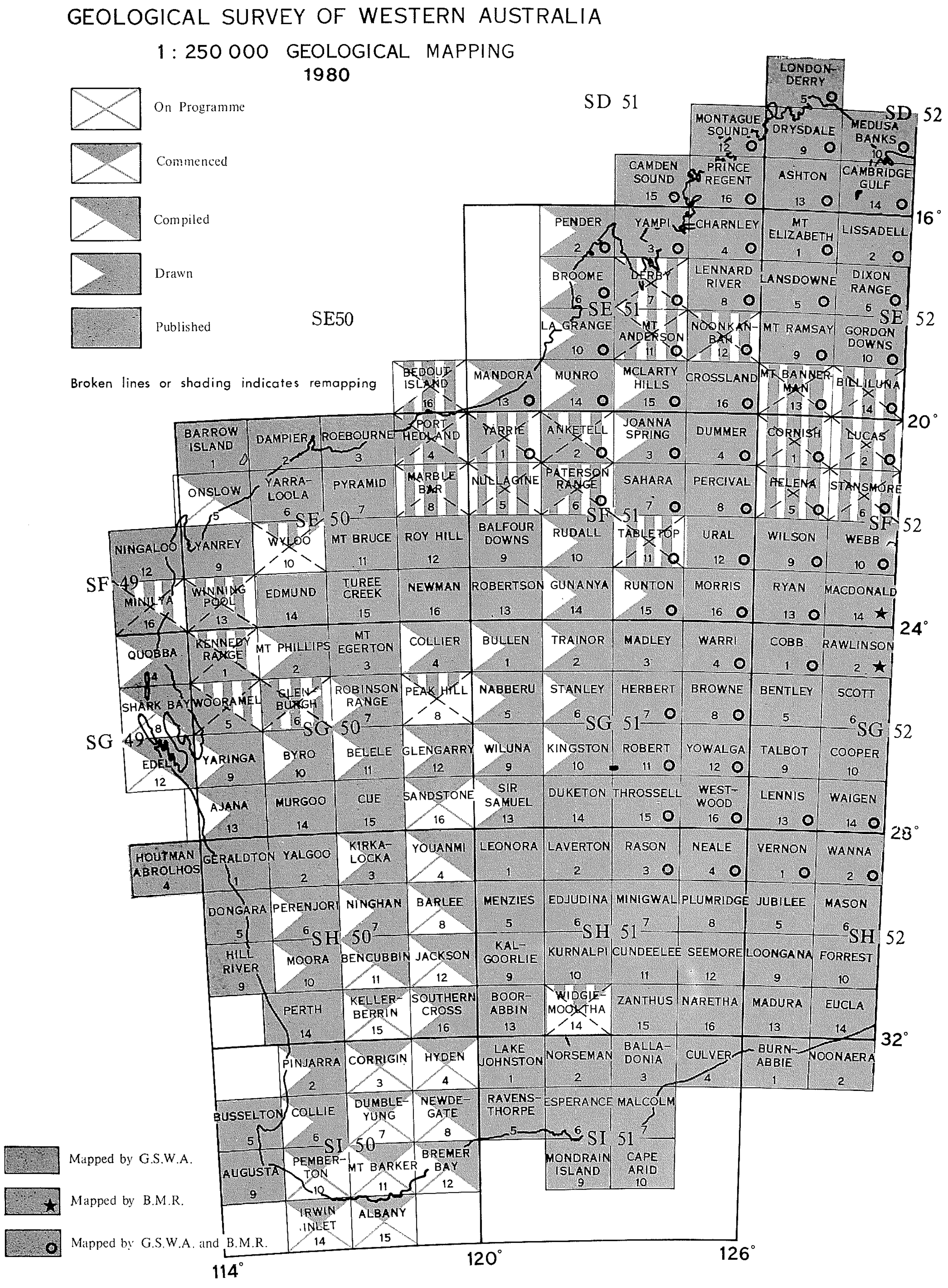


Figure 2 Progress of 1:250 000 and 4 mile geological mapping at the end of 1980.

Two thirds of the drilling effort was devoted to establishing monitoring and test-pumping bores north of the Gingin Brook as part of the Salvado shallow groundwater resources investigation. Twenty sites were drilled to depths of 38 to 126 m. Substantial resources of domestic quality water have been located as a result of this work. The second phase of drilling in the South West Coastal Groundwater Area has commenced with the construction of pumping bores on two sites near Lake Clifton.

Exploration of the deeper aquifers in the Perth area by the Metropolitan Water Supply Board has been further extended by drilling 11 bores to depths of between 327 and 755 m. The information provided will be of great value to the planning of water supply expansion. Liaison with officers of the Board continues to be close, particularly with respect to groundwater development and management. In addition, assistance has been provided with the assessment of consultants' reports on Yanchep-Two Rocks and urban water balance studies. A report has been prepared on the water resources of the Swan Valley Groundwater Control Area.

Reports have been written concerning public water supplies at Cue, Allanooka (Geraldton), Hopetoun, Mandurah, Peaceful Bay, and potential emergency supplies at Mendel-Wongoondy. The results of a drilling programme at Harvey were assessed and reported. Assistance was also provided to the Public Works Department with an investigation of a proposed saline river diversion involving the Tone and Kent rivers. An evaluation of the effects of groundwater abstraction by mining companies at Eneabba was completed, and comments made on consultants' reports on the expansion of Mount Newman Water Supply.

At the request of the Commonwealth Department of Aboriginal Affairs an important programme of drilling and testing was commenced in the Central Aboriginal Reserve surrounding Warburton and recommendations made regarding Cundeelee water supply. Sites have been successfully selected to locate water supplies for compaction along highway routes through Halls Creek and Mount Newman for the Main Roads Department.

A preliminary assessment of the geothermal resources of the State was commenced.

Groundwater pollution surveys were undertaken in three areas and assessments were made of consultants', and other reports, on accidental discharges of industrial effluents into shallow groundwater systems at Kwinana. Advice continued to be provided to the Public Works Department on the management of acid effluent disposal at Australind.

The effects on groundwater and stream salinities of bauxite mining and of the woodchip industry continued to be the subject of inter-departmental study. A drilling programme was undertaken to establish bores in the George Forestry Block to monitor the effects of different forest associations on rainfall infiltration.

The demand for hydrogeological investigations and advice has continued to expand to the extent that all available staff have been fully committed, and some highly desirable and important work has had to be postponed. This has unfortunately included the commencement of hydrogeological mapping in wheatbelt areas to be used as a basis for emergency water supply planning and possibly drought relief. However, advice has been given to the Farm Water Supply Committee and eight Shires with respect to specific water supply problems. A steady demand by farmers and other landowners for water supply advice was experienced and resulted in 122 inspections being completed. The borehole record system continued to be augmented by information collected by census; the southern Perth Basin and Perenjori area have been completed and work has commenced at Northam.

In response to an upsurge in mineral exploration and development there was some increase in groundwater exploration in the Goldfields by consultants to mining companies. Close liaison has been maintained with both the other government departments and the companies involved.

ENGINEERING GEOLOGY BRANCH

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

Activities were largely confined to investigations for other Government Departments and instrumentalities, including:

Department of Public Works:

(*a*) Reconnaissance of dam sites between Waroona and Collie, and in the Manjimup area.

(*b*) Geological and geophysical studies of the Ord River Dam spillway.

(*c*) Minor investigations including geological advice on Harding-Karratha Pipeline, Ravensthorpe bitumen catchment, and Kalbarri sewerage treatment plant.

Metropolitan Water Board:

(*a*) Geological mapping during the construction of the Wungong and Bibra tunnels.

(*b*) Geological and geophysical studies at a Little Dandalup dam site.

(*c*) Geological mapping in support of safety reviews of several existing dams.

In addition, miscellaneous minor investigations were carried out on behalf of Westrail, the State Energy Commission, the Department of Conservation and Environment and the Commonwealth Department of Housing and Construction. Contributions were also made to urban geology maps and to a report on the Cadoux earthquake. A feature of the year's work was the number of reports completed and issued in connection with past studies.

REGIONAL GEOLOGY BRANCH

Supervising Geologist (vacant following the promotion of R. D. Gee), I. R. Williams (Senior Geologist), R. J. Chin, S. J. Williams, T. J. Griffin, D. B. Seymour, A. M. Thorne.

Compilation and production of 1st edition 1:250 000—scale sheets, mapped prior to 1980, is nearing completion. Field mapping commenced on Wyloo 1:250 000 Sheet (2nd edition). This project marks the beginning of a long-term re-appraisal of the Ashburton Fold Belt and the southern margin of the Hamersley Basin.

One officer, based in the Kalgoorlie Regional Office, commenced remapping the Widgiemooltha 1:250 000 Sheet (2nd edition).

Sampling of banded gneiss for Rb-Sr geochronological work has been undertaken on the Byro 1 250 000 Sheet.

Work on the Bangemall Bulletin is complete, and the Nabberu Basin Bulletin is nearing completion. Field reassessment for a synthesis of Gascoyne Province was completed.

SEDIMENTARY BRANCH

M. H. Johnstone (Supervising Geologist), K. A. Crank, H. T. Moors (Senior Geologists), M. N. Megallaa (Senior Geophysicist), R. M. Hocking, B. P. Butcher, A. J. Mory, G. M. Beere.

The processing of data received from petroleum exploration companies continued on a routine basis. During 1980, 18 packages of microfilm data were prepared from this material for dissemination to the petroleum industry. Thirty-six petroleum exploration permits were issued during the year.

Preparation of the bulletin on the offshore and onshore portions of the Carnarvon Basin continued during the year. Finalization of the maps and preparation of the explanatory notes for the Wooramel, Kennedy Range and Winning Pool-Minilya 1:250 000 Sheets continued. A field party commenced mapping the Western Australian part of the Bonaparte Gulf Basin during 1980.

Preliminary maps for an assessment of the reserves of the Collie Coal Field were prepared during the year.

MINERAL RESOURCES BRANCH

J.G. Blockley (Supervising Geologist), J. D. Carter (Senior Geologist), J. L. Baxter, D. F. Blight, A. H. Hickman, S. L. Lipple, S. A. Wilde.

In co-operation with the Regional Mapping Branch, a start was made on the remapping of the Wyloo 1:250 000 Sheet. Compilation of the Pemberton Sheet was completed and the Explanatory Notes were almost finished.

The manuscript of a Mineral Resources Bulletin on nickel in Western Australia was completed and is in the hands of the editors. Further studies leading to a Bulletin on bauxite were undertaken.

Field investigations of the Warriedar Fold Belt were finalized and a report commenced. Work continued on the study of the Mount Monger area being undertaken from the Kalgoorlie Regional Office.

Assessments of the State's gold and manganese resources were completed. Forty-one rolls of microfilm were added to the library of open file reports on mineral exploration.

For the second Archaean Symposium held in May, divisional staff helped prepare four papers and assisted in running three field excursions. One staff member contributed to a course in heavy-mineral mining run by the Kalgoorlie School of Mines for the Australian Aid and Development Agency; another helped edit papers for a forthcoming issue of Economic Geology dealing with Western Australian nickel deposits; and a third organized a colloquim on the stratigraphy of the Marra Mamba Iron Formation.

Miscellaneous investigations included inspections of a proposed townsite in the Hamersley Range area, a manganese deposit in the Fitzgerald River National Park, a tungsten prospect near Nanutarra, a marble quarry on Wyloo Station and a new gold find near Leonora.

COMMON SERVICES BRANCH

Petrology

W. G. Libby, J. D. Lewis and M. E. Barley.

Demand for petrographic services eased slightly, with 74 petrological reports completed covering 1 408 thin sections. Further thin sections were studied for incorporation into the computer index system.

During the year a major report on the Cadoux earthquake was completed and several shorter papers were prepared for publication. Studies on kimberlites, the Corunna Downs and Mount Edgar batholiths, and on alkaline granites of the Eastern Goldfields continued.

The cooperative geochronology programme with the Western Australian Institute of Technology resulted in the publication of two papers and the preparation of four more papers. Nineteen projects were active in 1980; eleven are scheduled for 1981.

The laboratory prepared 1 767 petrographic thin sections, 327 sedimentary thin sections and 60 polished mounts. Two hundred and fifty nine samples were prepared for chemical or geochronological analysis. Two hundred and fifty one specific gravity determinations, 84 mineral separations and 31 grain size analyses were completed.

The Government Chemical Laboratories continued to identify mineral samples and to provide access to X-ray diffractometer and computer facilities.

Palaeontology

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

During the year 71 reports were written and 550 samples added to the fossil collection. Some 8 000 palaeontological samples from relinquished petroleum tenements were catalogued. Most of the section's work involved Perth Basin Mesozoic palynomorphs (for the Hydrogeology Division), Precambrian fossils (for the Regional Geology Division) and various Palaeozoic invertebrate fossils from the Bonaparte Gulf Basin (for the Sedimentary Division).

Geophysics

D. L. Rowston, L. Kevi.

Well-logging activity increased from 77 logging operations in 1979 to 148 in 1980; the aggregate total depth of all bores was 38 880 m. Much of the increase can be attributed to re-entry to a number of the deeper stratigraphic water bores in the Perth Basin to obtain temperature logs for an assessment of geothermal energy resources. Forty-three deep bores were logged for this reason.

Seven seismic refraction surveys were undertaken during the year. Water catchment salinity investigations at Collie, Lake Toolibin and George Block were augmented by the resultant seismic sections. The bedrock configuration was mapped at prospective dam sites at Manjimup and Little Dandalup and overburden velocity characteristics used to evaluate probable scouring of auxiliary spillways at the Ord Dam. Seismic velocities and depths to the bedrock refractor indicated the rippability of superincumbent material and depths to bedrock adequate for the construction of cuttings without encountering hard rock along the Worsley Alumina railway alignment.

A pulse induction metal detector with a penetration greater than those presently employed in the Warnbro Shell clearance project was evaluated. The ability to detect shells at about two metres was offset by difficulties in pinpointing the target.

Groundwater salinity prospects involved 300 conductivity measurements of samples from monitoring bores and salinity determinations for the public amounted to 200. Public enquiries on geophysical matters remained steady at about 85.

Environmental Geology

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

Work continued on the 1:50 000 Urban Geology map series with the completion of the De Witt - Picard Sheet and some progress on sheets in the Port Hedland and Bunbury areas.

Geological information was supplied for a variety of projects, including seven town planning scheme amendments, eight environmental review and management proposals and various nature conservation recommendations and studies. The section was involved in a continuing study of basic raw materials, such as clay, limestone and sand, in the Perth metropolitan area.

Appraisal also continued on all applications for mineral tenements in the South West Mineral Field in order to lessen the impact of mining on the environment.

Geochemistry

R. Davy.

Work was centred on three continuing studies: The geochemistry of the Pilbara granitoids (the Mount Edgar and Corunna Downs Batholiths), the geochemistry of Pilbara volcanic suites and problems in studying the chemistry of iron-formations.

A preliminary report on the Mount Edgar Batholith was given to the Archaean Symposium in Perth.

Technical Information

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

Two sheets in the 1:250 000 geological series with explanatory notes were published by the Geological Survey during 1980. One preliminary map in this series was received from the B.M.R.

This year the annual report, one bulletin, two mineral resources bulletins, one report, two geological maps with explanatory notes, two urban geology maps, and the booklet 'Mineral Resources of Western Australia' were published. The 1:1 000 000 map of the Pilbara Block was released (prior to the publication of the accompanying bulletin) for an excursion during the Archaean Symposium.

One bulletin and four explanatory notes were sent to press making a total of 7 explanatory notes and maps with the Government Printer. Eleven records were published and also issued on microfiche. One information pamphlet was revised.

Requisitions raised on the Surveys and Mapping Branch for drafting, photography and copying totalled 1 341.

Public enquiries continued at a high level. The section answered 1 880 requests for information, including rock identifications, 546 of which required detailed research.

Book and periodical loans to the staff totalled 8 497, and loans to and from other libraries 462; 5 472 members of the public visited the library for research purposes.

Forty-one rolls of microfilm were added to the 'M' Series. Public users of the microform facilities totalled 1 363.

Survey publications (especially those out of print) were progressively copied on to microfiche. Bulletins 1–115 and the more recent records became available for sale in this form.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

No geological field work was carried out by the Bureau of Mineral Resources in Western Australia during 1980, except for systematic collection of samples for chemical analysis from the Pilbara Block in support of its continuing joint geochemical project with this Survey.

The Geophysical Branch conducted airborne magnetic and radiometric surveys over the following 1:250 000 sheet areas: Pemberton (western third), Collie, Gordon Downs (southern half), Billiluna, Lucas and Stansmore.

With the co-operation of the CSIRO Division of Applied Geomechanics, the BMR Geophysics Branch made 9 in situ stress measurements in the South West Seismic Zone. Five of these were in the vicinity of Cadoux, the others farther south.

PROGRAMME FOR 1981

(Items marked * will be carried out from the Kalgoorlie Regional Office; the commencement of those marked † will depend on recruitment of adequate staff.)

HYDROGEOLOGY BRANCH

1. Continuation of the hydrogeological survey of the Perth Basin, including deep drilling on the Boyanup line and planning of the Gillingarra line.
2. Hydrogeological assessments and/or exploratory drilling for groundwater in the following areas:
   (a) Millstream-Weelumurra
   (b) East Pilbara
   (c) Collie Basin
   (d) Lake Clifton
   (e) Harvey-Waroona irrigation area
   (f) Rottnest Island
3. Town water supply investigations and/or drilling for: Mount Magnet, Bunbury, Lancelin-Salvado, Madora, Singleton, Pellhurst.
4. Hydrogeological investigations for the Metropolitan Water Supply Board, including:
   (a) Deep drilling for artesian monitoring scheme
   (b) Planning new wellfield at Pinjar

(c) Assessment of the effects of pumping at Mirrabooka, Wanneroo, Gwelup, and Jandakot
(d) Continuing study of water balance of coastal lakes
†(e) Assessment of recharge to the Gnangara Mound using tritium tracer
(f) Commencement of publication on Perth metropolitan groundwater resources
(g) Miscellaneous other evaluation, assessment, and advice.

5. Interdepartmental studies concerning groundwater salinity problems in the Darling Range bauxite and woodchip areas.

6. Regional hydrogeological studies, including:
(a) systematic bore census of selected areas
†(b) complete 1:250 000 scale hydrogeological mapping of Perenjori sheet, and commence Collie and Perth sheets.

7. Hydrogeological advice on groundwater pollution control in various areas including: Australind, Gnangara, Kwinana, and the Perth Metropolitan Area generally.

8. Continuing study of the feasibility of using geothermal energy resources.

9. Miscellaneous investigations and inspections as required by Government departments and the public.

ENGINEERING GEOLOGY BRANCH

1. South-West Division dam site investigations and/or continuing advice including: Manjimup, Waroona-Collie area, Wungong, South Canning, North Dandalup, Little Dandalup.

2. Continuing North West dam site and pipeline investigations.

3. Spillway studied for Ord River Dam.

4. Geological studies and advice during construction of the Wungong and Bibra tunnels.

5. Maintain an interest in geological aspects of earthquake activity.

6. Geological advice on quarry sites and miscellaneous problems for various Government Departments and authorities, including Public Works Department, Westrail, and State Energy Commission.

REGIONAL GEOLOGY BRANCH

1. Completion of compilation and explanatory notes for the remaining 1:250 000 first edition geological maps of Western Australia. Completion of additional field work needed to co-ordinate preparation of Kellerberrin, Corrigin, and Dumbleyung sheets.

2. Completion of geological synthesis of the Gascoyne Province.

3. Continuation of re-mapping of Wyloo and commencement of re-mapping of Cue 1:250 000 sheets.

4. Completion of the re-mapping of Peak Hill 1:250 000 sheet.

*5. Continuation of the re-mapping of the Widgiemooltha sheet.

6. Detailed mapping of the Mt Narryer metamorphic belt.

SEDIMENTARY BRANCH

1. Maintain an active interest in the progress and assessment of exploration and potential for fossil fuels in Western Australia, including the checking and assessing of all company reports on exploration, and preparation of microfilm open-file system.

2. Completion of the study of the surface and subsurface geology of the Carnarvon Basin, and submission for publication.

3. Continuation of mapping and study of the Bonaparte Gulf Basin, and commence mapping of the Ord Basin.

†4. Commencement of a reappraisal of the geology and coal resources of the Collie Basin.

5. Minor geological investigations as required.

MINERAL RESOURCES BRANCH

1. Maintain an active interest in the progress and assessment of exploration and potential for minerals other than fossil fuels in Western Australia, including the checking and assessing of all company reports on exploration, and preparation of microfilm open-file system.

2. Completion of study of the Warriedar fold belt.

3. Continue study of the bauxite of the Darling Range area.

4. Completion of assessment of iron ore on Ministerial Reserves.

5.† Study of economic geology of the Murchison Province.

6. Investigation of the geology and economic potential of the lower part of the Fortescue Group in the southwestern part of the Hamersley Basin.

7.* Detailed mapping and mineral study of the Mount Monger area.

8. Miscellaneous investigations as required.

COMMON SERVICES BRANCH

Petrology

1. Carry out petrological investigations as required by other Divisions.

2. Special topics for investigation (all continuing):
(a) Alkaline granitoids of the Eastern Goldfields
(b) Rb-Sr Geochemistry of the Black Range dolerite
(c) Petrology of the Kimberlites and related rocks of the Kimberley
(d) Petrology of the Corunna Downs and Mount Edgar batholiths.

3.† Study of regional metamorphic patterns in the Southern Cross Province of the Yilgarn Block.

Palaeontology

1. Carry out palaeontological investigations as required by other Divisions.

2. Completion of palynological study of the Early Cretaceous of the Perth Basin.

3. Completion of study of Nabberu Basin stromatolites, and continuation of miscellaneous stromatolite studies.

4. Completion of study of biostratigraphy and systematics of Devonian radiolarians from the Canning Basin.

5. Completion of study of Gneudna stromatoporoids (Carnarvon Basin).

6. Study of miscellaneous invertebrate material from Bonaparte Gulf Basin.

7. Initial review of Mesozoic palynology of Carnarvon Basin, including North West Shelf.

Geophysics

1. Well logging on groundwater drilling projects as required.

2. Seismic traverses to assist hydrogeological studies on the Perenjori, Perth, and Collie Sheets.

3. Seismic surveys required for dam site investigations.

4. Gravity surveys to assist geological interpretation:
(a) Southern Cross-Bullfinch area
(b) Warriedar Fold Belt.

5. Geothermal logging of bores in support of geothermal energy resource investigation.

6. Investigation of effects of jointing in crystalline rocks on seismic velocity.

7. Miscellaneous other geophysical investigations as required.

Geochemistry

1. Completion of geochemical studies of the Mount Edgar and Corunna Downs batholiths.

2. Completion of studies on:
(a) Mercury in sulphides
(b) Yarrie ironstones.

3. Continuation as required of geochemical studies on Warriedar Fold Belt, Mount Monger area, kimberlites, and Weeli Wolli Formation.

4. Maintain an active interest in exploration geochemical work carried out by companies.

Environmental Geology

1. Complete compilation of urban geology maps of the Bunbury, Harvey, and Port Hedland areas.

2.† Commence fieldwork for urban geology maps of the Perth, and possibly Carnarvon areas.

3. Assessment of environmental reports as required.
4. Mineral tenement appraisals as required.
5. Examination of miscellaneous environmental geological problems as required.

PUBLICATIONS

Issued during 1980

Annual Report 1979

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

Mineral Resources Bulletin 12: The tin deposits of Western Australia with special reference to the associated granites.

Mineral Resources Bulletin 13: Copper mineralization in Western Australia.

Report 10: A chemical and mineralogical study of low-grade zinc mineralization at three localities in the Proterozoic Bangemall Basin of Western Australia.

Geological map of Nullagine 1:250 000 sheet (SF51-5 International Grid) with explanatory notes.

Geological map of Yanrey-Ningaloo 1:250 000 sheet (SF50-9, SF49-12 International Grid) with explanatory notes.

Urban geology maps 1:50 000: Dampier, Roebourne.

Mineral Resources of Western Australia.

(Available in microfiche)

Record 1980/1 Wells drilled for petroleum exploration in Western Australia to the end of 1979; by K. A. Crank.

Record 1980/2 Explanatory notes on the Ninghan 1:250 000 geological sheet, Western Australia; by S. L. Lipple, J. L. Baxter and R. J. Marston.

Record 1980/3 Explanatory notes on the Kirkalocka 1:250 000 geological sheet, Western Australia; by J. L. Baxter, S. L. Lipple and R. J. Marston.

Record 1980/4 Explanatory notes on the Glenburgh 1:250 000 geological sheet, Western Australia; by S. J. Williams, I. R. Williams and R. M. Hocking.

Record 1980/5 Explanatory notes on the Byro 1:250 000 geological sheet, Western Australia; by I. R. Williams, I. W. Walker, R. M. Hocking and S. J. Williams.

Record 1980/6 Explanatory notes on the Belele 1:250 000 geological sheet, Western Australia; by M. Elias (in prep.).

In press

Bulletin 127: Geology of the Pilbara Block and its environs

Geological map of Broome 1:250 000 sheet (SE/51-6 International Grid) with explanatory notes.

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

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

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

Geological map of Joanna Spring 1:250 000 sheet (SF/51-3 International Grid) with explanatory notes.

Geological map of Kingston 1:250 000 sheet (SG/51-10 International Grid) with explanatory notes.

Geological map of La Grange 1:250 000 sheet (SE/51-10 International Grid) with explanatory notes.

Geological map of Mandora 1:250 000 sheet (SE/51-13 International Grid) with explanatory notes.

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

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

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

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

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

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

Geological map of Robinson Range 1:250 000 sheet (SG/50-7 International Grid) with explanatory notes.

Geological map of Rudall 1:250 000 sheet (SF/51-10 International Grid) with explanatory notes.

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

In preparation

Bulletin 128: Geology of the Bangemall Group—the evolution of a Proterozoic intra-cratonic sedimentary basin.

Bulletin: The geology of the Earaheedy Group, Nabberu Basin.

Mineral Resources Bulletin: Nickel

Report 11: The Cadoux earthquake, 2 June 1979

Report: Gascoyne Province

Geological maps 1:250 000 with explanatory notes, the field work having been completed: Ajana, Albany, Anketell, Barlee, Belele, Bencubbin, Bremer Bay, Byro, Collie, Collier, Corrigin, Dumbleyung, Glenburgh, Glengarry, Hyden, Irwin Inlet, Jackson, Kellerberrin, Kirkalocka, Moora, Mount Barker, Mount Phillips, Nabberu, Newdegate, Ninghan, Onslow, Paterson Range, Pemberton, Perenjori, Port Hedland, Quobba, Sandstone, Shark Bay-Edel, Southern Cross, Stanley, Wiluna, Yaringa, Yarrie, Youanmi.

Urban Geological maps 1:50 000: Boodarrie, de Witt-Picard, Port Hedland, and two sheets in the Bunbury-Harvey area.

Reports in other publications

Allen, A.D., 1979, Availability of groundwater from riverine environments in northern South Australia: South Australia Engineering and Water Supply Department Pub. 79/51.

Barley, M. E., 1980, Relations between magma types in the Warrawoona Group: Continuous or cyclic evolution?: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p.30-31.

——— 1980, Resource development in Archaean Shields: Second International Archaean Symposium, Perth, Western Australia, 12-16 May, 1980: Episodes v. 1980(3), p. 36-37.

Biggs, E. R., 1980, Geological hazards in Western Australia, *in* Hofmann, G. W. (ed.) Proceedings of the Third Urban and Environmental Geologists Symposium, Brisbane, 1980: Geol. Survey Queensland Rec. 1980/37.

Biggs, E. R., and Mather, R. P., 1980, Environmental and engineering mapping techniques, *in* Hofmann, G. W. (ed.) Proceedings of the Third Urban and Environmental Geologists Symposium, Brisbane, 1980: Geol. Survey Queensland Rec. 1980/37.

Cockbain, A. E., 1980, Conversion of microscope-stage co-ordinates: Micropaleontology v. 26, p. 95-96.

Commander, D. P., 1980, Groundwater flow in the northern Perth Basin: Int. Geol. Congress, XXVI, Abstracts p.1098.

Davy, R., and Lewis, J. D., 1980, Geochemistry of the Mount Edgar batholith, Pilbara area, Western Australia: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p.43-44.

Davy, R., Rossiter, A. R., and Wall, L. N., 1980, Stream sediments: Jour. Geochem. Exploration v. 12(2/3), p. 131–133.

Davy, R., and Ryall, W. R., 1980, Plants: Jour. Geochem. Exploration v. 12(2/3), p. 136–137.

——— 1980, Atmospheres: Jour. Geochem. Exploration v. 12(2/3) p. 137–138.

Gee, R. D., Williams, I. R., Wilde, S. A., and Baxter, J. L., 1980, Crustal development of the Yilgarn Block: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 79–80.

Glikson, A. Y., and Hickman, A. H., 1980, Geochemical stratigraphy of Archaean greenstone sequences, eastern Pilbara Block, Western Australia: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 28–29.

Grey, K., 1980, Aspects of Proterozoic stromatolite biostratigraphy in Western Australia: Intern. Geological Congress, XXVI, Abstracts p. 588.

Groves, D. I., and Gee, R. D., 1980, Regional geology and mineral deposits of the Kalgoorlie-Norseman region: Intern Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Excursion Guide.

Hamilton, P. J., Evensen, N. M., O'nions, R. K., Glikson, A. Y., and Hickman, A. H., 1980, Sm-Nd dating of the Talga-Talga Subgroup, Warrawoona Group, Pilbara Block, Western Australia: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 11–12.

Hickman, A. H., 1980, Archaean geology of the Pilbara Block: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Excursion Guide.

Hickman, A. H., 1980, Crustal evolution of the Pilbara Block: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 78–79.

de Laeter, J. R., Libby, W. G., Trendall, A. F., and Fletcher, I. R., 1980, The older Precambrian geochronology of Western Australia: Intern, Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 9–10.

Marston, R. J., and Groves, D. I., 1980, The metallogenesis of Archaean base-metal deposits in Western Australia: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts p. 46–47.

Marston, R. J., and Kay, B. D., 1980, The distribution, petrology, and genesis of nickel ores at the Juan Complex, Kambalda, Western Australia: Econ. Geol. v. 75(4), p. 546–565.

Playford, P. E., 1980, Devonian "Great Barrier Reef" of Canning Basin, Western Australia: Amer. Assoc. Petroleum Geologists Bull. v. 64, p. 814–839.

——— 1980, Australia's stromatolite stronghold: Natural History v. 89, No. 10, p. 58–61.

Wilde, S. A., 1980, The Jimperding Metamorphic Belt in the Toodyay area, and the Balingup Metamorphic Belt and associated granitic rocks of the southwestern Yilgarn Block: Intern. Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Excursion Guide.

THE HYDROGEOLOGY OF THE SWAN VALLEY PERTH BASIN, WESTERN AUSTRALIA

by A. D. Allen

ABSTRACT

The Swan Valley is situated at the eastern edge of the Perth Basin and is underlain by up to 13 000 m of Phanerozoic sedimentary rocks. The formations with significant groundwater resources extend to a depth of about 1 000 m. They occur in a gentle syncline overlain by a thin veneer of flat-lying surficial sediments.

The main aquifers containing fresh water are the Quaternary "superficial formations", and the Cretaceous Osborne and Leederville Formations. Of these, the Leederville Formation, which contains a regional groundwater flow system is by far the most important. It is recharged directly from the "superficial formations" or via the Osborne Formation, and has an upper fresh-water zone (<1 000 mg/L TDS) and lower brackish-water zone, each about 160 m thick. Annual throughflow of fresh groundwater is estimated to be 5 x 10^6 m^3/y, and private annual abstraction, mainly for irrigation of vineyards, is about 3·5 x 10^6 m^3/y. Only limited scope for increased abstraction is possible before a "mining situation" is reached. A further limitation is the underlying brackish groundwater, which has an upward head, and which may be induced to move upwards to cause an unacceptable increase in salinity.

INTRODUCTION

LOCATION

The name Swan Valley is applied to a broad area adjacent to the Swan River, an area which extends from where the Swan River enters the coastal plain to its confluence with the Helena River (Fig. 1), near the towns of Midland and Guildford. The statutory Swan Groundwater Area of about 170 km^2 (Fig. 1) includes most of the area generally regarded as the Swan Valley.

BACKGROUND

Vineyards were first established in parts of the Swan Valley in 1850. Since then, it has become the major grape-growing area in Western Australia, producing wine, table grapes and dried fruit.

Prior to the late 1950s, apart from some local irrigation, grape production relied mainly on rainfall. Since then, irrigation of the vineyards during the summer from artesian and sub-artesian bores has become a generally accepted practice. Between 1960 and 1970, about 200 bores were drilled, and currently there are about 400 non-domestic bores in use, mainly for irrigation of vineyards.

In the early 1970s, concern was expressed about the decline in artesian head and reputed increase in salinity of groundwater from some bores. A preliminary assessment of the groundwater resources was made by Allen (1975), and subsequently, on 10 September 1975, the Swan Groundwater Area was proclaimed by the Public Works Department (PWD) under the *Rights in Water and Irrigation Act*, 1914–1976. This enabled the licensing and control of all bores in the statutory area.

CLIMATE AND LAND USE

The climate in the Swan Valley is of the Mediterranean type characterized by mild, wet winters and hot, dry summers.

Average rainfall statistics are available for Guildford and for the Department of Agriculture Research Station in Upper Swan, and are given in Table 1.

TABLE 1. AVERAGE MONTHLY RAINFALL (mm), DEPARTMENT OF AGRICULTURE RESEARCH STATION, UPPER SWAN, AND GUILDFORD (COMMONWEALTH BUREAU OF METEOROLOGY DATA)

J	F	M	A	M	J	J	A	S	O	N	D	Average
Guildford (1877–1954)												
8	10	17	43	122	177	172	139	86	56	20	13	863
Department of Agriculture Research Station (1957–1978)												
8	12	13	40	100	149	172	104	68	45	18	10	739

The rainfall tends to decrease northward, and to increase eastward as a result of the orographic effect of the Darling Scarp. Over 85% of the annual rainfall is received in the winter, between May and October. However, the annual rainfall may vary between wide limits, as at Guildford where it has varied from 496 mm (1914) to 1 312 mm (1926). As well, sequences of years of above or below average rainfall are common.

The warmest month is February and the coolest, August; the mean maximum temperatures, as measured at Guildford, are 33·3°C and 17·8°C, and the mean minimum temperatures, 16·2°C and 6·4°C respectively. The average potential evaporation, which is about three times the annual average rainfall, is greatest in January (331 mm), least in June (79 mm), and has an annual average of 2 156 mm (Department of Agriculture Research Station).

With the exception of the townsites, clay pits and associated brick and tile manufacturing plants, the Swan Valley is a rural area, divided into small and medium holdings which are mainly under pasture and used for cattle raising, horse breeding and training, kennels, poultry farms, piggeries, and cereal production. Irrigated agriculture is practiced mainly on suitable soil types adjacent to the Swan River (Pymm, 1955). In these areas, there are irrigated vineyards (about 12 km^2) and smaller areas of citrus orchards, olive trees, and market gardens (Fig. 9).

SOURCES OF DATA

Geological, salinity and head data are available from the Geological Survey (GSWA) for about 1 000 bores and wells located during a bore census in March and July 1969 and September 1970. Similar data are available from 20 PWD monitoring bores, and exploratory bores drilled by the Metropolitan Water Supply Sewerage and Drainage Board (MWB).

Wire-line logs, mainly gamma-ray and long- and short-normal resistivity, are available for about 90 bores in the Swan Valley. Most have been obtained since 1962 by the GSWA, and a few, by a private contractor. Most deep bores drilled since 1975 have been logged, and these provide the most reliable data on geology and groundwater salinity.

Chemical analyses of groundwater from selected deep and shallow bores, and of surface waters have been made by the Government Chemical Laboratories and are on file at the GSWA.

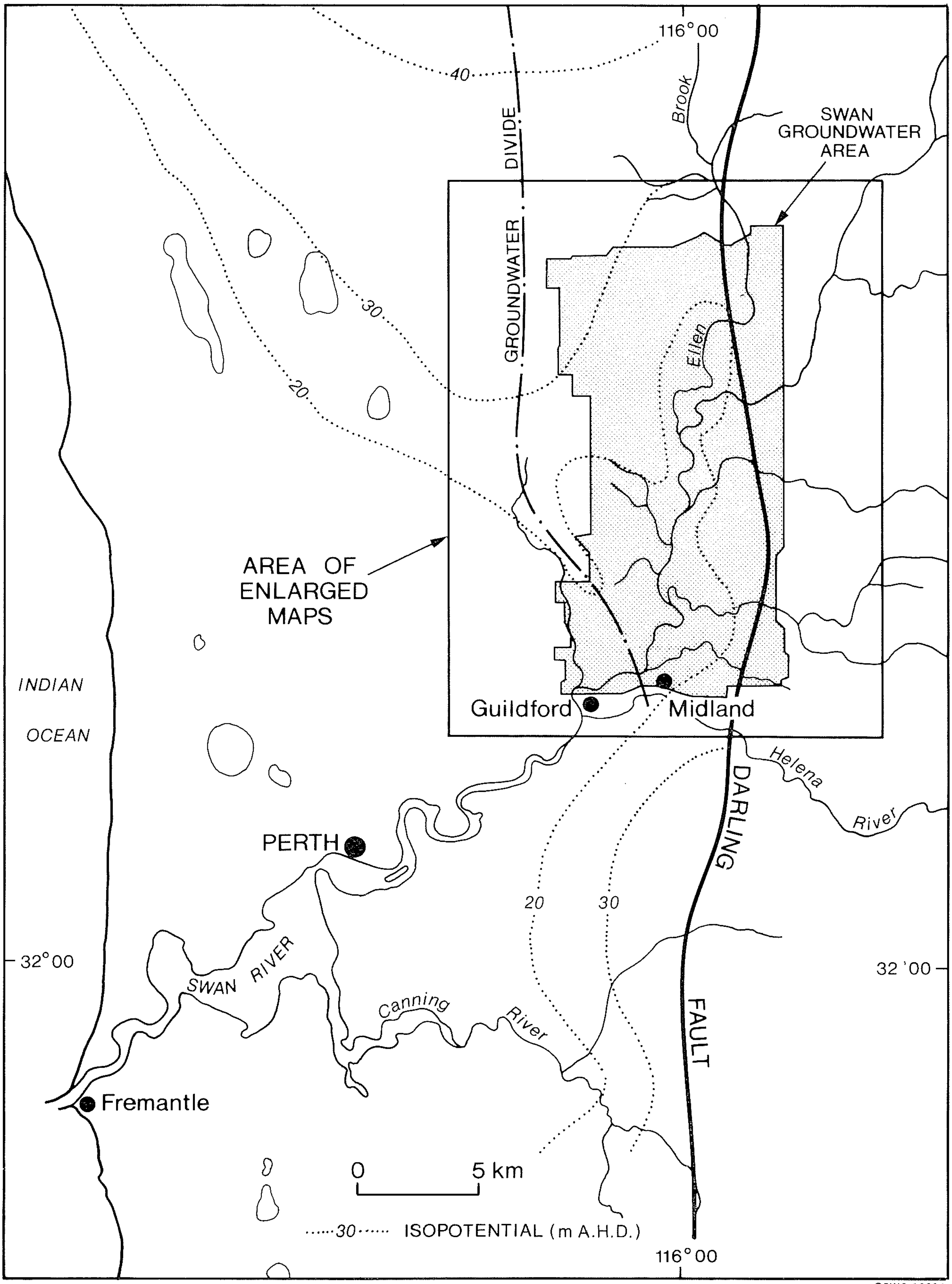


Figure 1 Locality map showing area of larger scale maps, Swan Groundwater Area, and regional isopotentials in the Leederville Formation.

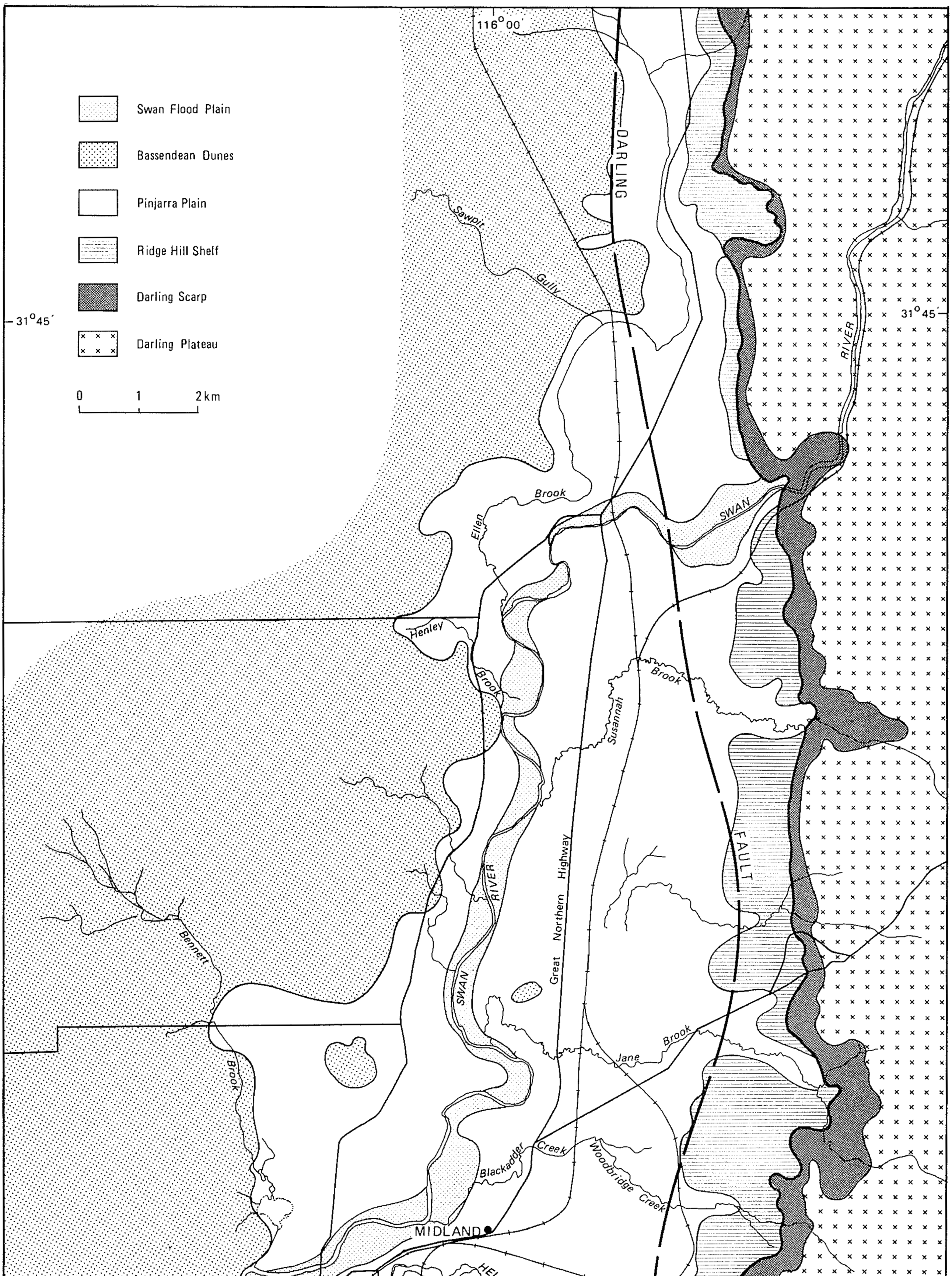


Figure 2 Physiographic divisions of the Swan Valley.

PHYSIOGRAPHY

LANDFORMS

The Swan Valley is at the eastern edge of the Swan Coastal Plain, adjacent to the Darling Plateau (Playford and others, 1976). The Darling Scarp, which forms the boundary between the Swan Coastal Plain and the Darling Plateau, originated as the edge of an upthrown fault-block and has subsequently undergone several periods of shoreline erosion resulting in the retreat of the scarp up to 2 km inland from the fault (Fig. 2).

At the base of the scarp is the Ridge Hill Shelf (Woolnough, 1918), a wave-cut platform 25–50 m above sea level, consisting of lateritized Cretaceous sedimentary rocks overlain by eolian sand. It merges westward with the Pinjarra Plain (McArthur and Bettenay, 1960), a relatively smooth alluvial plain 5–25 m above sea level. The Pinjarra Plain has been incised by the Swan River which has formed a flood plain (up to 0·5 km wide), levees, and silt-covered terraces (Somerville, 1920; Aurousseau and Budge, 1921). Locally overlying the Pinjarra Plain, and forming its western boundary are the Bassendean Dunes (McArthur and Bettenay, 1960). The Dunes reach 45 m above sea level and have smoothed areas in the vicinity of swamps which result from groundwater outflow.

DRAINAGES

The Swan River is the major drainage. It has a catchment area of about 7 000 km² on the Darling Plateau. The reach of the river in the Swan Valley follows a mature meandering course within the flood plain. The river is perennial and tidal to about Guildford. It has a low gradient and is only about 10 m above sea level where it leaves the Darling Plateau. The main flow in the river occurs during the winter, and major floods exceed 500 m³/s (Anon., 1978). There are no systematic salinity data, but Moncrieff (1974) recorded salinities ranging from 2 110 to 9 720 mg/L TDS and observed that the salinity tended to increase at the onset of the first major winter flow, then decrease, and afterwards increase gradually until the following winter or major flow. He noted significant dilution downstream of the freshwater tributaries, Ellen and Henley Brooks.

The main tributary to the Swan River is the Helena River. It rises on the Darling Plateau and has a catchment of about 2 500 km². Flows to 150 m³/s can occur, but these are regulated by Mundaring Weir. The flows and salinity vary seasonally as for the Swan River except that flows are fresh and the salinity more constant, varying between 200 and 500 mg/L TDS (Anon., 1978).

The next most important tributary is Ellen Brook, whose catchment covers about 600 km². It carries runoff from the Darling Plateau and groundwater discharge from the Coastal Plain. The brook is intermittent, and during the summer may only persist as a series of groundwater-fed pools. Major flows are to 40 m³/s, and the runoff has a weighted average salinity of 485 mg/L TDS (Anon., 1978).

A number of small tributaries to the Swan River rise on the Darling Plateau and are referred to as scarp drainages. These include Susannah and Jane Brooks and Blackadder Creek, which have loop-shaped courses, flowing initially northwestward from the scarp and then, at about the 20 m topographic contour, diverting sharply to the southwest. Jane Brook is perennial; the others are intermittent but maintain some permanent pools along their courses. They carry runoff as well as groundwater outflow and show a seasonal pattern of salinity variation similar to that of the Swan River. Maximum salinities vary from 220 to 3 840 mg/L TDS; the highest value was recorded from Jane Brook (south branch), presumably reflecting the salinity of groundwater base-flow (Moncrieff, 1974).

A number of drainage lines rise on the coastal plain and are referred to as plain drainages. The major plain drainages are Bennett and Henley Brooks, which are tributaries to the Swan River. Several ill-defined minor drainages originate in extensive areas of seasonal swamps (wetlands), which are groundwater discharge areas. Flows are small and intermittent, occurring mainly during the winter months and, in many cases, are enhanced by drainage systems and canalizing of the drainage lines. The lower reaches of the drainages are often deeply incised and suggest higher flow rates during more pluvial conditions in the past. The salinity of the runoff is not known but is expected to be in the range 200 to 500 mg/L TDS, similar to the unconfined groundwater.

GEOLOGY

SETTING

The Swan Valley is situated about midway along the eastern edge of the Perth Basin (Playford and others, 1976). At this locality, the margin of the basin is the Darling Fault, which separates about 13 000 m of Phanerozoic sediments in the basin from Archaean crystalline rocks of the Yilgarn Block. The Basin also includes up to 200 m of Cretaceous and Quaternary sediments which overlie a shelf cut into the Yilgarn Block, and extend up to 2 km east of the Darling Fault (Fig. 5).

STRATIGRAPHY

Fresh and brackish groundwater resources may occur to a depth of about 1 000 m beneath the Swan Valley. The various formations which are recognized to this depth are given in Table 2, together with brief notes on their lithology and groundwater potential. More detailed descriptions of the formations, with the exception of the Yarragadee Formation and South Perth Shale, are given below. For descriptions of the last two, reference should be made to Playford and others (1976) or Allen (1979).

MESOZOIC

Leederville Formation

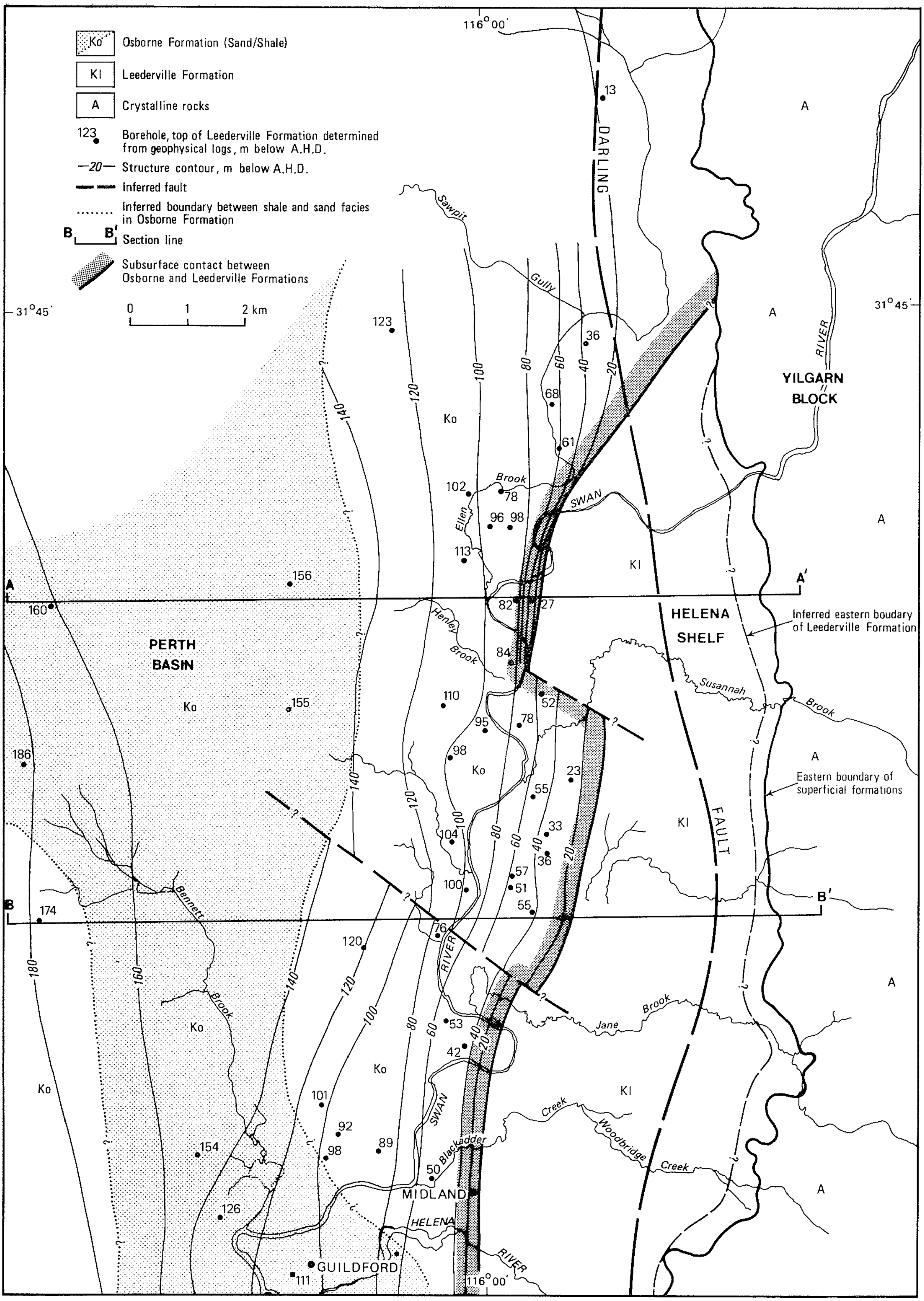
The Leederville Formation (Cockbain and Playford, 1973) is grey, or mottled white, red, and yellow (where weathered near the Darling Scarp), fine to coarse, poorly sorted, unconsolidated to lightly cemented sandstone; and grey to black, laminated, carbonaceous, slightly micaceous siltstone and shale. Locally, the sandstones may be pyritic or glauconitic and, adjacent to the scarp, may contain well-rounded cobbles and small boulders of granite, dolerite, and quartz. The sandstones consist of angular to subangular quartz in discontinuous beds up to 10 m thick but averaging 3 m. Sandstone comprises about 50% of the formation in cyclical sequences of sandstone, siltstone, and shale. In general, sandstone is more common in the lower part of the formation. The formation was deposited in a fluviatile environment in the east, and paralic and marine environments in the west (Whincup, 1966).

The Leederville Formation conformably overlies the South Perth Shale and is either conformably overlain by the Osborne Formation, or unconformably overlain by the "superficial formations" where the Osborne Formation has been removed by erosion (Fig. 3). The contact with the Osborne Formation is usually distinctive on gamma-ray logs. The formation extends throughout the subsurface west of the Darling Fault,

TABLE 2—STRATIGRAPHIC TABLE FOR THE SWAN VALLEY

Formal age		Rock unit	Maximum thickness (m)	Lithology	Hydrogeology
CAINOZOIC	Quaternary	"Superficial formations" (a)	50	Sand; limestone; clay; minor gravel	East of Swan River, minor aquifer, small supplies of fresh to brackish water; west of Swan River, major aquifer, large supplies of fresh water except in vicinity of river.
				UNCONFORMITY	
MESOZOIC	Late Cretaceous	Osborne Formation	160	Shale; siltstone; sand; silty sand	Local aquifer, moderate supplies of fresh water
	Early Cretaceous	Leederville Formation	325	Interbedded sandstone	Major aquifer, moderate to large supplies of fresh water in the upper half of the formation; brackish water in the lower half.
	Early Cretaceous	South Perth Shale	110	Shale and siltstone	Aquiclude
				UNCONFORMITY	
	Early Cretaceous-Middle Jurassic	Yarragadee Formation	2 500	Interbedded sandstone, siltstone and shale	Major aquifer, large supplies brackish water.

(a) Informal name



GSWA 19336

Figure 3 Subcrop map and structure contours on the stratigraphic top of the Leederville Formation.

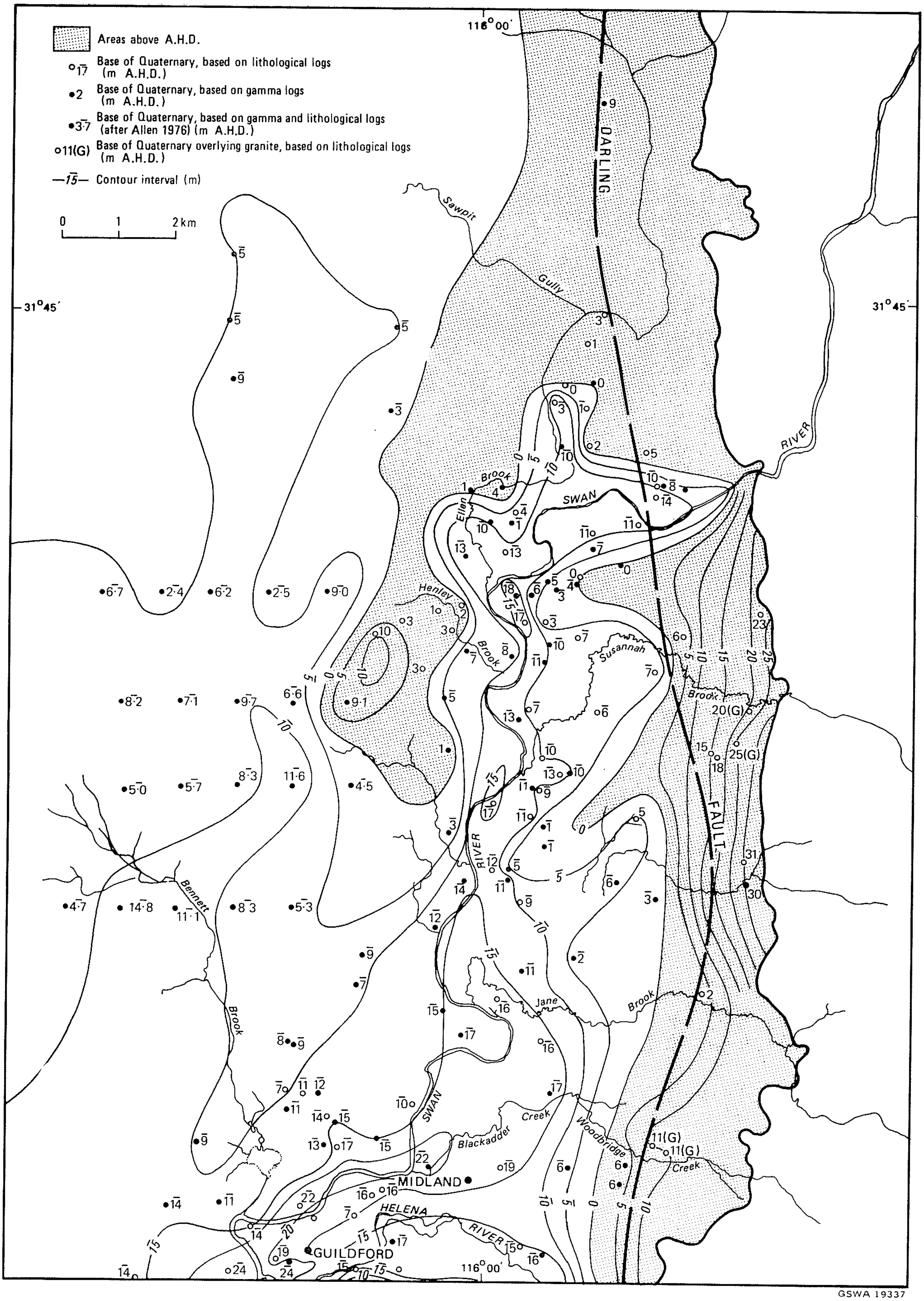


Figure 4 Contours on unconformity surface at the base of the "superficial formations".

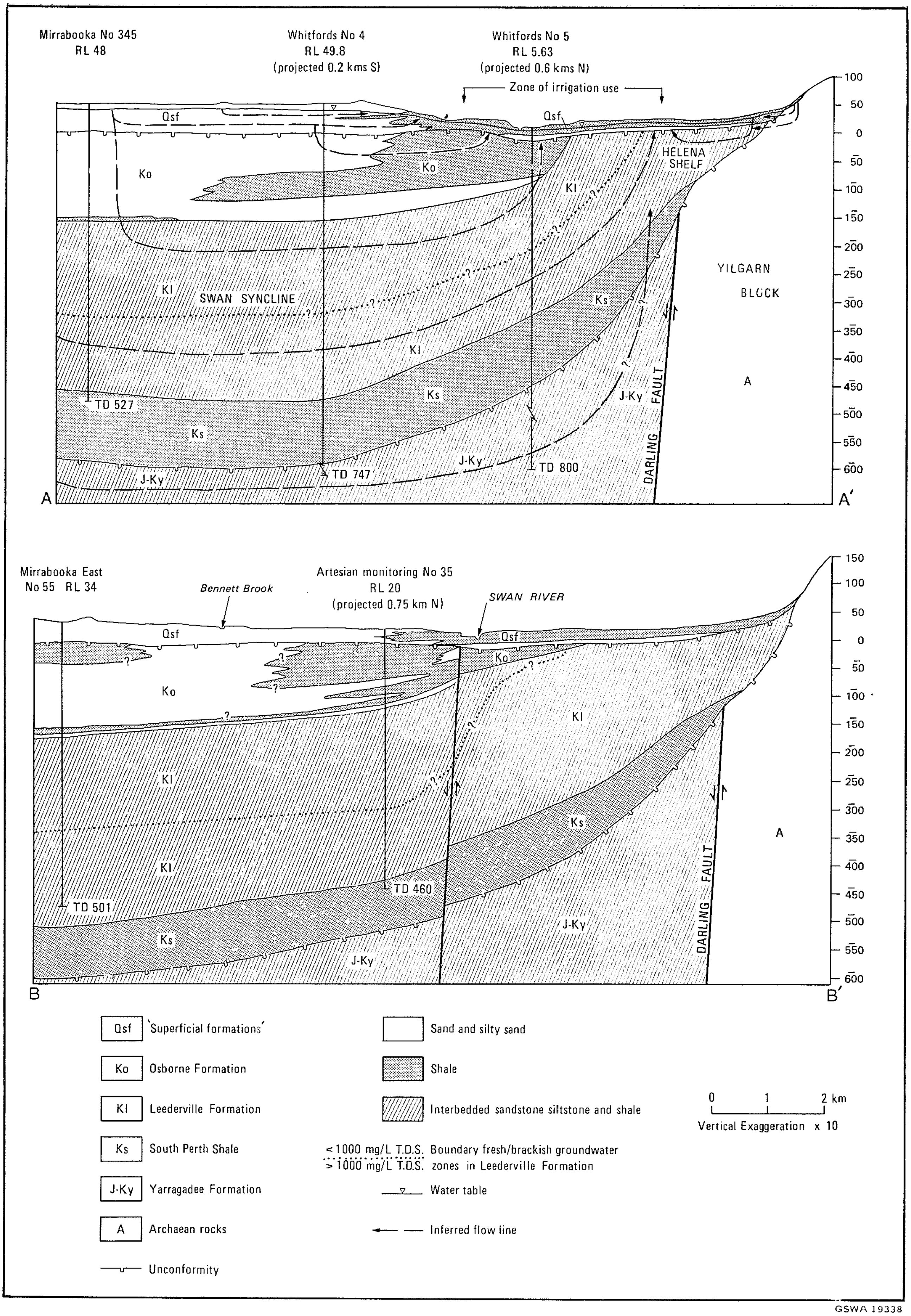


Figure 5 Hydrogeological cross-sections of the Swan Valley.

but to the east, where it laps on to the Yilgarn Block, its subsurface extent is not reliably known. Locally, as in Loton Road, it is poorly exposed. The formation is up to 325 m thick west of the Darling Fault and up to 200 m thick where it laps on to the Yilgarn Block.

Osborne Formation

The Osborne Formation (McWhae and others, 1958) consists of laterally and vertically variable, black to olive-green sandy shale and siltstone, and of olive-green to grey, silty and clayey, well-sorted, glauconitic, fine to medium, rounded to well-rounded, sand that was deposited in a shallow-water marine environment. The formation appears to exhibit marked vertical and lateral facies variations between sand, siltstone and shale. Allen (1977) interpreted unfossiliferous glauconitic sand ("channel sand") in the East Mirrabooka well field, as the infilling of a submarine channel with material derived from the Late Cretaceous formations. Subsequent drilling by the MWB has shown that a more likely explanation is that it is a sandy facies interfingering with siltstone and shale within the Osborne Formation (Fig. 5).

The Osborne Formation overlies the Leederville Formation and is unconformably overlain by the "superficial formations". It occurs in the subsurface to about 2 km west of the Darling Fault except in the north where both the Osborne and Leederville Formations extend across the fault and on to the Yilgarn Block (Fig. 3). West of the Darling Fault, the partly eroded Osborne Formation is up to 160 m thick, but to the east its thickness and extent are uncertain.

CAINOZOIC

"Superficial formations"

The "superficial formations" (Allen, 1976; 1977) are a complex series of sediments in which various formations are recognized (Playford and others, 1976) but which for convenience are considered as one unit. From the bottom upwards they consist of erosional remnants of limestone; fine to very coarse, bimodal, heavy-mineral-rich sand; coarse feldspathic sand grading eastward into sandy clay and southwards into carbonaceous clay; medium-grained eolian sand; clayey and gravelly colluvium and alluvium; and alluvial sand, gravel, and silt. In general, to the east of the Swan River the "superficial formations" are predominantly clayey, whereas to the west they are mainly sandy, The "superficial formations" were deposited in shallow-water marine, paralic, estuarine, eolian, colluvial and alluvial environments during oscillations in sea level and various climatic phases during the latter part of the Cainozoic.

The "superficial formations" unconformably overlie the Archaean granitic rocks, the Leederville, and the Osborne Formation, and extend from the foot of the Darling Scarp westward across the coastal plain (Fig. 5). They exhibit complex intra-unit unconformities, disconformities, cut and fill, and facies variations. The "superficial formations" are up to 50 m thick depending on the topography and the elevation of the basal unconformity, but tend to thicken toward the northwest.

STRUCTURE

The main elements of the geological structure in the Swan Valley are the Perth Basin and Yilgarn Block, separated by the Darling Fault. Within the Perth Basin, the Yarragadee Formation forms a gently east-dipping block of sediments (Playford, 1976), on which is superimposed the Swan Syncline (Allen, 1979), which appears to result from differential compaction of the pre-existing sediments (Cope, 1972). The eastern limb of the Swan Syncline extends across the Darling Fault on to a 2 km-wide shelf, here referred to as the Helena Shelf (Fig. 3), along the western edge of the Yilgarn Block. The Swan Syncline is overlain and concealed by a flat-lying cover of "superficial formations" that rest on an irregular erosion surface in which an ancestral valley of the Swan River is evident (Fig. 4).

HYDROGEOLOGY

FLOW SYSTEMS

In the Swan Valley, the "superficial formations", and the Osborne, Leederville and Yarragadee Formations are multilayer aquifers. They contain strata-controlled flow systems which may cross formation boundaries at intake and discharge areas.

The groundwater in the aquifers originates from rainfall. The location of the intakes and discharge areas, and configuration of the flow systems is determined by the topography and geological structure. The relationship of the flow system is shown diagrammatically in Figure 5, Section A-A'.

AQUIFERS

"Superficial formations"

General: The "superficial formations", despite wide variability in lithology, form a distinct aquifer. However, the major drainages, form hydraulic boundaries to the groundwater which is contained by the "superficial formations", and several distinct areas are recognizable (Fig. 6). Of these, the Swan-Helena area is described here.

For a description of the part of the Gnangara Mound in the western part of the Swan Valley, reference should be made to Allen (1976 and 1977).

Groundwater occurrence: The "superficial formations" in the Swan-Helena area are composed primarily of clayey sediments and subordinate beds of sand and gravelly sand. They contain a groundwater flow system bounded by hydraulic boundaries formed by the Swan and Helena Rivers. The flow system is probably in lateral hydraulic connection with groundwater in the Archaean crystalline rocks and is in downward (east) and upward (west) hydraulic connection with the Leederville Formation on the Helena Shelf (Fig. 5, Section A-A').

Recharge: Recharge is directly from rainfall, lateral movement of groundwater from the crystalline rocks, and upward discharge from the Leederville Formation (Fig. 5). The main sites of rainfall recharge, as indicated by the water table contours (Fig. 6) and by the groundwater salinity (Fig. 7), are on the Ridge Hill Shelf and on the interfluves between the scarp drainages. Near the Swan River, upward heads, and the preponderance of clay in the "superficial formations", limit recharge, apart from a small downward accretion to the water table each winter. Moncrieff (1974) observed that the water table rose 1 to 4·5 m during the winter and that the main changes occurred near drainage lines. This may be related to flow stage in the drainages over intake areas, or to raised heads in the Leederville Formation where it discharges into the "superficial formations".

Movement and discharge: Groundwater movement is westward toward the Swan River. Discharge occurs into the Swan River and the major scarp drainages as indicated by the re-entrants on the groundwater contours, and by permanent flow and pools on some of the drainages. Discharge is also presumed to occur from extensive areas of low-lying land, which are waterlogged during the winter as a result of the raised water table and from which drains and evapotranspiration remove large volumes of water.

Storage and throughflow: The Swan-Helena area extends from the hydraulic boundaries formed by the Swan and Helena Rivers to the edge of the Perth Basin sediments (Fig. 6). The approximate volume of groundwater in storage for the area (52 km^2), assuming an average saturated thickness of 12·5 m (Figs. 4 and 6) and specific yield of 0·05 is:

$$V = 52 \times 10^6 \times 12{\cdot}5 \times 0{\cdot}05$$
$$= 33 \times 10^6 \text{ m}^3$$

The groundwater throughflow past the 10 m water-table contour between the Swan and Helena Rivers (Fig. 6) can be calculated from the form of the Darcy equation:

$$Q = KbIL \quad .... \quad .... \quad .... \quad (1)$$

where Q = throughflow (m^3/d)
K = hydraulic conductivity (m/d)
b = thickness of saturated aquifer (m)
I = groundwater gradient (dimensionless)
L = width of flow section (m)

The average saturated aquifer thickness is 18 m, of which 40% is assumed to be sand (Figs. 3 and 5); the flow section is 18 km wide and has a groundwater gradient of 0·004 5 (Fig. 6). If the hydraulic conductivity is assumed to be 5 m/d then the throughflow (Q) is:

$$Q = 5 \times 18 \times 0{\cdot}40 \times 0{\cdot}004\,5 \times 18\,000$$
$$= 2\,916 \text{ m}^3\text{/d (or } 1{\cdot}1 \times 10^6 \text{ m}^3\text{/year)}$$

Quality: An isohaline map showing spatial variation in groundwater salinity is given in Figure 7. It is based mainly on field analyses (TDS by conductivity) of groundwater from about 700 wells sunk 3–4 m below the water table and shows in an extremely generalized fashion the variation of groundwater salinity at the water table. The groundwater salinity generally increases with depth so that groundwater with a higher salinity than indicated on the map can be obtained from deeper bores or wells.

The groundwater salinity varies from 150 to 5 000 mg/L TDS. The lowest salinities occur at the intake on the Ridge Hill Shelf, and the highest salinities occur adjacent to the discharge areas near the scarp drainages. Some analyses of groundwater from the "superficial formations" in the Swan-Helena area are given in Table 3 and by Moncrieff (1974).

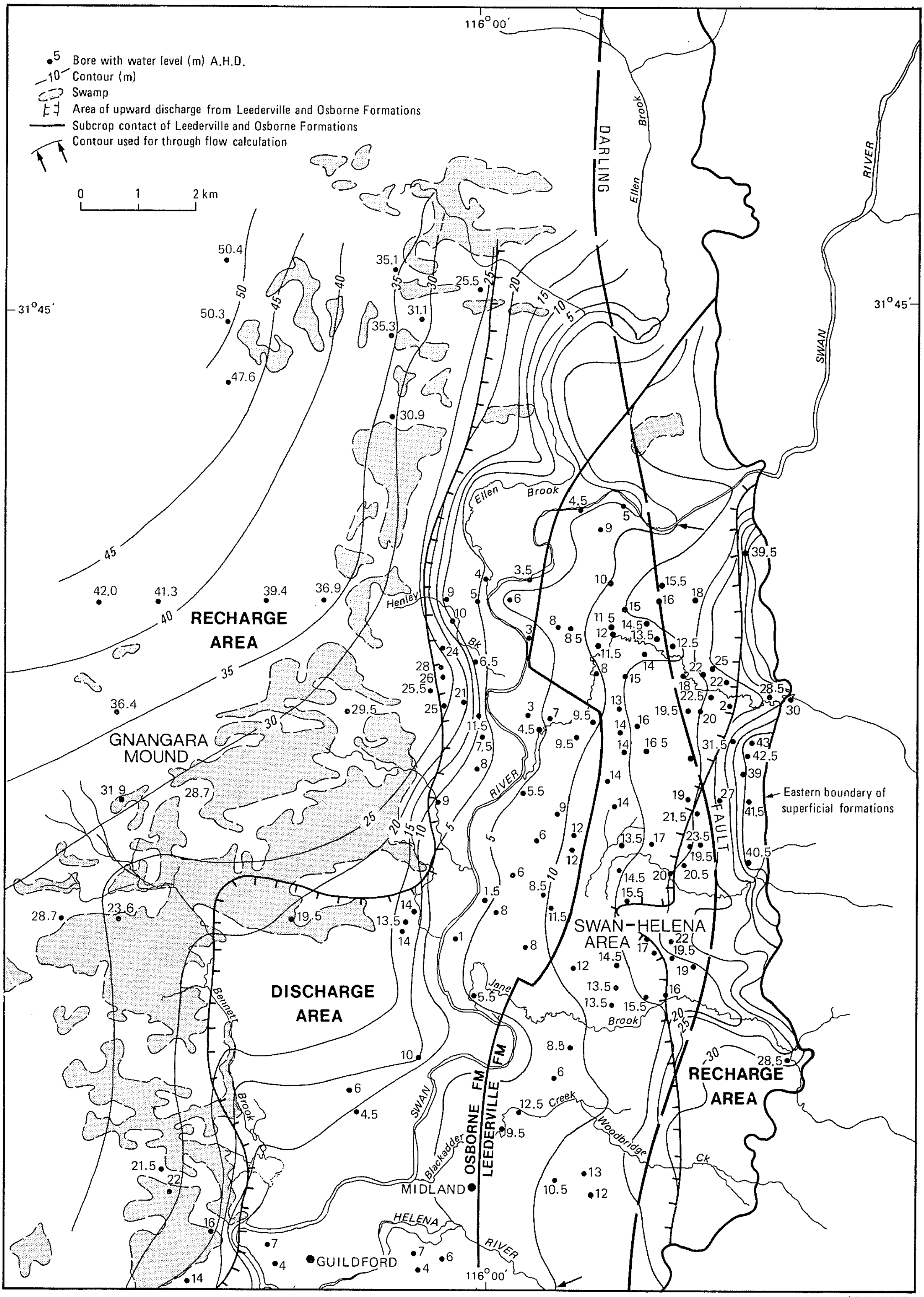


Figure 6 Non-synoptic water-table map, showing swamps and area of upward recharge from the Osborne and Leederville Formations.

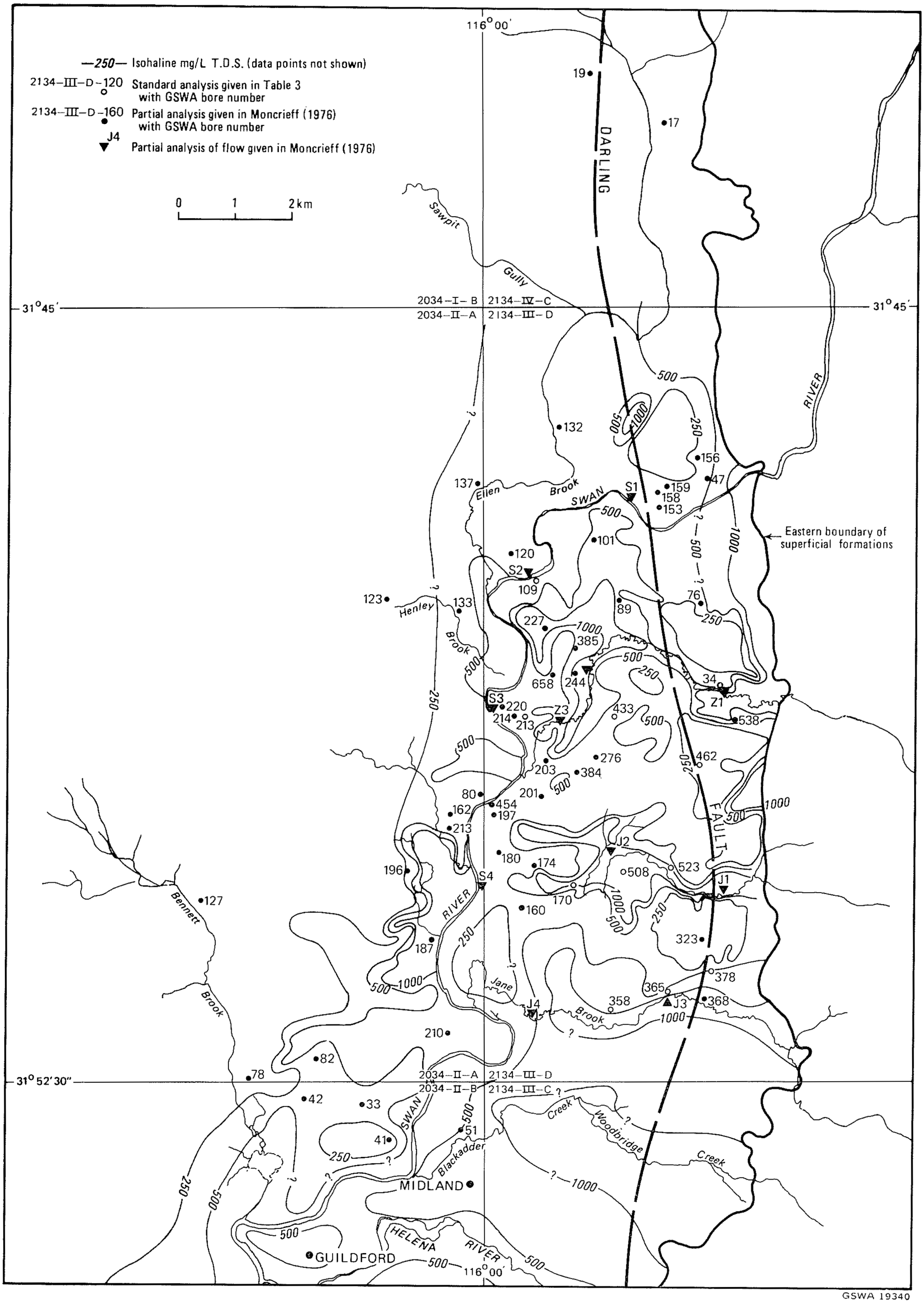


Figure 7 Isohaline map for "superficial formations" and location of standard and partial water analyses.

Development: Prior to 1976 almost every allotment had a bore or well for domestic or reticulation use. Since then, the MWB has provided scheme water, and most of the bores and wells are disused or have been abandoned. Many wells have been infilled with household refuse and may be sources of groundwater pollution.

In the Swan-Helena area, groundwater yields from the "superficial formations" are generally low (5 m^3/d or less) because of the clayey nature of the sediments. For this reason, most of the supplies were obtained from wells, some of which had their supplies enhanced by the construction of horizontal drives or, by the drilling of shallow bore(s) from the bottom of the well. The latter technique allows groundwater under higher heads in the deeper sands of the "superficial formations" or the top of the Leederville Formation to flow into the well.

The annual abstraction from the Swan-Helena area is not known but is expected to be less than $0{\cdot}5 \times 10^6$ m^3/year. Future large-scale abstraction is not expected because of the low yields and variable salinity.

Osborne Formation

General: The Osborne Formation was previously considered to be an aquiclude and to have only limited groundwater potential from sands occurring at the base of the formation. However, the discovery of an extensive silty-sand facies within the formation, toward the axis of the Swan Syncline, has changed this view and shown that, locally, the formation may be a significant aquifer and may be an important source of recharge to the underlying Leederville Formation.

Groundwater occurrence: Groundwater in the formation originates as downward seepage from the "superficial formation". It is in downward hydraulic continuity with groundwater in the Leederville Formation to the northwest of the Swan Valley, and in upward continuity with that in the "superficial formations" in the vicinity of the Swan River and Bennett Brook (Fig. 6). Artesian flows may occur in the areas of upward head.

The configuration of the potentiometric surface is only known in the Mirrabooka well field (Fig. 7). Elsewhere it is expected to be similar to that in the underlying Leederville Formation except that heads would be higher at intakes and lower in discharge areas.

Recharge: Recharge to the Osborne Formation is by downward leakage from the "superficial formations" to the west and northwest of the Swan Valley (Fig. 8), and by upward leakage from the Leederville Formation in the vicinity of the Swan River. The area of Osborne Formation subcrop where there is potential for recharge is given in Allen (1979, Fig. 3) and is approximately 400 km^2.

Movement and Discharge: Groundwater movement in the Osborne Formation is toward the south and southeast (Fig. 8). Discharge is presumed to occur by upward leakage into the "superficial formations" in the vicinity of the lower reaches of Bennett Brook and along the Swan River, where it is ultimately lost by evapotranspiration or as streamflow. Discharge by downward leakage into the Leederville Formation occurs to the northwest of the Swan Valley. Presumably, downward leakage is impeded by interbedded shale and siltstone, but because of the large area over which downward head gradients occur, discharge to the Leederville Formation is probably quite large.

Storage and throughflow: Groundwater storage in the Osborne Formation must be very large, judged from the extent and thickness of the formation (Figs 3 and 5), and the proportion of sand, silty sand, and siltstone.

Groundwater flow is approximately normal to sections A-A' and B-B' given in Figure 5 and, judged from the isopotentials in the Leederville Formation, would ultimately be discharged in the Swan Valley. The throughflow can be calculated from the form of the Darcy equation:

$$Q = KAI \quad \ldots \quad (2)$$

where Q = throughflow (m^3/d)
K = hydraulic conductivity (m/d)
A = vertical area through which flow occurs (m^2)
I = groundwater gradient (dimensionless)

The hydraulic conductivity was taken as $2{\cdot}5$ m/d (Davidson, 1979); the area of sand was measured from Figure 5; and the hydraulic gradient was measured from contours given in Figure 8. Solving equation (2) the throughflow in section A-A' is:

$$Q = 2{\cdot}5 \times 1\,125\,000 \times 0{\cdot}002\,0 = 5\,625\ m^3/d\ (\text{or } 2{\cdot}05 \times 10^6\ m^3/y)$$

and in section B-B' is:

$$Q = 2{\cdot}5 \times 1\,031\,250 \times 0{\cdot}002\,9 = 7\,477\ m^3/\text{day}\ (\text{or } 2{\cdot}70 \times 10^6\ m^3/y)$$

The average throughflow for the two sections ignoring any recharge from the "superficial formations" or loss to the Leederville Formation is about $2{\cdot}4 \times 10^6$ m^3/y.

Quality: Groundwater salinity in the Osborne Formation estimated from wire-line logs ranges from 190 to 750 mg/L TDS and averages about 300 mg/L TDS. Partial analyses of groundwater from the proposed extension of the Mirrabooka well field (Allen, 1977) show the groundwater salinity is similar to that estimated. Several standard analyses of groundwater from the Osborne Formation are given in Table 3.

Development: Bores in the Osborne Formation are known, to yield up to 3 000 m^3/d (depending on the bore construction) but are generally lower yielding than bores in the Leederville Formation. There are about 30 bores in the Swan Valley known to abstract from the Osborne Formation. Their annual abstraction is unknown but is estimated to be about $0{\cdot}6 \times 10^6$ m^3/y. Further abstraction from the formation is possible, which, should it exceed throughflow, will be compensated for by increased leakage from the "superficial formations".

Leederville Formation

Groundwater occurrence: The Leederville Formation is a multi-layer aquifer consisting of interbedded sandstone, siltstone, and shale, in which the individual beds of sandstone are discontinuous. In the Swan Valley, the formation is believed to contain two flow systems (Fig. 5, Section A-A'): a very small system originating at the foot of the Darling Scarp on the Helena Shelf (eastern system) and a regional system beneath the Gnangara Mound (western system). An isopotential map based on non-synoptic head measurements from bores of different depth, and poorly controlled elevation and head data is given in Figure 8. The isopotentials show a regional groundwater divide in the west and an apparent minor divide about 3 km east also extending into the Swan Valley. The complexity of the isopotentials in the Swan Valley probably result from it being a discharge area, the effect of pumping, and nature of the available data.

The eastern system is in downward hydraulic continuity with the "superficial formations" at the foot of the Darling Scarp and upward continuity in the west near the inferred discharge area between the subcrop contact of the Osborne and Leederville Formations and the Darling Fault. In some areas adjacent to the Darling Scarp, there may be direct infiltration of rainfall or runoff into the formation, and lateral hydraulic connection with the crystalline rocks.

The western system is in downward hydraulic continuity with the "superficial formations" and the Osborne Formation over the inferred recharge area, and upward continuity in the discharge area (Fig. 5). Adjacent to the Darling Fault, the flow system may be in upward hydraulic connection with the Yarragadee Formation as indicated in MWB Whitfords 5 and 5A, where the head is nearly equal in the two formations. The inter-relationship between the eastern and western flow systems is inferred to be as shown in Figure 5.

Recharge: Recharge to the eastern system is from rainfall, either directly on small areas of outcrop or via the "superficial formations". Localized recharge may occur along drainage lines at the foot of the Darling Scarp and possibly by lateral inflow of groundwater from the Archaean crystalline rocks. The recharge area, determined by overlaying Figure 6 on Figure 8, is shown in Figure 8, it lies mainly on the Helena Shelf and has an area of about 16 km^2. If it is assumed that 5% of the annual rainfall (860 mm) on the intake area is recharge, then the approximate recharge is $16 \times 10^6 \times 0{\cdot}86 \times 0{\cdot}05 = 0{\cdot}69 \times 10^6$ m^3/y. Some runoff may also contribute to the recharge but the contribution is likely to be small.

The western flow system has a recharge area of about 1 300 km^2 and is recharged directly via the "superficial formations" or via the Osborne Formation, where downward heads between the "superficial formations" and Leederville Formation occur (Allen, 1979). The inferred area of recharge adjacent to the Swan Valley is shown in Figure 8; it appears to form a mound in the isopotential surface which coincides with the sandy facies of the Osborne Formation.

Movement and Discharge: Groundwater flow in the eastern system is to the west. Groundwater discharge is presumed to occur where the two flow systems meet (Fig. 5, Section A-A') by upward flow into the "superficial formations" from which it is lost by evapotranspiration and surface outflow along the lower reaches of the scarp drainages.

In the western system, the regional direction of groundwater flow is southeastward till it reaches the Darling Fault, where it is discharged as the flow is deflected southward. Discharge takes place in the vicinity of the Swan River via the "superficial formations" between the subcrop contact of the Osborne and Leederville Formations and the Darling Fault.

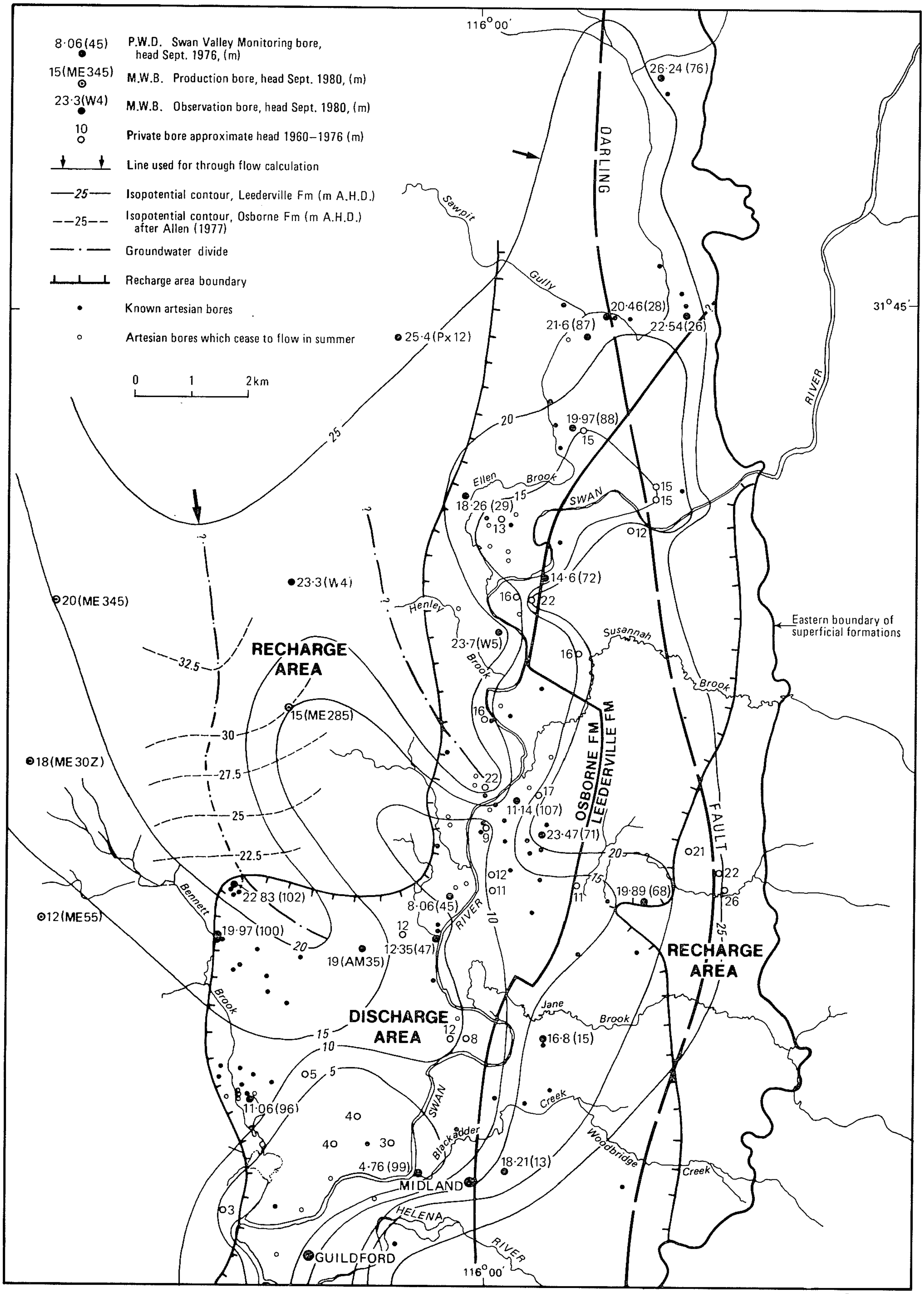


Figure 8 Non-synoptic isopotential contours for groundwater in the Leederville Formation (upper zone), recharge and discharge areas, and location of artesian bores.

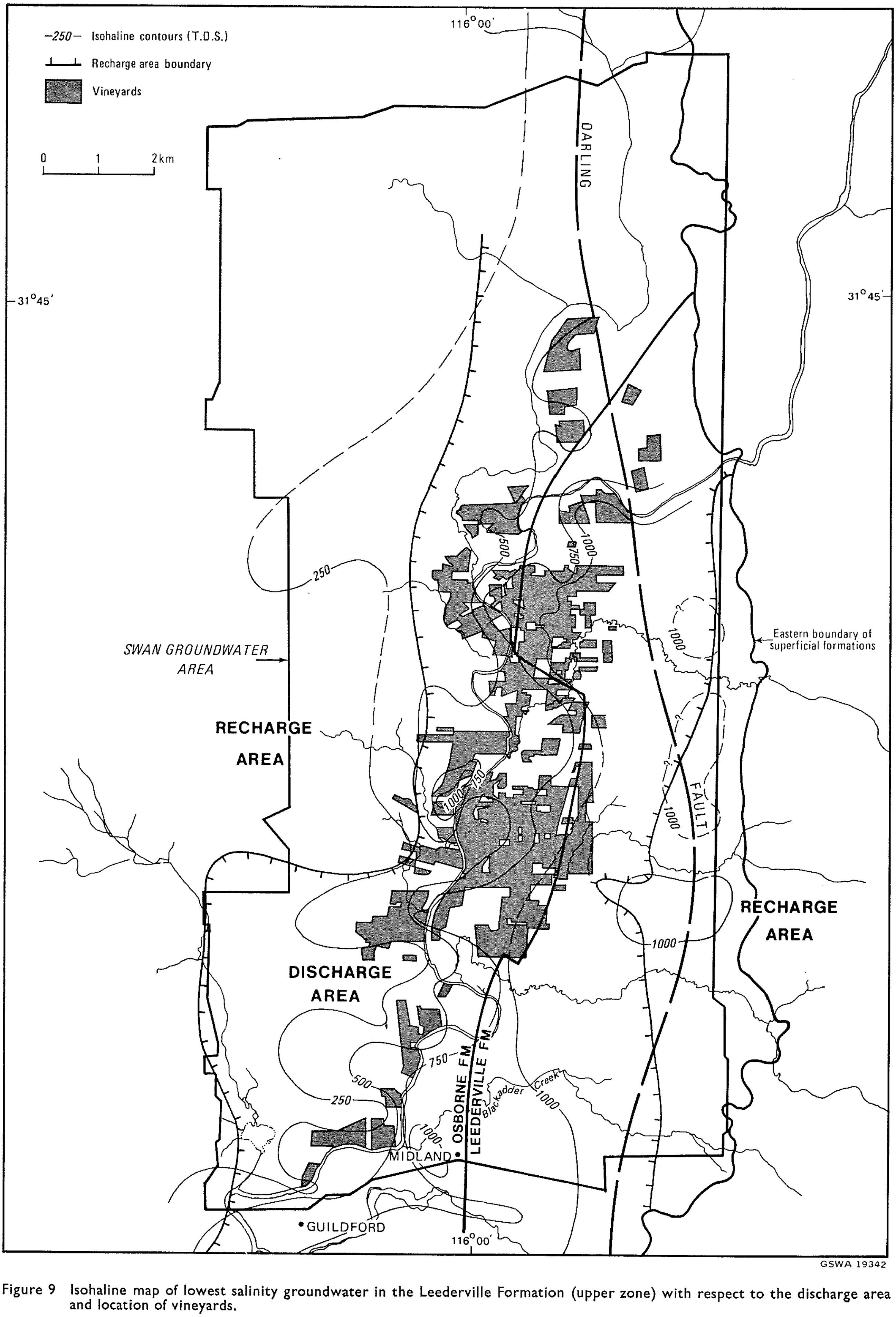


Figure 9 Isohaline map of lowest salinity groundwater in the Leederville Formation (upper zone) with respect to the discharge area and location of vineyards.

TABLE 3. STANDARD ANALYSES OF GROUNDWATER

Geological Survey Number	Name	Government Chemical Laboratories No.	pH	Conductivity mSm @ 20°C	Total Dissolved Solids by Conductivity (mg/L)	Total Dissolved Solids by Evaporation (mg/L)	Total Hardness as $CaCO_3$ (mg/L)	Total Alkalinity as $CaCO_3$ (mg/L)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Chloride (Cl)	Sulphate (SO_4)	Nitrate (NO_3)	Silica (SiO_2)	Boron (B)	Fluoride (F)	Iron (Fe)	Formation	Depth (metres)
									mg/L													
SH/50–14:																						
2134–III–D–174	Svicarovich	6095/69	7·6	910	640	540	111	72	25	12	140	13	88	228	38	<1	32	....	....	<0·1	LF	121·9
–180	Bignell AR	6096/69	8·0	580	410	350	57	93	11	7	108	9	113	144	6	<1	22	....	....	<0·1	LF	91·8
–197	Purnich S	6097/69	7·6	990	690	590	104	65	22	12	164	14	79	270	32	<1	32	....	....	<0·1	OF	83·8
–203	Thorn	6098/69	7·5	970	680	580	99	62	18	13	166	13	76	263	42	<1	34	....	....	<0·1	LF	97·6
–220	Barrett	6099/69	7·7	670	470	420	61	65	13	7	118	10	79	166	30	<1	38	....	....	<0·1	LF	107·9
2034–II–B– 59	Morris B	6100/69	7·7	1 420	990	830	114	50	13	20	257	16	61	415	57	<1	28	....	....	<0·1	LF	186
2134–III–D–164	Houghton Wine	6101/69	7·5	1 110	780	670	108	52	17	16	187	14	64	311	40	<1	35	....	....	<0·1	LF	201·2
–454	Sokal D	6102/69	7·9	1 000	700	600	109	57	19	15	166	14	70	272	44	1	32	....	....	<0·1	LF	147·9
–214	Hatch G	6103/69	7·7	1 060	740	640	98	48	16	14	182	14	58	292	48	1	32	....	....	<0·1	LF	152·4
–368	Erhardt	6104/69	8·1	5 050	3 540	3 380	313	273	53	44	1 190	32	332	1 730	220	5	14	....	....	<0·1	LF	129·3
–IV–C– 19	Rogold Inc	1817/71	6·1	410	290	290	35	38	4	6	69	7	46	104	9	<1	62	....	....	0·34	OF	61
– 17	Higgins Inc	1818/71	6·4	1 690	1 180	950	291	128	31	52	242	7	156	476	28	<1	54	....	....	0·06	LF	91·5
–III–D–127	Ag Dept	1819/71	6·8	560	390	360	56	55	11	7	87	10	67	128	23	<1	45	....	....	31	LF	78·7
–156	Worthington	1820/71	6·0	200	140	150	18	17	4	2	32	4	21	42	2	18	29	....	....	<0·03	?SF	27·4
–153	Pavlinovich	1821/71	6·4	1 060	740	590	103	70	17	15	169	14	85	277	28	<1	35	....	....	<0·05	LF	47·3
2034–II–A–213	Lendich	1812/71	6·6	1 570	1 100	930	128	62	15	22	282	17	76	463	45	<1	22	....	....	0·19	LF	169·2
–127	Whiteman	1813/71	6·1	270	190	160	33	24	7	4	43	3	34	74	<1	1	7	....	....	1·8	OF	54·3
–II–B– 42	Sarich	1814/71	7·3	420	290	280	11	100	3	1	90	7	122	81	2	<1	40	....	....	0·46	OF	48·8
–II–A– 78	Schwinkowski	1815/71	6·6	310	220	210	59	57	19	3	42	6	70	71	<1	1	19	....	....	1·1	SF	18·3
–II–B– 41	Antunovich	1816/71	7·6	340	240	230	56	108	11	7	54	8	131	53	<1	1	28	....	....	0·19	OF	93·3
2134–III–D–201	Harkness	8294/70	7·7	950	670	570	96	60	19	12	164	14	73	260	42	<1	27	....	....	<0·1	LF	152·4
–538	Bowman	8295/70	7·6	870	610	530	82	62	15	11	150	13	76	230	37	<1	27	....	....	<0·1	LF	153·4
2034–II–A– 82	Taylor W	8296/70	8·0	410	290	240	72	117	11	11	63	11	143	74	2	<1	4	....	....	<0·1	OF	133·5
–162	Yakich	8297/70	7·8	1 120	780	660	98	67	16	14	196	14	82	308	39	<1	26	....	....	<0·1	LF	181·4
–187	Beros M	8298/70	7·4	1 220	850	730	106	65	16	16	217	16	79	343	48	<1	27	....	....	<0·1	LF	189·0
2134–III–D–120	Mateljan	8290/70	7·6	520	360	340	50	78	10	6	98	9	95	121	25	<1	38	....	....	0·2	LF	132·3
2034–II–A–133	Yujnovich	8291/70	7·7	530	370	340	51	76	12	5	97	10	92	123	24	<1	36	....	....	0·3	LF	170·7
2134–III–D– 80	Rosic	8292/70	5·3	1 470	1 030	850	123	5	15	21	256	18	6	402	125	1	20	....	....	<0·1	LF	182·9
2034–II–B– 42	Sarich P	8293/70	7·5	710	500	390	64	95	14	7	124	11	116	177	1	3	11	....	....	<0·1	OF	48·8
2134–III–D–227	Udiljack	6130/69	6·8	1 380	970	840	151	110	26	21	237	12	134	377	39	1	35	....	....	<0·1	LF	76·2
–384	Swan Athletic Club	6131/69	7·1	910	640	540	91	77	17	12	152	12	95	233	44	<1	30	....	....	<0·1	LF	67·1
–276	Klematis	6132/69	6·5	1 080	760	640	159	37	16	29	162	5	46	311	35	5	28	....	....	<0·1	LF	45·1
–399	Gorizinski	6133/69	5·9	1 900	1 330	1 100	400	62	27	81	249	7	76	623	9	<1	31	....	....	0·4	LF	25·6
2024–II–A–123	Meakins	1822/71	6·9	330	230	220	93	93	34	2	34	3	113	55	<1	<1	13	....	....	1·8	SF	....
2134–III–D–383	Sangalli	1823/71	6·2	2 140	1 500	1 290	295	60	16	62	343	5	73	666	47	1	39	....	....	0·05	LF	46·7
–323	Petrich	1824/71	4·8	340	240	220	13	2	2	2	65	2	3	73	41	11	17	....	....	<0·05	?SF	....
2034–II–A–196	O'Brien	1825/71	7·5	300	210	190	59	98	12	7	41	7	120	41	<1	1	28	....	....	0·09	?OF	....
–II–B– 33	Lovreta	1826/71	7·1	800	560	470	82	83	15	11	137	5	101	187	39	<1	15	....	....	<0·05	LF	....
–II–A–210	Roe	1811/71	7·4	460	320	280	59	103	12	7	74	11	125	88	7	1	26	....	....	0·34	?OF	....
2134–III–D–158	Burgh	2997/69	6·7	770	540	460	81	67	11	13	125	12	82	194	27	<1	23	....	....	0·1	?SF	30·5
–159	Hebiton (River land)	2998/69	7·3	5 010	3 510	3 480	563	170	97	78	1 048	36	207	1 782	194	3	10	....	....	0·1	LF	166·2
2034–II–A–137	Barrett-Lennard	2999/69	7·0	490	340	320	51	75	12	5	91	9	91	114	24	<1	25	....	....	3·3	LF	147·9
2134–III–D–385	Mateljan	3000/69	6·7	1 700	1 190	1 030	151	80	24	22	309	15	98	509	42	<1	16	....	....	0·1	LF	82·9
– 47	Hebiton	71/68	7·1	4 600	3 220	3 240	434	263	78	58	1 050	34	320	1 630	192	1	14	....	....	0·1	LF	....
–132	Kendall D	85879/78	7·1	*62	400	†340	55	73	12	6	94	9	89	131	22	<1	14	0·13	0·3	....	OF	....
–658	Rullo B	85880/78	7·6	*178	1 140	†980	148	70	25	21	294	17	85	463	69	<1	29	0·26	0·3	....	LF	29·8
–101	U Swan School	85881/78	7·1	*138	880	†730	121	89	14	21	219	6	109	377	5	<1	20	0·18	0·2	....	LF	....
–214	Hatch	85882/78	7·4	*101	650	†560	89	61	16	12	152	14	74	247	39	<1	31	0·14	0·2	....	LF	....
–244	Newman Bros	85883/78	7·0	*178	1 140	†950	175	46	14	34	279	6	56	476	62	<1	32	0·16	0·1	....	LF	21·3
	Hampton Hatchery	19859/78	5·5	540	380	340	47	28	4	9	96	6	34	156	14	<1	32	0·1	0·1	0·9	....	....

* mSm @ 25°C † calculated.

LF = Leederville Formation OF = Osborne Formation SF = "superficial formations"

Storage and throughflow: In the Swan Valley, the volume of groundwater in storage in the Leederville Formation is extremely large. However, because of inadequate data about the thickness and extent of the zone of fresh groundwater, it is not possible to make reliable estimates of the relative volumes of fresh and brackish groundwater in the eastern and western flow systems.

Data is also not reliable enough to estimate the throughflow in the eastern flow system. It is expected, from the limited extent of fresh groundwater, to approximate to the estimated recharge of $0 \cdot 69 \times 10^6$ m³/y.

In the western flow system, the throughflow is difficult to estimate because of the complexity of the isopotentials. The isopotentials given in Figure 8 show that all groundwater throughflow between the main groundwater divide and the Darling Fault moves into the Swan Valley. The throughflow past the 25 m isopotential between the bounding flow lines (Fig. 8) may be estimated by assuming that: the average thickness of the formation is 320 m (Fig. 5); half the formation is sand with an hydraulic conductivity of 10 m/d (Allen, 1979); the average groundwater gradient (Fig. 8) is 0·001 5; and the width of the flow section is 9·7 km (Fig. 8). Then substituting in equation (1), the throughflow (Q) is:

$$Q = 10 \times 320 \times 0 \cdot 5 \times 0 \cdot 001\,5 \times 9\,700$$
$$= 23\,280 \text{ m}^3\text{/d (or } 8 \cdot 5 \times 10^6 \text{ m}^3\text{/y)}$$

Because the fresh water zone is about half the aquifer thickness, the fresh water throughflow is estimated to be $4 \cdot 2 \times 10^6$ m³/y. However, the quantity of freshwater throughflow entering the Swan Valley exceeds this figure as the flow section lies upstream of areas of recharge (Fig. 8), and the throughflow ultimately discharging in the Swan Valley is probably about 5×10^6 m³/y.

Quality: In the eastern system, groundwater salinity varies from 250 to 4 000 mg/L TDS but averages about 1 500 mg/L TDS. In general, the salinity increases with depth and toward the west. Thin zones of fresh groundwater may occur on the Ridge Hill Shelf beneath areas of fresh groundwater in the "superficial formations".

In the western system, the upper half of the Leederville Formation contains a zone of groundwater with a salinity ranging from 250 to 1 000 mg/L TDS. Below this, the lower half of the formation contains groundwater of 1 000 to 3 500 mg/L TDS. The thickness of these zones, as determined from wire line logs, is shown in Figure 5. They are remarkably constant except near the discharge area in the Swan Valley, where there is a marked decrease in the thickness of the zone of fresh groundwater.

An isohaline map based on analyses from bores of various depths, but mainly in the upper zone is given in Figure 9. It shows groundwater salinity increasing westward in the eastern flow system and eastward in the western flow system toward the discharge area. Standard analyses for groundwater from some bores (Fig. 9) in both systems are given in Table 3.

Development: In the eastern system there are about 30 non-domestic bores in the Leederville Formation. Their abstraction is unknown but is likely to be less than $0 \cdot 5 \times 10^6$ m³/y. In addition, particularly in the Herne Hill area, there are 15 known wells, which have bores sunk from their bottom allowing artesian flow into the well (presumably mainly from the Leederville Formation). However, most of the land is unsuitable for viticulture, and the groundwater salinity is generally too high for irrigation.

In the western system there are about 400 licensed non-domestic bores up to 215 m deep but averaging about 120 m. About 100 of these in the discharge area (Fig. 8) are, or were, artesian. Yields from bores may be as high as 8 000 m³/d but average 1 000 m³/d. The usual method of construction is to use screens, but in older bores slotted-casing, or occasionally, open-hole, construction was used.

PWD data indicate that bores in the Leederville Formation abstract about $3 \cdot 6 \times 10^6$ m³/yr of fresh and brackish groundwater. Of this, about 80% is used for irrigation of vineyards. There is scope for further development of the aquifer provided there are no problems of ingress of brackish groundwater from the underlying brackish zone.

CONCLUSIONS

In the Swan Valley, the major fresh groundwater resources occur in the upper half of the Leederville Formation in the western part of the Swan Valley. The zone of fresh water only extends about 2 km east of the Swan River. Consequently the eastern part of the Swan Valley from about the Great Northern Highway eastwards, is underlain by Leederville Formation containing brackish groundwater.

About 75% of the estimated renewable groundwater resources (throughflow) are being used so that there is only moderate scope for increased abstraction. Should abstraction exceed throughflow groundwater "mining" will occur, possibly leading to an increase in salinity of groundwater from production bores. This could result because most of the bores are situated in an area of upward head-gradients where groundwater will tend to move upward from the underlying zone of brackish groundwater.

REFERENCES

Allen, A. D., 1975, Swan Valley: Outline of the occurrence of groundwater resources and proposals for management: West. Australia Geol. Survey Hydro. Rept 1257 (unpublished).

——— 1976, Outline of the hydrogeology of the superficial formations of the Swan Coastal Plain: West. Australia Geol. Survey Ann. Rept 1975, p. 31–42.

——— 1977, The hydrogeology of the Mirrabooka East Area, Perth: West. Australia Geol. Survey Ann. Rept 1976, p. 14.

——— 1979, An outline of the confined groundwater resources in the vicinity of Perth, Western Australia: West. Australia Geol. Survey Ann. Rept 1978, p. 30.

Anon., 1978, Streamflow records of Western Australia to 1975: West. Australia Public Works Dept Water Resources Section Publication.

Aurousseau, M. and Budge, E. A., 1921, The terraces of the Swan and Helena Rivers and their bearing on recent displacement of the strand line: Royal Soc. West. Australia Jour., v. 7, p. 24–43.

Cockbain, A. E. and Playford, P. E., 1973, Stratigraphic nomenclature of Cretaceous rocks in the Perth Basin: West. Australia Geol. Survey Ann. Rept 1972, p. 26–31.

Cope, R. N., 1972, Tectonic style in the southern Perth Basin: West. Australia Geol. Survey Ann. Rept 1971, p. 46–50.

Davidson, W. A., 1979, East Mirrabooka 172 pumping test: West Australia Geol. Survey Hydro Rept 1975 (unpublished).

McArthur, W. M. and Bettenay, E., 1960, The development and distribution of the soils of the Swan Coastal Plain, Western Australia (2nd Edition 1974): Australia CSIRO, Soil Pub. no. 16.

Moncrieff, J. S., 1974, The relationship between geology, drainage and shallow groundwater in the Middle-Upper Swan Area, Western Australia: Uni. West. Australia B.Sc. Hons thesis (unpublished).

Playford, P. E., Cockbain, A. E., and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull. 124.

Pymm, L. W., 1955, Soils of the Swan Valley vineyard area, Western Australia: Australia CSIRO Division of Soils, Soils and Land Use Series No. 15.

Somerville, J. L., 1920, Evidence of uplift in the neighbourhood of Perth: Royal Soc. West. Australia Jour., v. 6, p. 1–20.

Whincup, P., 1966, Hydrogeology of the Pinjar exploratory drilling: West. Australia Geol. Survey Ann. Rept 1965, p. 19–24.

Woolnough, W. G., 1918, The Darling peneplain of Western Australia: Royal Soc. N.S.W. Jour., v. 32, p. 385–396.

THE GEOLOGY AND HYDROGEOLGY OF THE QUINDALUP BOREHOLE LINE

by P. H. Wharton

ABSTRACT

The Quindalup borehole line consists of sixteen boreholes at ten sites, drilled to depths of between 54 m and 1 469 m. The line extends across the Perth Basin, from 16 km west of Busselton to 8 km south of Donnybrook.

Drilling has shown that the Sue Coal Measures (Early Permian), Cockleshell Gully Formation (Early Jurassic), and the Yarragadee Formation (Middle to Late Jurassic) occur in major fault blocks, and are unconformably overlain by the Bunbury Basalt (Early Cretaceous) and the Leederville Formation (Early Cretaceous). These formations are concealed by a thin veneer of flat-lying Quaternary sediments on the Swan Coastal Plain.

The Leederville Formation is a multilayered aquifer consisting of sandstone interbedded with siltstone and shale. In low-lying areas, bores in the formation commonly flow. The salinity of groundwater in the formation is generally less than 500 mg/L TDS, except near the coast between Busselton and Dunsborough where salinities up to 42 000 mg/L TDS result from a salt-water wedge which extends inland.

The Yarragadee Formation is composed of sandstone and shale, with the percentage of sandstone ranging from about 90% near the base of the formation (in Q4) to about 25% in the younger part of the formation and towards the Darling Fault. Fresh groundwater, generally less than 500 mg/L TDS, extends to a depth of between 770 m and 1 250 m below sea level. Groundwater in the formation moves northwards, and is recharged by rainfall on the Blackwood Plateau, possibly in areas where the lateritized surface of the formation crops out.

The Cockleshell Gully Formation contains fresh groundwater, probably to a depth of about 450 m below sea level, although there is some saline water in the top of the formation near the coast. Between the Busselton and Darling Faults the formation is deeper than 500 m below sea level, and contains brackish or saline groundwater.

Major fresh groundwater resources which are virtually unexploited occur across the southern Perth Basin in the Leederville Formation, in the Yarragadee Formation between the Busselton and Darling Faults, and in the Cockleshell Gully Formation between the Busselton and Wirring Faults.

INTRODUCTION

The Quindalup Line consists of sixteen bores drilled at ten sites on an east-west line across the Perth Basin at about latitude 33°39′ south, from 16 km west of Busselton to 8 km south of Donnybrook (Fig. 1).

The drilling was carried out in two stages. Quindalup bores Q1 to Q5 were drilled primarily to determine the availability of groundwater between Busselton and Dunsborough (Probert, 1967). Later, bores at sites Q6 to Q10 were drilled to complete the section across the Perth Basin, and form part of a long-term drilling programme to evaluate the deep groundwater resources, and to investigate the stratigraphy and structure of the basin.

PHYSIOGRAPHY

The Quindalup Line bores are situated in the southern Perth Basin, where two major physiographic units are recognized (Fig. 2): the Blackwood Plateau (Low, 1972) and the Swan Coastal Plain (Saint-Smith, 1912). These units are bounded to the west by the Leeuwin-Naturaliste Ridge, and to the east by the Darling Plateau.

The Blackwood Plateau has an elevation of about 130 m, occasionally up to 200 m, above sea level, and is dissected by well-developed consequent drainage systems. The northern and northwestern margin of the plateau is formed by the Whicher Scarp, a Late Tertiary or Pleistocene shoreline (Playford and others, 1976).

The Swan Coastal Plain lies to the north and northwest of the Whicher Scarp, and can be sub-divided into three physiographic units (Low, 1972): the Pinjarra Plain, formed by fine-grained alluvial and piedmont deposits; the Bassendean Dunes,

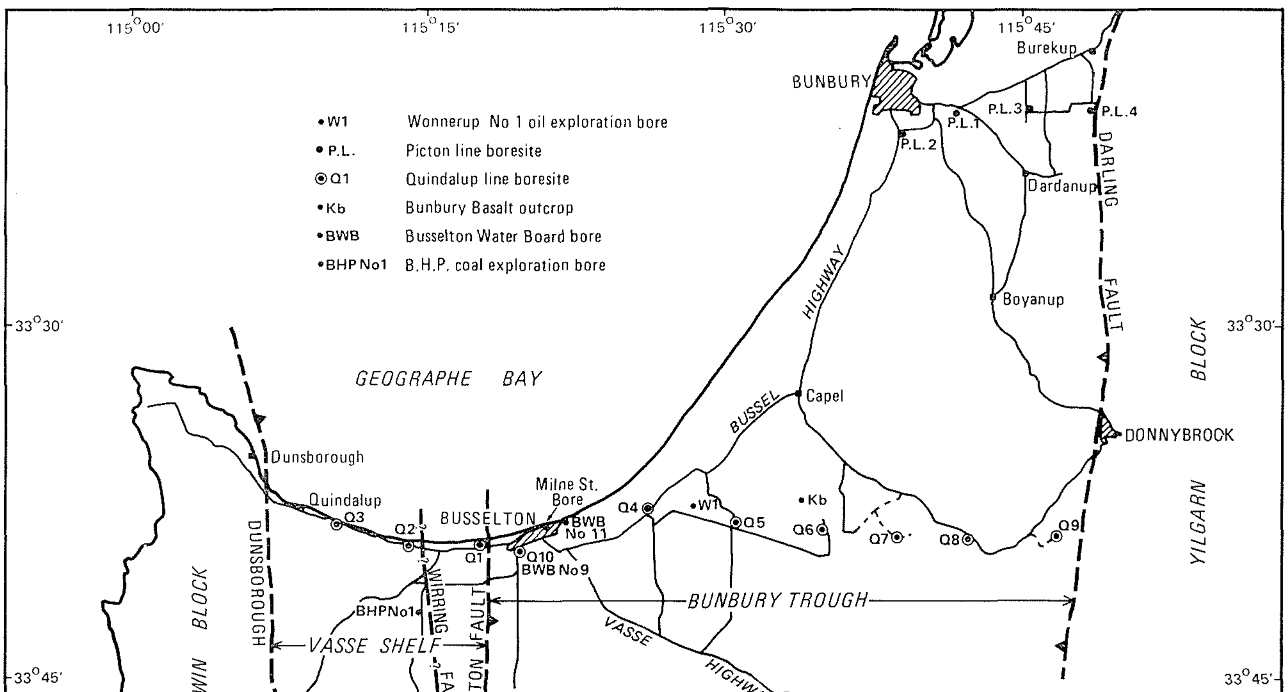


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Figure 1 Locality map, Quindalup Line.

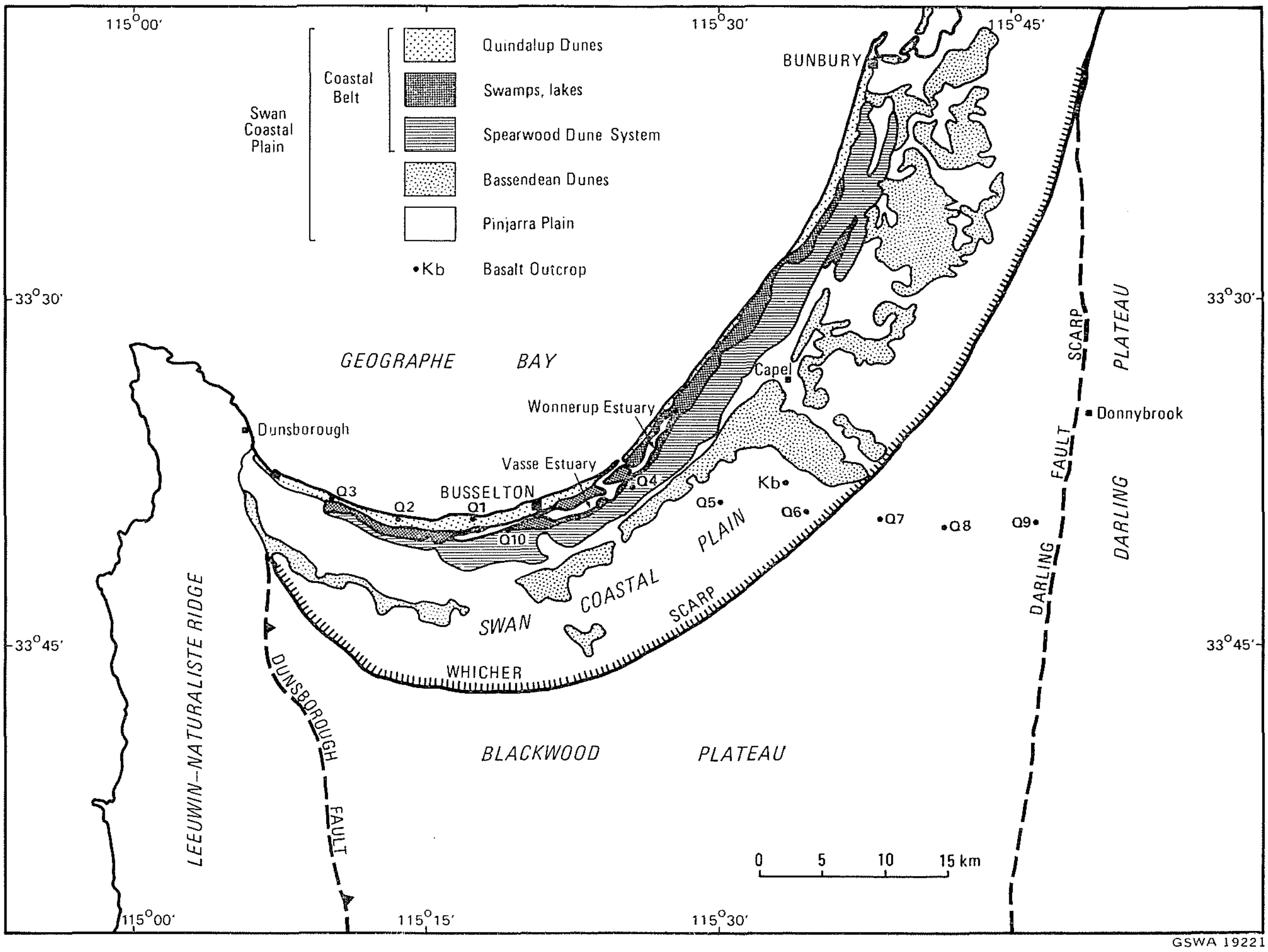

Figure 2 Physiographic subdivisions.

which comprise low dunes of quartz sand overlying the Pinjarra Plain; and the Coastal Belt, which consists of a narrow belt of active dunes along the coast (Quindalup Dunes), separated from an inland band of fixed calcified dunes (Spearwood Dune System) by lagoons, estuaries and swamps.

INVESTIGATION PROGRAMME

A summary of drilling and bore information is given in Table 1. The bores were drilled using mud-flush rotary rigs, and all bores were drilled by the Mines Department Drilling Section, except Q6 which was by private contract.

Sludge samples were collected at 3 m intervals except where conventional cores were taken in bores Q1 to Q5, at about 50 m intervals. A 3-m core barrel was used but recovery was generally poor. On completion of drilling, gamma-ray and long- and short-normal resistivity logs were run in each bore (except Q9C and Q9D), and various other wire-line logs were run in the bores as required. Sidewall cores were recovered from shale or siltstone beds at about 40 m intervals in the deep bores at sites Q6 and Q10.

In bores Q1 to Q5 the groundwater from 5 to 10 aquifer intervals was sampled using a formation tester, but the method proved to be unreliable. Static water-level measurements made by this method were inaccurate, and have been disregarded. After the formation tests, bores Q1 to Q3, and Q5 were sealed with cement plugs and abandoned. Q4, a flowing bore, was fitted with a gate-valve so the bore could be used as an emergency water supply.

The bores at sites Q6 to Q10 were completed as observation bores, and were constructed so that one or more aquifer intervals could be tested or monitored in each bore. Each interval was developed either by air-lifting and surging, or with a swabbing tool, until the water cleared and the salinity stabilized. Water samples taken after development were analyzed by the Government Chemical Laboratories.

A detailed account of the investigation procedures and bore construction methods is given by Wharton (in prep.).

GEOLOGY

SETTING

The Quindalup Line bores were drilled in the southern Perth Basin between the Leeuwin Block in the west, and the Yilgarn Block in the east. The southern Perth Basin is subdivided into two major structural units; the Bunbury Trough and the Vasse Shelf (Fig. 1). The Bunbury Trough, between the Darling and Busselton Faults, is a deep graben which probably contains at least 10 000 m of Phanerozoic sediments. The Vasse Shelf lies between the Bunbury Trough and the Leeuwin Block, and is bounded by the Busselton and Dunsborough Faults. Sediments on the shelf are about 3 000 m thick and are mostly of Permian age, but include a relatively thin sequence of Mesozoic sediments.

STRATIGRAPHY

The formations intersected by the Quindalup Line bores range in age from Quaternary to Early Permian. The stratigraphic succession is given in Table 2, and the formations are described below.

Permian

Sue Coal Measures: The Sue Coal Measures, intersected in bores Q2 and Q3, are composed of generally well-consolidated sandstone (locally calcareous) with some siltstone and shale. The sandstone is light grey, white, or green (chloritic), generally fine- to coarse-grained, commonly clayey, and with poor or moderate sorting. Accessory minerals include feldspar, mica, and heavy minerals, and seams and partings of coal and carbonaceous material are common.

The Sue Coal Measures are 1 838 m thick in Sue 1, an oil exploration well located 45 km south of Busselton. The maximum thickness intersected by a Quindalup Line bore was 442 m in Q2. The formation unconformably overlies the Precambrian basement in Sue 1, and is unconformably overlain by the Leederville Formation in bores Q2 and Q3.

The palynology of cores from the Sue Coal Measures indicated that the formation is younger at Q3 than at Q2. In Q2, samples from 150 m to 300 m depth are of Late Artinskian age, and samples from 400 m to 500 m depth are of Early Artinskian

TABLE 1. SUMMARY OF BORE DATA

Bore	Latitude S	Longitude E	Drilling		Elevation (m AHD)		Total Depth (m)	Tested Interval (m bns)	Head (m AHD) 15/10/80	Salinity TDS by summation (mg/L)	Aquifer (Formation)	Status
			Commenced	Completed	Surface	Casing Top						
Q1	33°39′36″	115°17′41″	26/9/66	23/12/66	~2	....	588	Various formation tests	....	742–2 813	....	Abandoned
Q2	33°39′26″	115°13′55″	27/1/67	3/3/67	~2	....	551	do.	....	....	....	do.
Q3	33°38′37″	115°10′30″	19/4/67	22/5/67	~3	....	453	do.	....	1 346–8 779	....	do.
Q4	33°38′13″	115°26′00″	30/5/67	1/7/67	5·0	6·21*	585	Various formation tests 18–96	11·6	243–512	Leederville	Flowing observation bore
Q5	33°38′38″	115°30′22″	12/7/67	18/8/67	~20	....	613	Various formation tests	....	330–651	....	Abandoned
Q6	33°38′56″	115°35′02″	14/6/74	15/7/74	42·38	43·18	1 118	237–245	~14·4	252	Yarragadee	Abandoned
								370–378	~14·7	281	do.	do.
								615–623	~15·4	241	do.	do.
								829–837	~15·1	298	do.	do.
								1 017–1 025	14·03	412	do.	Observation bore
						101·386		917–923	14·51	230	do.	do.
Q7A	33°39′05″	115°38′39″	8/9/78	10/11/78	100·83	101·25	1 049	429–435	20·37	296	do.	do.
Q7B	do.	do.	30/10/78	21/3/79	99·70	100·552	123	104–110	56·17	245	Leederville	do.
Q8A	33°39′17″	115°42′12″	21/11/78	6/4/79	58·94	59·496	1 160	1 065–1 071	18·57	390	Yarragadee	do.
						59·420		786–792	18·89	274	do.	do.
						59·794	....	402–408	30·08	260	do.	do.
Q8B	33°39′17″	115°42′12″	6/4/79	8/5/79	59·05	59·770	436	256–262	31·56	350	do.	do.
Q8C	33°39′17″	114°42′12″	4/4/79	10/4/79	59·55	61·475	54	48–54	62·98	317	Leederville	Observation bore (flowing)
Q9A	33°39′06″	115°46′52″	17/5/79	3/9/79	96·1	96·720	1 469	1 200–1 315	13·50	543	Yarragadee	Observation bore
						96·666		902–908	17·85	452	do.	do.
Q9B	33°39′06″	115°46′52″	12/9/79	4/12/79	....	....	371	356–362	....	452	do.	Abandoned
Q9C	33°39′06″	115°46′52″	22/11/79	29/11/79	96·23	96·505	135	127–133	61·00	806	Leederville	Observation bore
Q9D	33°39′06″	115°46′52″	5/12/79	13/2/80	96·20	96·46	367	356–362	44·44	468	Yarragadee	do.
						3·72	....	808·5–814·5	~12	1 940	Cockleshell Gully	Abandoned
Q10	33°39′53″	115°19′26″	31/10/79	19/12/79	2·20	3·71	1 064	726–732	12·35	461	Yarragadee	Observation bore
								430–436	10·09	354	Leederville	do.

AHD—Australian Height Datum. bns—below natural surface *—centre of 25 mm gate-valve

age, whereas in Q3 samples from the formation are Late Artinskian to ?Tatarian age. The younger sediments intersected in Q3 may indicate that the fault block has been tilted, with a dip of a few degrees to the west; bedding dips of about 5° were measured in cores from Q2. The palynology of samples from the formation in bores Q2 and Q3 indicate a non-marine environment of deposition.

Triassic

Lesueur Sandstone: The Lesueur Sandstone was not intersected by the Quindalup Line bores, but conformably underlies the Cockleshell Gully Formation between the Wirring and Darling Faults. The formation is not relevant to the hydrogeology of this area, and is not discussed further.

Jurassic

Cockleshell Gully Formation: The Cockleshell Gully Formation was intersected in bores Q1 and Q10. It comprises interbedded sandstone and grey shale, with minor seams of coal and carbonaceous shale. The sandstone is mainly clayey, fine to very coarse, variably sorted, and weakly to moderately consolidated. The shale is commonly silty, and well consolidated. Coal and carbonaceous material were common in sludge samples in bores Q1 and Q10, but only in Q1 were thin coal seams (up to 1 m thick) indicated on the wire-line logs. The formation is about 1 500 m thick in the Bunbury Trough (Playford and others, 1976), and possibly about 1 000 m thick on the Vasse Shelf between the Busselton and Wirring Faults. The maximum thickness of this formation intersected by the Quindalup Line bores was 504 m in Q1.

The formation conformably overlies the Lesueur Sandstone, and is in turn overlain, conformably by the Yarragadee Formation in the Bunbury Trough, and unconformably by the Leederville Formation on the Vasse Shelf (Fig. 3). The Eneabba Member of the Cockleshell Gully Formation was intersected in Q1, as erosion on the Vasse Shelf removed the upper part of the formation prior to deposition of the Leederville Formation. The Cattamarra Coal Measures member was intersected in Q10.

The lithology and palynology of all samples from the formation are consistent with a non-marine environment of deposition.

Yarragadee Formation: The Yarragadee Formation was intersected at sites Q4 to Q10. It consists of interbedded sandstone, shale and minor siltstone, with the percentage of sandstone ranging from about 90% in Q4 to about 25% in the top 500 m of the formation in Q9A (Fig.3). The sandstone is generally pale grey, clean or slightly clayey, and is composed of weakly consolidated, fine to very coarse sand or granules, mostly with poor or moderate sorting. The shale is generally dark grey or brown-grey, slightly silty or sandy, and well consolidated. Carbonaceous material is common, and ranges from carbonaceous shale or carbonized plant material to hard vitreous coal. It occurs in thin seams and lenses, rarely up to 2 m thick, and as coal chips embedded in shale. Layers containing heavy minerals and pyrite are also common.

The Yarragadee Formation is absent on the Vasse Shelf. The formation in the Bunbury Trough is about 300 m thick (in Q10) to 1 400 m thick (in Q9). It conformably overlies the Cockleshell Gully Formation, and is unconformably overlain by the Bunbury Basalt at Q6, and between Q8 and Q9, and elsewhere by the Leederville Formation.

Palynomorphs from the Yarragadee Formation indicate a Middle or Late Jurassic age. Some samples have distinct assemblages which can be assigned to bio-stratigraphic zones erected by Filatoff (1975) and Backhouse (1978), shown in Figure 3. One sample from the formation in Q5 contains reworked Permian spores and pollen (Backhouse, 1980), suggesting that Permian sediments were being eroded, possibly from the Vasse Shelf, during deposition of the Yarragadee Formation. The palynology of all samples from the formation is consistent with a non-marine environment of deposition.

Cretaceous

Bunbury Basalt: The Bunbury Basalt was intersected in Q6, between 32 m and 104 m depth, and has been intersected in private bores between Q8 and Q9. A previously unrecorded outcrop was discovered in a small swampy area located approximately 2·8 km northwest of Q6, at latitude 33°37′46″S and longitude 115°33′57″E (Fig. 1). The outcrop consists of a few boulders of slightly weathered basalt, and, according to the landholder, the basalt occurs at about 1 m depth beneath the swamp.

The Bunbury Basalt is believed to have filled valleys eroded into the Yarragadee Formation. Its age is probably Neocomian (Playford and others, 1976). It is generally unweathered with columnar jointing, but may weather to a chocolate-brown clay.

The basalt in Q6 contains an interbedded layer of clay between 52 m and 55 m. This clay may be a sediment rather than weathered basalt as it has relatively high gamma radiation on the gamma-ray log, whereas basalt (weathered or fresh) usually has low radiation. A sludge sample from this interval contains palynomorphs which indicate a possible Early Cretaceous age. If this age is correct, then the presence of a sediment in the basalt indicates at least two flows of basalt which are possibly contemporaneous with deposition of the Leederville Formation.

Leederville Formation: The Leederville Formation was intersected in all Quindalup Line bores. It consists of interbedded sandstone, siltstone, and shale, with rare conglomerate and coal seams. The sandstone is composed of weakly consolidated, poorly to moderately sorted, fine- to very coarse-grained sand, with varying proportions of intergranular clay. The siltstone and shale are generally dark grey or brown-grey, micaceous,

TABLE 2. STRATIGRAPHIC SUCCESSION INTERSECTED IN THE QUINDALUP LINE BORES

Age	Formation	Member	Thickness (m) Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q 8	Q9	Q10	Summary of Lithology	Remarks
Quaternary	....	....	?9	?9	10	11	7	11	....	....	....	3	Sand, clay, limestone	Minor local aquifer
Tertiary	....	....	....	....	....	....	....	....	?1	4	?1	....	Laterite	
E. Cretaceous	Leederville	....	75	100	199	78	144	21	?138	249	?349	?495	Sandstone, siltstone, and shale	Multilayered aquifer
E. Cretaceous	Bunbury Basalt	....	....	....	....	....	....	72	....	....	....	....	Basalt	Local aquiclude
M.—L. Jurassic	Yarragadee	....	....	....	....	>496	>462	?>1 014	>905	>905	>1 115	?298	Sandstone, minor shale	Major aquifer
E. Jurassic	Cockleshell Gully	Cattamarra Coal Measures	....	....	....	....	....	....	....	....	....	>268	Sandstone and shale	Contains brackish or saline groundwater
E. Jurassic	Cockleshell Gully	Eneabba	>504	....	....	....	....	....	....	....	....	....	Sandstone and shale	Minor multilayered aquifer
E. Permian	Sue Coal Measures	....	....	>442	>244	....	....	....	....	....	....	....	Sandstone, some shale and siltstone	?Minor aquifer

moderately- to well-consolidated, and are commonly carbonaceous. Accessory minerals include feldspar, heavy minerals and pyrite. A conglomerate was intersected near the base of the formation in Q5, and includes boulders of granite, basalt and greywacke. Chloritic shale is common in bores Q1 to Q3. Carbonaceous material in the Leederville Formation ranges from carbonaceous shale and carbonized plant material to lignite. It occurs mostly in thin lenses or as disseminated chips in shale; only minor thin coal seams up to 1 m thick were indicated on the short-normal resistivity and point-resistance logs.

The Leederville Formation unconformably overlies the Sue Coal Measures, the Cockleshell Gully Formation and the Yarragadee Formation; conformably overlies the Bunbury Basalt; and at some localities unconformably overlies Precambrian rocks of the Leeuwin and Yilgarn Blocks. A thin layer of Quaternary sediments unconformably overlies the Leederville Formation on the Swan Coastal Plain. The formation crops out on the Blackwood Plateau where it has been deeply weathered and lateritized.

The thickness of the Leederville Formation ranges from 21 m (Q6) to about 500 m (Q10) in the Quindalup Line bores, and the formation has been completely removed by erosion where the Bunbury Basalt crops out near Q6.

The formation in this area is mainly non-marine, with minor marine intercalations indicated by the palynology of some samples from Q5, Q9 and Q10, and the presence of glauconite in some samples from Q2 and Q3.

Several samples from the lower part of the Leederville Formation at sites Q7 and Q9 contain mixed Leederville and Cretaceous Yarragadee Formation assemblages of non-marine spores and pollen (Backhouse, 1980). These assemblages indicate probable re-working of the Cretaceous Yarragadee Formation during deposition of the Leederville Formation, which implies that deposition in the Bunbury Trough commenced while Mesozoic sediments were still being eroded in other areas of the Perth Basin.

Thick beds of shale with minor sandstone occurring at the base of the Leederville Formation in Q2, Q3 and Q9 may be equivalent to the South Perth Shale (Playford and others, 1976) on the basis of lithology and stratigraphic position. However, the shale is non-marine, at least in Q9, and it is not known whether the shale is older than the Leederville Formation.

Tertiary

Laterite: Laterite and associated sand were intersected in bores at sites Q7, Q8 and Q9 on the Blackwood Plateau. The laterite ranges from massive to pisolitic gravel, and in places overlies a mottled zone developed in weathered shale of the Leederville Formation. The sand is commonly iron-stained, generally poorly sorted, and fine to coarse grained. The laterite ranges from 1 m to 4 m thick where intersected by the Quindalup Line bores.

Laterite in the Perth Basin is presumed to be Tertiary or Pleistocene in age (Playford and others, 1976).

Quaternary

Guildford Formation: The Guildford Formation was not intersected by the Quindalup Line bores. It underlies the Pinjarra Plain (Fig. 2) and consists of clay and clayey sand with rare lenses of gravel. A band of ferruginized sand ("coffee rock") commonly occurs in the formation near the water-table.

Bassendean Sand: The Bassendean Sand was intersected by bores Q5 and Q6, and consists of light grey or yellow-grey sand, moderately to well sorted, mostly medium to coarse grained, and subangular to rounded. The thickness of the formation is 7 m in Q5 and 11 m in Q6. The formation unconformably overlies the Leederville Formation at both sites.

Tamala Limestone: The Tamala Limestone was intersected in bores Q4 and Q10. It consists of light brown or orange-brown, medium- to coarse-grained (in Q10) or fine- to very coarse-grained (inQ4) sand and limestone, containing abundant shells and shell fragments. The formation is 3 m thick in Q10 and approximately 11 m thick in Q4, and unconformably overlies the Leederville Formation in both bores.

Calcilutite: A calcilutite was intersected beneath the Safety Bay Sand in bores Q1 and Q3. It consists of light brown, calcareous clay with abundant shell fragments and minor thin bands of grey clay, and is considered to be an estuarine deposit. The calcilutite is 3 m to 4 m thick, and unconformably overlies the Leederville Formation.

Safety Bay Sand: The Safety Bay Sand was intersected in bores Q1 to Q3, and consists of calcareous sand and shell fragments with minor limestone bands. The sand is light

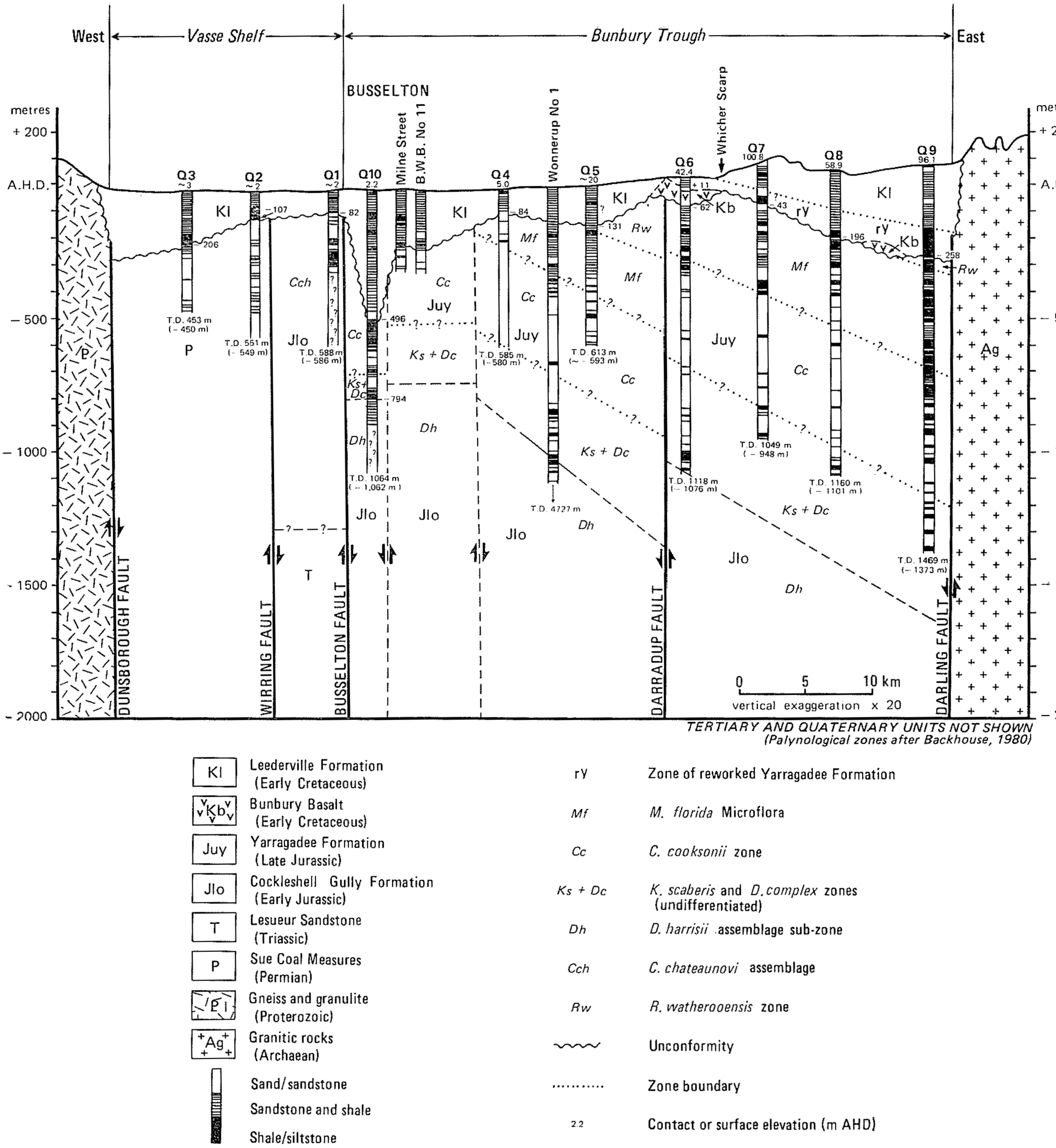

Figure 3 Geological section. GSWA 19222

grey, light brown, and white, and fine to medium grained. The Safety Bay Sand is 9 m to 10 m thick, and overlies the calcilutite.

STRUCTURE

The inferred geological structure is illustrated by a section through the Quindalup Line bores (Fig. 3).

Pre-Cretaceous sediments in the southern Perth Basin have been block-faulted along north-south trending faults, dividing the basin into two major structural elements: the Vasse Shelf, between the Busselton and Dunsborough Faults, and the Bunbury Trough, between the Busselton and Darling Faults. The Vasse Shelf is itself block-faulted by the Wirring Fault, resulting in the juxtaposition of the Sue Coal Measures and the Cockleshell Gully Formation.

The Cockleshell Gully and Yarragadee Formations thicken and gently dip towards the east. These sediments are cut by several faults, including the Darradup Fault (Fig. 3) which has a down-throw of about 300 m to the west.

The positions of faults and formation boundaries shown in Figure 3 have been determined from geological evidence from the drilling of the Quindalup Line, and from geological sections and structural contour maps based on geophysical surveys, given in Playford and others (1976).

The Bunbury Basalt unconformably overlies the Yarragadee Formation in the Bunbury Trough, and is overlain by the Leederville Formation except where the basalt is exposed near Q6. The Leederville Formation unconformably overlies Jurassic and Permian sediments, and occasionally the crystalline rocks of the Leeuwin and Yilgarn Blocks. The formation is draped over the underlying fault blocks in a series of anticlines and synclines which result from deposition accompanying differential compaction of the Phanerozoic sediments over a faulted basement, as proposed by Cope (1972).

The Quaternary formations form a flat-lying cover over the Leederville Formation on the Swan Coastal Plain, except where the Bunbury Basalt crops out.

HYDROGEOLOGY

INTER-RELATIONSHIP OF AQUIFERS

A section showing the apparent vertical component of groundwater flow in the Leederville and Yarragadee Formations is given in Figure 4. Water-levels measured in bores Q1 to Q3 are unreliable, and could not be used to determine groundwater flow directions to the west of Busselton.

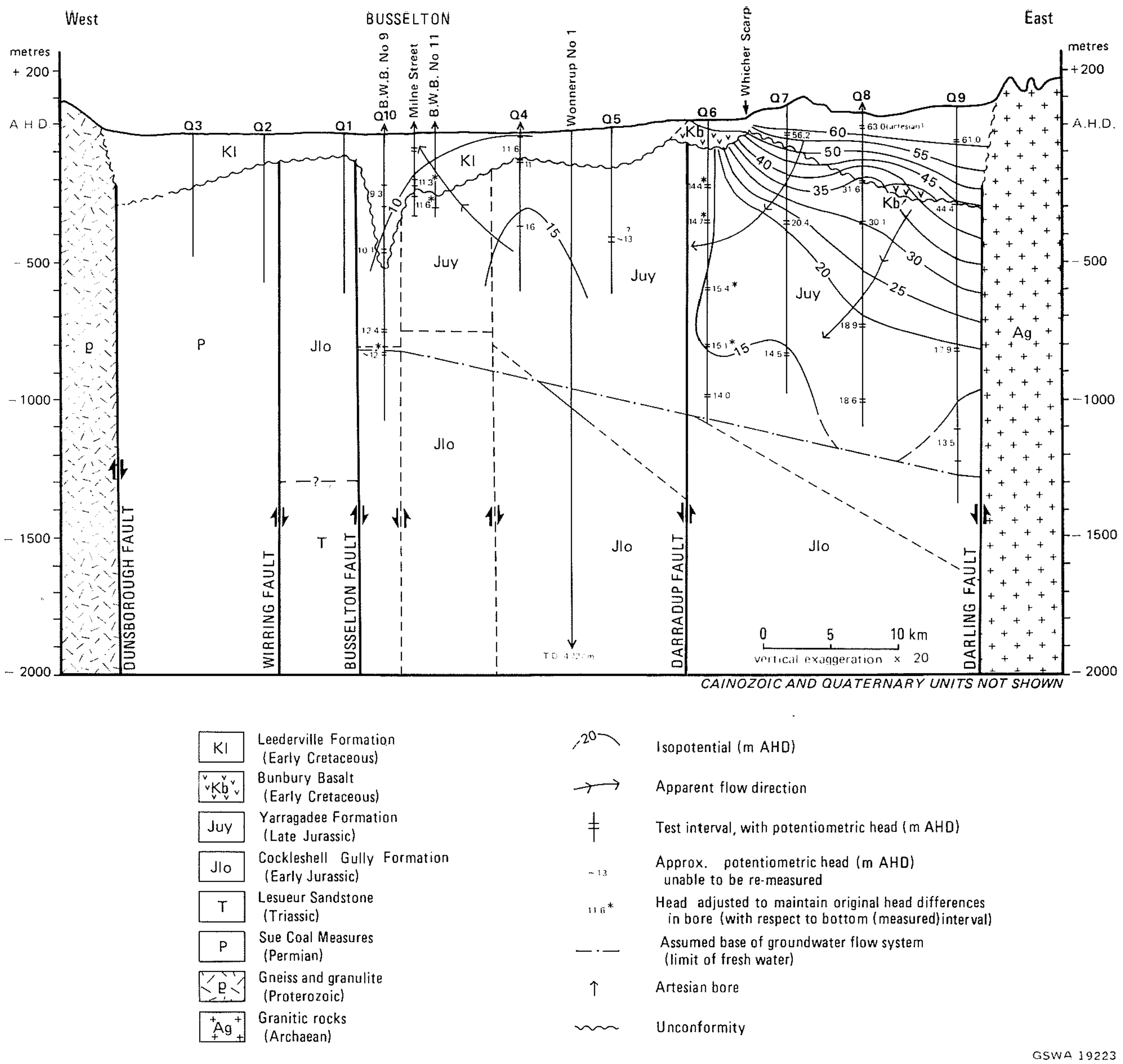

Figure 4 Isopotentials, and apparent groundwater flow directions (15 October, 1980).

The groundwater flow system can be divided into two sections based on the vertical hydraulic gradient; one in the Leederville Formation and the upper part of the Yarragadee Formation east of the Darradup Fault, the other in the lower part of the Yarragadee Formation east of the Darradup Fault and the Yarragadee and Leederville Formations west of the fault. The groundwater flow is predominately northwards (Commander, in prep.), with only a small component of flow in the vertical and east-west directions.

The abrupt change from fresh to saline groundwater at depths of between -770 m AHD (Australian Height Datum) (in Q10) and -1 250 m AHD (Q9) marks the lower limit of relatively rapid groundwater movement, and is assumed to be the base of the groundwater flow system. The saline groundwater at depth indicates that there is only minor groundwater movement as a result of confinement by shale beds, increased consolidation, friction losses, and high formation pressures.

The high, downward head-gradient east of the Darradup Fault indicates a low vertical permeability in the Leederville Formation and the shaly section of the Yarragadee Formation, and also the potential for recharge to the Yarragadee Formation from the Leederville Formation. The upward head-gradient between the Darradup Fault and Busselton shows there is some discharge from the Yarragadee Formation to the Leederville Formation, and presumably to the sea via the Quaternary sediments.

AQUIFERS

Safety Bay Sand

The Safety Bay Sand is a minor aquifer along the coast, and contains a layer of fresh groundwater overlying saline groundwater. The aquifer is recharged directly from rainfall, discharges to the sea, and yields small supplies of fresh groundwater from shallow depths.

Tamala Limestone

The Tamala Limestone crops out parallel to the coastline and inland of the low-lying area which includes the Wonnerup and Vasse estuaries.

Groundwater supplies of up to 2 400 m^3/day are recorded from the formation, however in some areas the formation contains slightly brackish or, rarely, saline groundwater with with a salinity of up to 6 000 mg/L TDS. High iron concentrations are also common in water from the limestone.

Groundwater from the Tamala Limestone is used for stock and domestic water supplies.

Bassendean Sand

The area underlain by the Bassendean Sand is largely undeveloped, consequently very few bores intersect the formation in this area. However the larger areas of Bassendean Sand (Fig. 2) are likely to contain large volumes of fresh groundwater recharged directly from rainfall.

Guildford Formation

Groundwater in the Guildford Formation is generally fresh near the Whicher Scarp, but is mostly brackish in areas away from the scarp. The salinity ranges from 200 mg/L TDS to more than 8 000 mg/L TDS, but is mostly less than 2 000 mg/L TDS. The moderately high salinity is due to a combination of high evaporation and transpiration losses from the shallow water-table, and the slow movement of water through the formation. High iron concentrations are common in water from the formation.

The Guildford Formation underlies most of the intensively farmed areas, and yields small stock and domestic water supplies of usually less than 100 m^3/day.

Leederville Formation

The Leederville Formation is a multilayered aquifer system which extends across the Perth Basin near the Quindalup Line, except for an area near Q6 where the Bunbury Basalt crops out (Fig. 3). The Leederville Formation has a maximum thickness of about 500 m (Q10) and an average thickness of about 200 m. The formation consists of discontinuous beds of sandstone, siltstone and shale, generally less than 5 m thick.

Groundwater in the formation is recharged from rainfall on the Blackwood Plateau, as indicated by the downward head gradient (Fig. 4), with infiltration occurring via the laterite and sand capping. Near the coast between the Busselton and Darradup Faults, the formation recieves some recharge from the underlying Yarragadee Formation, in which there is an upward head gradient.

Groundwater moves northwards in the Leederville Formation east of Q6 (Commander, in prep.) and is presumed to move northwards west of Q6. It is confined, except where sandstone beds underlie Quarternary sands on the Swan Coastal Plain and Tertiary deposits on the Blackwood Plateau. Bores in the formation commonly flow when drilled in low-lying areas of the coastal plain, or in valleys cut into the Blackwood Plateau (Q8C).

The salinity of groundwater in the Leederville Formation in the Bunbury Trough is less than 400 mg/L TDS (Fig. 5), except in bores Q5 and Q9, where salinity is up to 900 mg/L TDS. High salinity is attributed to the restriction of groundwater movement by beds of shale and siltstone. The salinity of groundwater in the formation intersected by bores Q1, Q2 and Q3 on the Vasse Shelf, ranged from 600 mg/L TDS to more than 40 000 mg/L TDS. The bores, all about 300 m from the coast, probably intersected a salt-water wedge, whereas private bores which are more than 1 km from the coast yield fresh groundwater from the formation. Evidence for the existence of a salt-water wedge comes from two private bores near the coast between Q1 and Q2. One bore intersected fresh water, but salt water intruded after pumping commenced, and the other intersected fresh water overlying saline water at depth. In a confined aquifer it is unusual for a salt-water wedge to be inland at such a shallow depth, and, because groundwater in the formation is virtually unexploited in this area, it is inferred that the formation discharges to the swamps, drains and estuaries which parallel the coastline behind the Quindalup dunes.

Water from the Leederville Formation commonly has a high iron concentration (3·5 mg/L in Q10) and at Busselton requires treatment before use for town water supplies.

Groundwater from the Leederville Formation is used for urban water supplies at Quindalup, Busselton, Capel and Donnybrook, and for some farm, irrigation and industrial supplies. The formation is a major aquifer, the most important on the Vasse Shelf. It is capable of substantial further development.

Yarragadee Formation

The Yarragadee Formation underlies the Leederville Formation in the Bunbury Trough, and is composed of weakly consolidated sandstone with minor beds of shale. The formation is generally at least 70% sandstone, however the percentage decreases to about 25% in the upper part of the formation and adjacent to the Darling Fault (Fig. 3). This change was also found in the Picton Line bores (Wharton, 1980). The thickness of the formation intersected in the Quindalup Line bores varies from about 300 m (Q10) to greater than 1 115 m (Q9).

Recharge to the Yarragadee Formation is presumed to originate from rainfall on the Blackwood Plateau. Outcropping Yarragadee Formation has not been recognized on the plateau, however the large thickness of fresh water in the formation, and the low vertical permeability of the Leederville Formation, suggests predominantly direct recharge to the Yarragadee Formation, rather than downward movement through the Leederville Formation. In addition, the salinity of water in the Yarragadee Formation is sometimes lower than is found in the Leederville Formation where intersected by the Quindalup Line bores (Fig. 5). The Leederville Formation is absent on the Blackwood Plateau where the Bunbury Basalt crops out, and is likely to be absent in other areas.

Groundwater in the Yarragadee Formation is confined by shale and siltstone within the formation and in the overlying Leederville Formation, and bores between Q5 and Busselton may flow where the surface elevation is between 10 m and 15 m above sea level.

The salinity of groundwater in the Yarragadee Formation ranges from 200 mg/L TDS to more than 20 000 mg/L TDS, and averages about 400 mg/L TDS. The fresh groundwater extends to depths of between —770 m AHD (Q10) and —1 250 m AHD (Q9) in the formation, with brackish or saline water below (Fig. 5). The eastward increase in thickness of fresh groundwater corresponds with the increase in thickness of the Yarragadee Formation, which is less consolidated and contains less shale than the underlying Cockleshell Gully Formation. The thickness of fresh groundwater may also be directly related to the distance from the recharge area; fresh groundwater extends to a greater depth below the Quindalup Line than below the Picton Line (Wharton, 1980), which is further from the recharge area.

Dissolved iron in groundwater from the formation ranges from 0·55 mg/L to 9·5 mg/L.

The Yarragadee Formation is the most important aquifer in the region, and contains an extremely large volume of fresh groundwater in storage. Large supplies of groundwater are available from the formation and are used for town water and industrial supplies at Busselton and Capel. The Milne Street bore in Busselton is 300 m deep and yields 3 800 m^3/day with 14 m drawdown. The groundwater resources in the formation are capable of substantial further development.

Cockleshell Gully Formation

The Cockleshell Gully Formation is composed of interbedded sandstone and shale. The sandstone is weakly to moderately consolidated and commonly contains intergranular clay. The formation occurs at depth between the Wirring and Darling Faults, but is only at a sufficiently shallow depth to contain fresh groundwater between the Wirring and Busselton Faults on the Vasse Shelf (Fig. 3). The salinity of groundwater in the formation in Q10 is 1 900 mg/L TDS, and is expected to increase with depth, as the formation in the Bunbury Trough is below the main groundwater flow system (Fig. 4).

The salt-water wedge intersected in the Leederville Formation in Q1 extends into the top of the underlying Cockleshell Gully Formation. Brackish or saline groundwater was intersected in the Cockleshell Gully Formation to a depth of about 275 m, and was underlain by fresh water to about 450 m depth (Fig. 5). The fresh-water layer between 275 m and 450 m depth probably results from an increasing potentiometric head with depth, which prevents salt water intrusion. The brackish to saline groundwater below 450 m depth is probably a result of a reduction in groundwater flow with depth, rather than being part of the salt-water wedge.

The Cockleshell Gully Formation between the Wirring and Busselton Vaults, and inland from the salt-water wedge. is likely to contain fresh groundwater to a depth of about 450 m. Groundwater in the formation is not being used, but large supplies of fresh groundwater could be obtainable in this area.

Sue Coal Measures

The Sue Coal Measures lie unconformably beneath the Leederville Formation between the Wirring and Dunsborough Faults on the Vasse Shelf, at a depth of between —100 m AHD and —300 m AHD. In bores Q2 and Q3, the Sue Coal Measures are composed of consolidated sandstone with some siltstone and shale. A core of the sandstone from Q2 had a porosity of 22%.

Groundwater in the formation is probably recharged by leakage from the overlying Leederville Formation. The direction of groundwater flow is not known, as no reliable head measurements were made, but is expected to be northwards as for the Leederville Formation.

The salinity of groundwater in the Sue Coal Measures generally increases with depth, and in Q1 and Q2 ranges from 1 370 mg/L TDS to approximately 9 000 mg/L TDS (Fig. 5). A coal exploration bore drilled by Broken Hill Proprietary Co Ltd, Busselton 1 (Fig. 1), intersected Sue Coal Measures between 102 m depth and 462 m (total depth). The bore flowed during construction, both from the Leederville Formation and from the Sue Coal Measures. A water sample taken after drilling was completed, and with casing run to below the Leederville Formation, had a salinity of 1 400 mg/L TDS.

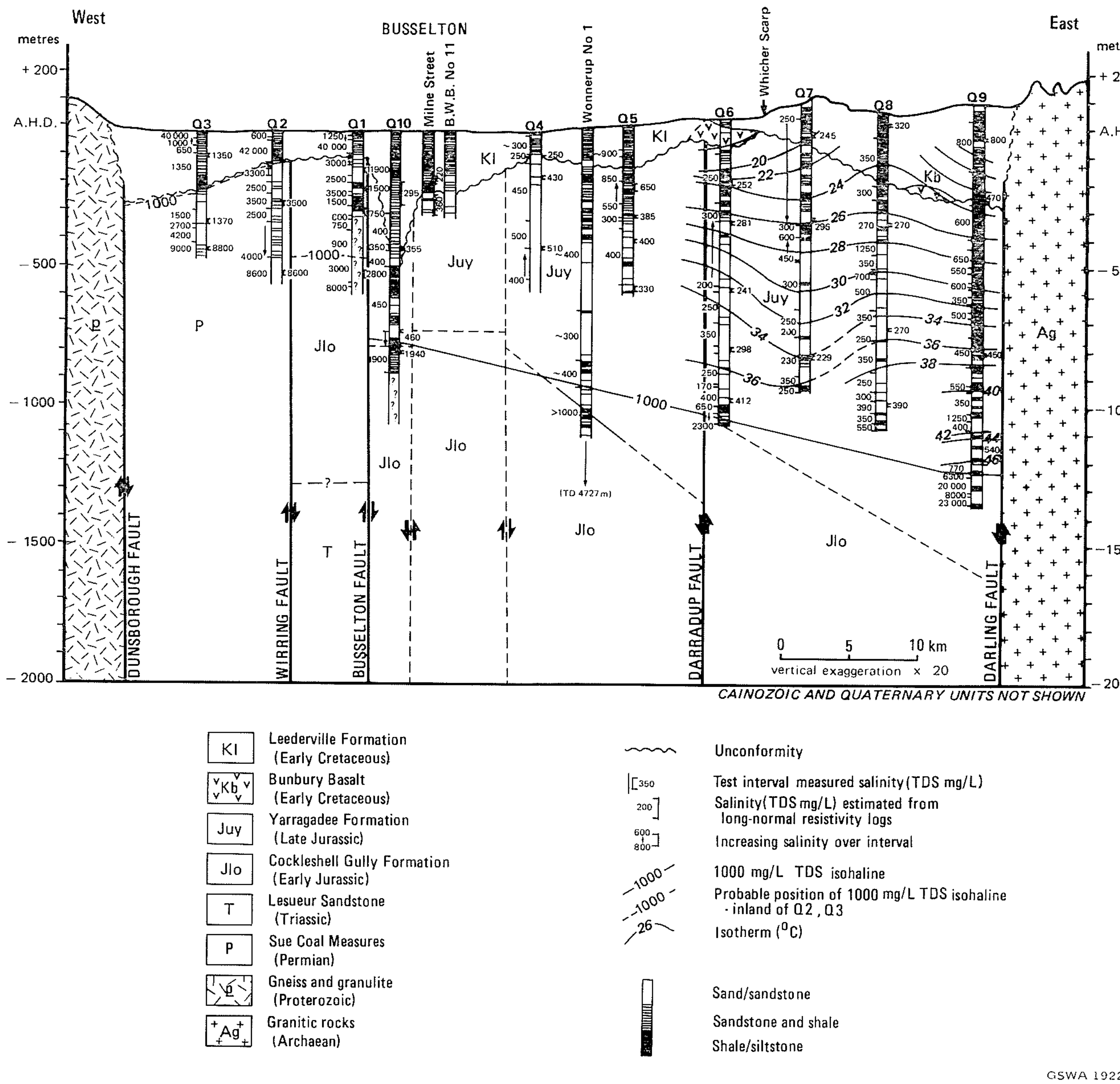

Figure 5 Variation in groundwater salinity, and geothermal temperatures.

Groundwater in the Sue Coal Measures is not being used, but could be developed for stock or industrial supplies.

GROUNDWATER TEMPERATURE

Differential temperature logs were run to the top of the packers in bores Q6, Q7A and Q8A, and through the packer to the top of the cement plug in Q9A.

The average temperature gradients over the measured intervals are 1·8°C/100 m (Q7A, Q8A), 2·3°C/100 m (Q6) and 2·4°C/100 m (Q9A). The results are shown as isothermal contours in Figure 5.

CONCLUSIONS

Drilling of the Quindalup Line bores has provided considerable new geological and hydrogeological information on a section across the Perth Basin from west of Busselton to Donnybrook.

The Yarragadee Formation, the Cockleshell Gully Formation and the Sue Coal Measures have been juxtaposed by faults trending north-south. The Leederville Formation is draped unconformably over the fault blocks in the form of small anticlines and synclines, which are believed to have developed by differential compaction of the underlying sediments.

A major groundwater flow system exists in the Leederville and Yarragadee Formations between the Busselton and Darling Faults. Fresh groundwater with a salinity generally less than 500 mg/L TDS extends to a depth of between —770 m AHD and —1 250 m AHD. West of the Busselton Fault a coastal salt-water wedge was intersected in the Leederville Formation, but further inland the formation yields large supplies of fresh groundwater.

Groundwater in the Leederville and Yarragadee Formations is presumed to be recharged by rainfall on the Blackwood Plateau.

Further drilling is required on the Blackwood Plateau, south of the Quindalup Line, to locate intake areas and to provide the hydrogeological data necessary to caclulate annual throughflow.

The Leederville and Yarragadee Formations contain a very large volume of fresh groundwater which is capable of substantial further development.

REFERENCES

Backhouse, J., 1978, Palynological zonation of the Late Jurassic and Early Cretaceous sediments of the Yarragadee Formation central Perth Basin Western Australia: West. Australia Geol. Survey Report No. 7.

———— 1980, A reassessment of palynological investigations in the Quindalup Line boreholes: West. Australia Geol. Survey Palaeont. Report No. 18/1980 (unpublished).

Commander, D. P., in prep., Bunbury area groundwater investigation: West. Australia Geol. Survey Rec.

Cope, R. N., 1972, Tectonic style in the southern Perth Basin: West. Australia Geol. Survey Ann. Rept 1971, p. 46–50.

Filatoff, J., 1975, Jurassic palynology of the Perth Basin, Western Australia: Palaeontographica Abt. B, v. 154.

Low, G. H., 1972, Explanatory notes on the Phanerozoic rocks of the western part of the Collie 1:250 000 geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1972/10 (unpublished).

Playford, P. E., Cockbain, A. E. and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull. 124.

Probert, D. H., 1967, Groundwater in the Busselton area, progress report on exploratory drilling: West. Australia Geol. Survey Rec. 1967/15 (unpublished).

Saint-Smith, E. C., 1912, A geological reconnaissance of a portion of the South-West Division of Western Australia: West. Australia Geol. Survey Bull. 44.

Wharton, P. H., 1980, The geology and hydrogeology of the Picton borehole line: West. Australia Geol. Survey Ann. Rept 1979, p. 14–19.

——————in prep., The geology and hydrogeology of the Quindalup borehole line: West. Australia Geol. Survey Rec.

MESOZOIC AND CAINOZOIC SEDIMENTS IN THE WESTERN FORTESCUE PLAIN

by J. C. Barnett

ABSTRACT

The western part of the Fortescue plain is underlain by a complex sequence of alluvial, lacustrine, and colluvial sediments, ranging in age from Cretaceous to Holocene. The sediments are up to 120 m thick and have been deposited in a valley incised in Proterozoic rocks. The valley formed by headward erosion along the strike of the Proterozoic rocks, at least as long ago as the Late Jurassic; it is not a rift valley.

The sediments infilling the valley include conglomerate, massive and pisolitic ironstone, clay, and dolomite. The dolomite contains fossils of brackish- and fresh-water origin and formed in a lacustrine environment.

The catchment of the Fortescue plain has been captured twice from the northwest, first by the Robe River, and then by the Fortescue River.

INTRODUCTION

Much information on the stratigraphy, thickness, and extent of Mesozoic and Cainozoic sediments underlying the western part of the Fortescue plain has been gained as a result of drilling for groundwater during the last twelve years. The geology of these sediments is described in this paper, and a formalized stratigraphy is proposed for the Cainozoic strata.

The sediments have economic importance as a source of groundwater; more recently, they have been investigated for other possible economic deposits that may have accumulated in the Fortescue valley, for example iron ore and lignite. Since 1968, a bore field near Millstream has supplied groundwater by pipeline to the coastal towns of Cape Lambert, Dampier, Karratha and Wickham.

The Fortescue plain occupies a broad valley that bisects the Pilbara region of Western Australia. It is about 450 km long, ranges in width from 8 to 72 km, and is wider in the east than in the west; it covers an area of about 13 000 km² (Fig. 1). The plain is bounded on the south by the Hamersley Range, and on the north by the Nullagine plateau. The area discussed in this report is that part of the plain between its western end and Weelumurra Creek, some 120 km to the east.

The regional geology of the area has been described by Kriewaldt and Ryan (1967) and Williams (1968). Since 1967, about 100 exploratory bores have been drilled by the Mines and Public Works Departments (Fig. 2) in the search for water on the western part of the Fortescue plain. Geological data from the initial drilling in the Millstream area are given by Davidson (1969), and a summary of the geology of the western part of the plain is given by Barnett and others (1977).

PHYSIOGRAPHY

LANDFORMS

The western part of the Fortescue plain ranges in width from 10–25 km; it has a very low gradient, sloping from about 345 m above sea level at Weelumurra Creek, to about 315 m at the Robe-Fortescue watershed 90 km to the west. Coalescing alluvial fans form a piedmont slope, 5–10 km wide, flanking

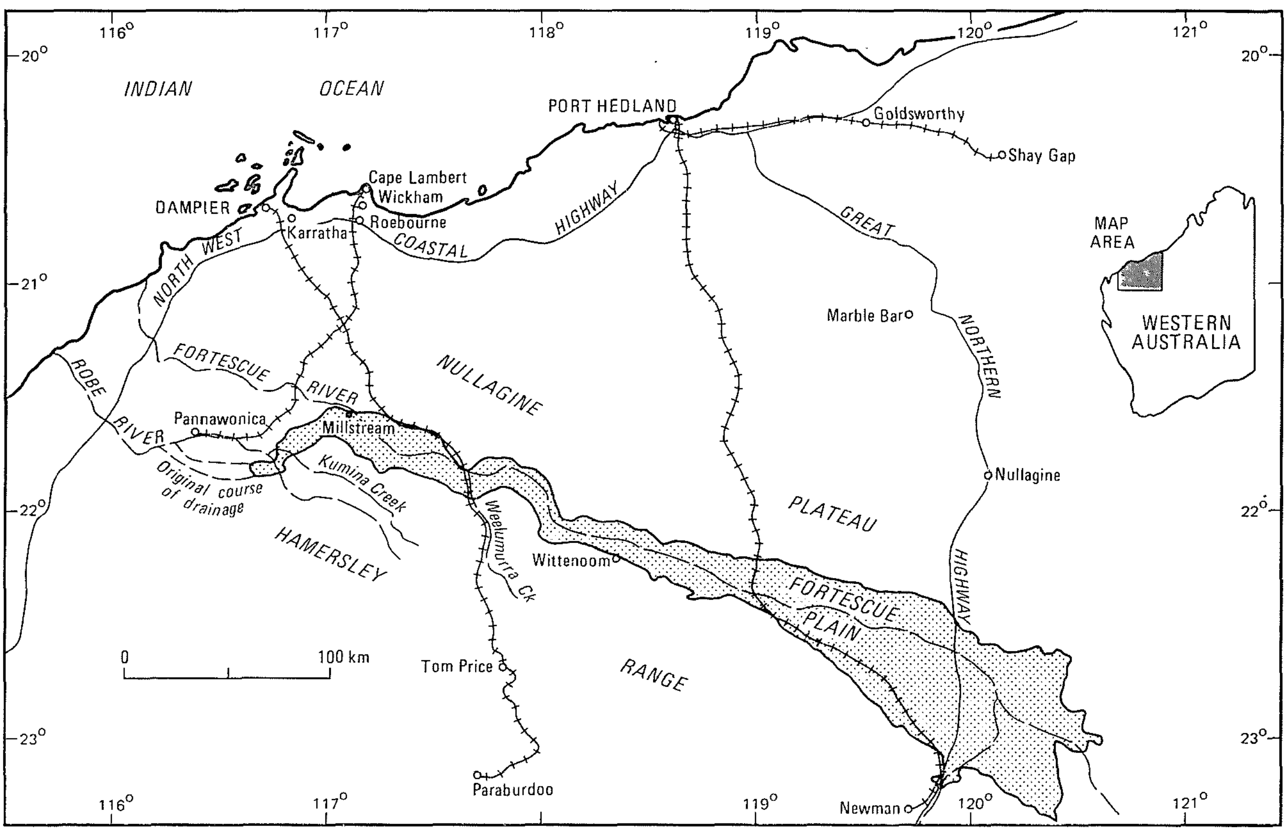

Figure I Locality Plan

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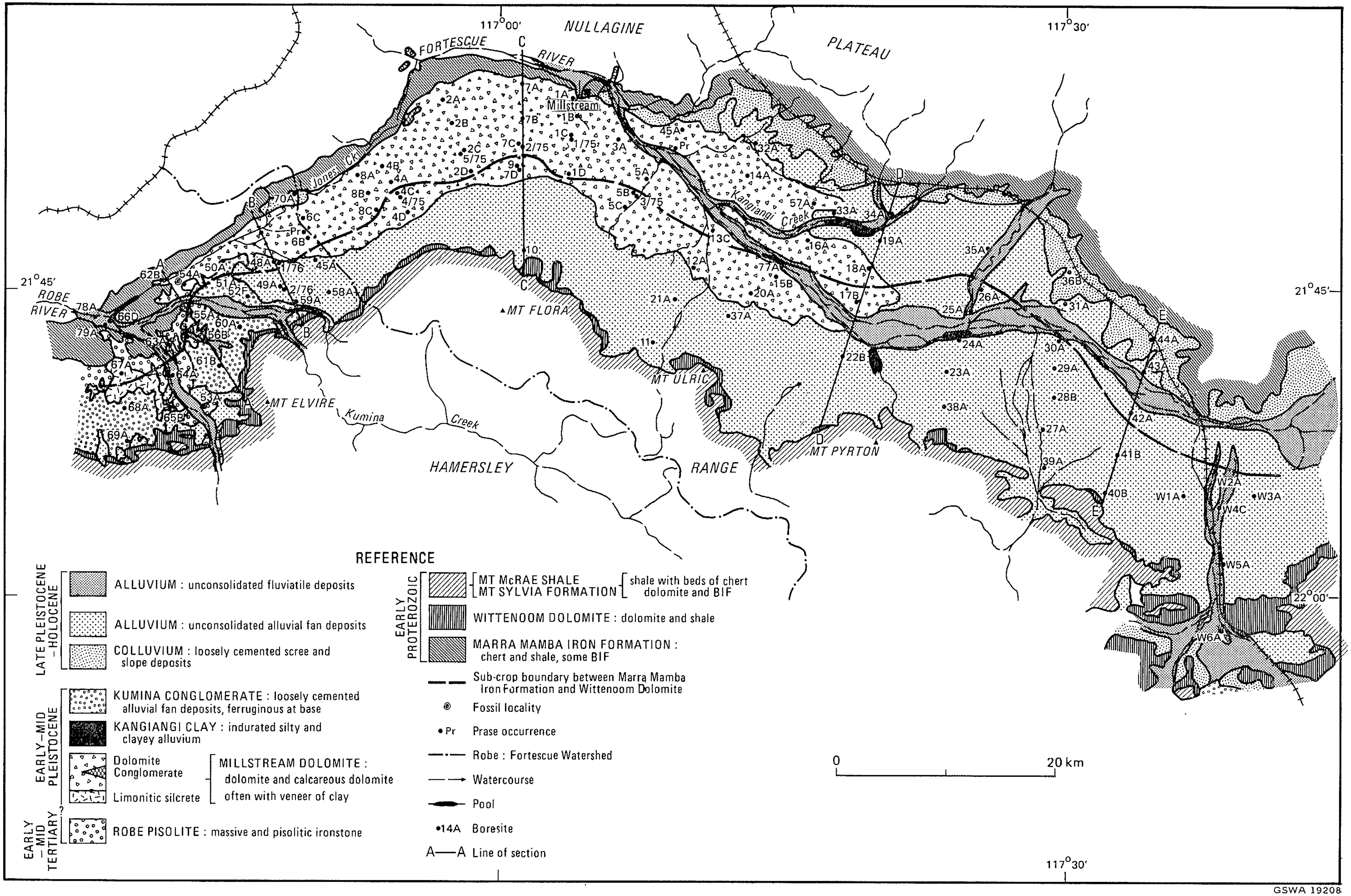


Figure 2 Revised and modified geology, after Kriewaldt and Ryan (1967) and Williams (1968).

the Hamersley Range; a talus slope up to 5 km wide borders the Nullagine plateau. The Millstream surface (Kriewaldt and Ryan, 1967) is the erosional surface corresponding to the Fortescue plain.

The Fortescue plain is bounded to the south by a steep erosion scarp that forms the edge of the Hamersley Range, which reaches a maximum elevation of 842 m above sea level at Mount Pyrton in the western Fortescue area. The Nullagine plateau, which borders the northern side of the plain, is more subdued, rising to just over 400 m. The plateau of the Hamersley Range and Nullagine plateau form an erosional surface, known as the Hamersley surface (Campana and others, 1964).

DRAINAGE

The Fortescue River follows a braided course along the plain as far west as Millstream, where the river becomes constricted and diverts to the northwest through a series of rocky gorges incised in the Nullagine plateau. Several pools up to 14 m deep, have formed near Millstream where the river is constricted. They are permanent and are maintained by springs from a dolomite aquifer beneath the plain.

The watershed between the Robe and Fortescue Rivers crosses the plain near its western end (Fig. 2), which is defined by the limit of headward erosion by the Robe River and its tributaries. Between Millstream and the watershed, the northern margin of the plain is being eroded by the Fortescue River and its tributaries, including Jones Creek.

Tributaries of the Fortescue drain the Nullagine plateau and the Hamersley Range. Those draining the Hamersley Range mainly dissipate into alluvial fans before reaching the main course of the river.

GEOLOGY

GENERAL

The Fortescue plain is underlain by a complex sequence of alluvial, colluvial, and lacustrine sediments, ranging in age from Cretaceous to Holocene; the sediments are flat lying and apparently not affected by folding or faulting.

This sequence of sediments has been deposited in a valley incised in the Proterozoic Hamersley Group, which forms the bedrock beneath the Fortescue plain. Except for minor undulations superimposed on the regional dip, the Proterozoic rocks dip gently to the south. The stratigraphy of the Hamersley Group, insofar as it is relevant to this paper, is given in Table 1 and is not discussed in any further detail.

Jutson (1950) considered the eastern part of the Fortescue plain to be a rift valley, but this view is not supported. In the western Fortescue plain, there is no evidence of faulting along the flanks of the plain, nor of the vulcanism which is normally associated with rift valleys. The plain, which follows the strike of the Proterozoic rocks, formed along a drainage which first developed along the strike of the Wittenoom Dolomite and then migrated slowly downdip to the south.

The surface geology is shown in Figure 2, upon which is also shown the subsurface boundary between the Marra Mamba Iron Formation and the Wittenoom Dolomite. Representative diagrammatic sections are shown on Figure 3.

MESOZOIC

Yarraloola Conglomerate

At bore 65 (Fig. 2), 36 m of conglomerate, which is overlain by Robe Pisolite, was encountered above the Wittenoom Dolomite; this conglomerate is correlated on lithological grounds with the Yarraloola Conglomerate, which outcrops about 25 km to the west of bore 65, beyond the margin of the Fortescue plain. The conglomerate contains subrounded to rounded pebbles of chert, quartzite, jaspilite, and quartz (up to 50 mm in diameter) in a matrix of sand, silt, clay, and a little carbonized wood. It contains layers of yellow and grey silty clay and is very clayey towards the base.

Bore 56, 7 km north-northeast of bore 65, penetrated 30 m of conglomerate, which consists almost entirely of angular to rounded clasts of Wittenoom Dolomite. This conglomerate may also be equivalent to the Yarraloola Conglomerate, as it underlies Robe Pisolite.

Yarraloola Conglomerate is absent from other bores in this area, and appears to be confined to a narrow channel (Fig.3, section A–A).

The Yarraloola Conglomerate is thought to be transgressive on to Early Cretaceous marine deposits (Nanutarra Formation) in the Carnarvon Basin further to the west (Williams, 1968).

CAINOZOIC

Robe Pisolite

The Robe Pisolite has a diverse lithology, ranging from massive ironstone to cemented pisolitic ironstone. In places, pisolitic ironstone overlies massive ironstone; but over most of the area, only one type is present in any particular bore. The formation contains layers of yellow limonitic clay, grey clay, and ferruginous shale; a layer of clay with pebbles, a few metres thick, is common at the base. In places, for example bores 53A and 3/75, there are thin layers of calcrete and calcareous clay.

The massive ironstone is siliceous and goethitic. It is usually dark brown, but may also be red brown, and has irregular vugs ranging in size from 1 mm to greater than 0·3 m; these vugs are commonly lined with limonite or translucent chalcedony.

The pisolitic ironstone contains pisoliths, which are generally less than 2 mm in diameter but range up to 12 mm; they are mainly composed of goethite or goethite-hematite. Some of the pisoliths are magnetic and some have skin of limonite; they are cemented by goethite and limonite.

Scattered clasts of chert, banded iron-formation, and hematite shale occur in the ironstone, but they are more common towards the base of the formation. "Ghost" pebbles, entirely replaced by hematite and goethite are common. Fossil wood is common in both the massive and pisolitic ironstone and it shows well-preserved cell structures.

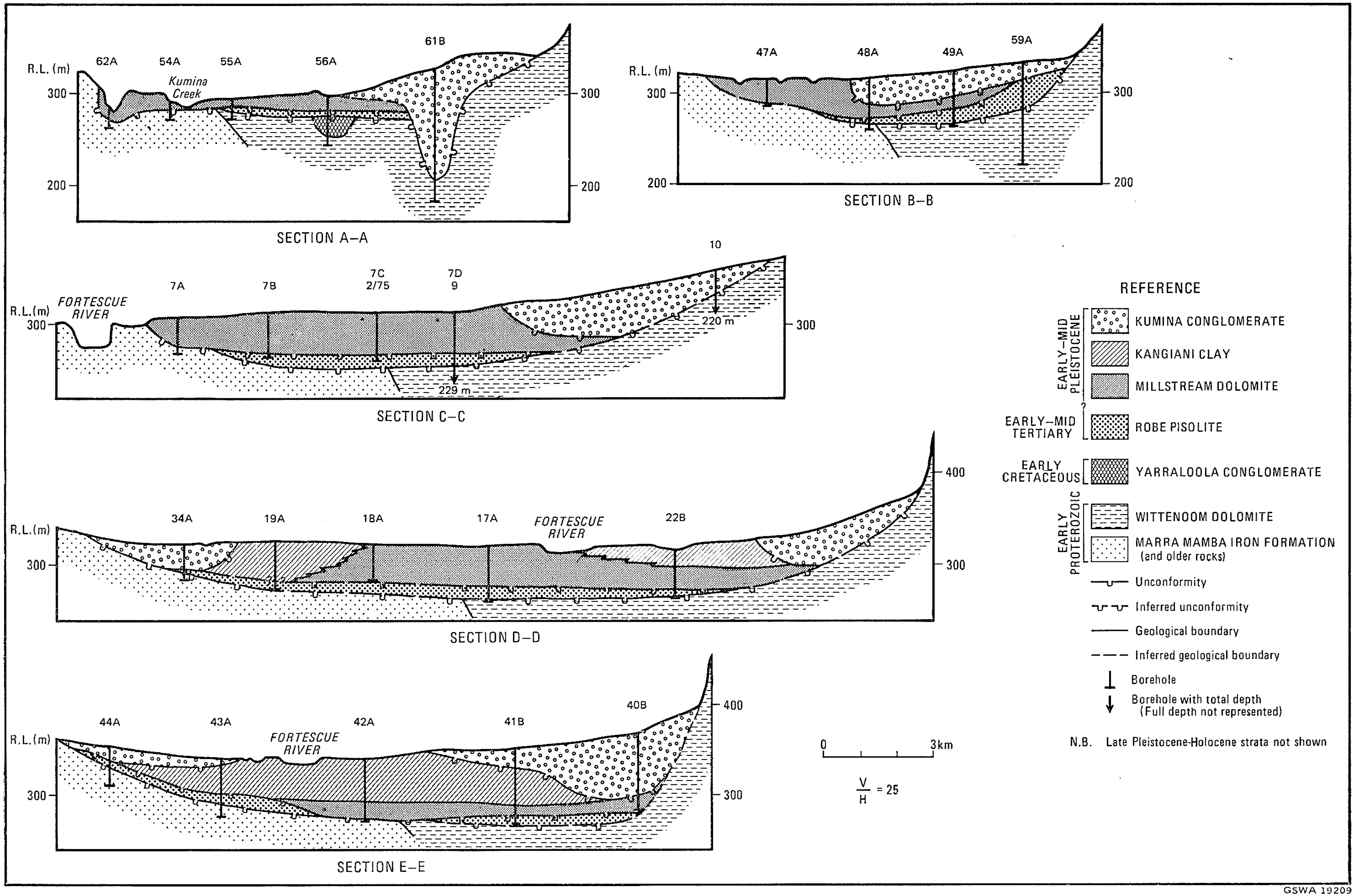
The Robe Pisolite ranges in thickness from 3–33 m; it crops out along both sides of the Robe River, is widespread in the subsurface, unconformably overlies either the Proterozoic bedrock or the Yarraloola Conglomerate, and is disconformably overlain by younger Cainozoic deposits.

Previous workers (MacLeod and others, 1963; Harms and Morgan, 1964; MacLeod, 1966; Zimmerman and others, 1973) have postulated that the Robe Pisolite formed in a fluviatile

TABLE 1. STRATIGRAPHIC SEQUENCE OF THE WESTERN FORTESCUE PLAIN

Age	Stratigraphic unit	Maximum recorded thickness (m)	Lithology and remarks
Late Pleistocene-Holocene	Alluvium	15	Alluvium along present water-courses
	Calcareous silt	5	Grey calcareous silt with tufa
	Residual clay	3	Residual clay overlying Millstream Dolomite
	Alluvium	3	Alluvial fan deposits, unconsolidated
	Colluvium	5	Colluvium
Early-Mid Pleistocene	Kumina Conglomerate	120	Boulders, cobbles, gravel and sand in matrix of silty clay. Commonly ferruginous at base. Consolidated
	Kangiangi Clay (a)	47	Indurated well-bedded silty clay with sand and gravel beds. Ferruginous at base
	Millstream Dolomite (a)	50	Dolomite and calcareous dolomite with layers of silcrete, clay and gravel
Early-Mid Tertiary	Weelumurra Beds (b)	34	Dark grey pyritic shale
	Robe Pisolite (b)	33	Massive and pisolitic ironstone, with clayey layers
Early Cretaceous	Yarraloola Conglomerate	36	Fluviatile conglomerate
Proterozoic	Hamersley Group		
	Wittenoom Dolomite	150	Grey calcitic crystalline dolomite. Upper part mainly shale
	Marra Mamba Iron Formation	20	Interbedded shale and chert, minor BIF
	Fortescue Group		
	Roy Hill Shale	35	Black carbonaceous shale with bands and nodules of marcasite and pyrite

(a) These units are penecontemporaneous. (b) The relative age of these two units is uncertain.



GSWA 19209

Figure 3 Diagrammatic cross section.

TABLE 2. CHEMICAL ANALYSES OF ROBE PISOLITE

Lab. sample No.	Bore	Percent on dry basis							Remarks
		Fe	Al	Si	P	S	V	Ti	
26301	5/75....	41·1	3·1	11·6	0·006	>0·001	>0·01	0·26	Massive Ironstone (Core)
26302	36B	35·9	2·2	16·5	0·018	>0·001	>0·01	0·31	Massive Ironstone (rotary cuttings)
26305	49A	39·3	2·0	15·4	0·034	>0·001	0·02	0·22	Ferruginous gravel (rotary cuttings)
62006/78	59A	57·7	4·75	8·47	0·039	0·03	>0·01	0·17	Cemented pisolite (rotary cuttings)

Analyst—Government Chemical Laboratories

environment by direct precipitation of iron as pisoliths and ferruginous cement, or by replacement of fluviatile sediments by iron-charged waters, or by a combination of these processes. The general lack of coarse clastic material in the ironstone has been ascribed to the fact that little erosion could occur because of stabilization of valley slopes by vegetation (Harms and Morgan, 1964). However, in the western Fortescue plain, "ghost" pebbles attest to at least some replacement of clastic material by iron oxides.

Previous authors agree that the formation was probably deposited during a time of warm pluvial climate in the early to mid Tertiary. MacLeod (1966) considered that the Robe Pisolite formed at a late stage of the development of the Hamersley surface. On the other hand, Harms and Morgan (1964) and Zimmerman and others (1973), concluded that the Robe Pisolite postdates the Hamersley surface. In the western Fortescue plain, the Robe Pisolite appears to be laterally equivalent to the duricrust which caps the Hamersley surface.

At Pannawonica (Fig.1), the Robe Pisolite is mined as iron ore by Cliffs Robe River Iron Associates. Three samples of Robe Pisolite from the western Fortescue Plain were analysed; the results are given in Table 2.

Weelumurra Beds

A sequence of clay, recorded only in bore W6A, is referred to in this paper as the Weelumurra Beds. The sequence is 34 m thick; the upper 13 m is pale grey and pale brown, the lower 21 m, dark grey or black and pyritic. Thin veins of white and clear quartz are present in the basal 9 m of the deposit. Early Tertiary palynomorphs, of possible lacustrine origin, have been identified from the clay (Backhouse, 1975).

The Weelumurra Beds overlie a dark-grey shale, which is presumed to correlate with a shale zone in the Wittenoom Dolomite, and are overlain by gravelly conglomerate and calcrete, which are probably equivalent to the Millstream Dolomite. The Weelumurra Beds are probably a lacustrine deposit which formed behind a bedrock bar across the ancestral Weelumurra Creek where it discharged on to the Fortescue plain from the Hamersley Range.

Millstream Dolomite

The Millstream Dolomite has been referred to informally in the past as the Millstream Calcrete. However, in view of the different senses in which the term calcrete has been used in Western Australia (Carlisle, 1978), and its implication of a dominantly calcium carbonate composition, it is proposed in this paper to formally name the formation Millstream Dolomite, after Millstream homestead (latitude 21°35′40″, longitude 117°04′20″) The type section, in bore 3/75, comprises 46 m of dolomite with layers of silcrete, illite-nontronite clay, and calcareous clay; the summary lithological log of bore 3/75 is set out below.

Depth (m)	Description
0– 4·0	Silcrete and calcified clay
4·0–13·0	Dolomite, earthy
13·0–15·5	Silcrete
15·5–22·1	Dolomite, hard, grey-brown
22·1–25·4	Silcrete and silicified dolomite
25·4–30·5	Dolomite, brown and buff
30·5–34·7	Clay, illite-nontronite, waxy, mottled green and yellow
34·7–37·3	Dolomite, white and yellow
37·3–38·7	Ferruginous silcrete
38·7–44·6	Dolomite, yellow, grey and white
44·6–46·3	Calcareous clay, white

The dolomite, which ranges from soft and earthy to hard and massive, may be white, pink, yellow buff, or may have a marbled appearance. Isolated grains of quartz and ironstone pisoliths are common. In thin section, the dolomite can be seen to consist of either a matrix of very fine-grained carbonate cut by veins of coarser grained carbonate, or of patches of fine-grained carbonate in a coarser matrix of carbonate.

Some layers consist of irregular nodules of carbonate in a matrix of calcareous clay; in some cases, "ghost" nodules of carbonate are visible in more massive varieties of dolomite. In places, the dolomite contains broken fragments of carbonate in a siliceous matrix, and can be described as breccia.

The dolomite is usually vuggy, and often cavernous; cavities up to 0·5 m high are known. The vugs and cavities are best developed at or near the present water table and are commonly lined with botryoidal chalcedonic silica. In places there are small sinkholes at the surface.

Beds of calcified clayey alluvium and red-brown clay occur throughout the formation, but are more common in the upper part. Along the northern margin of the formation at the western end of the outcrop area, there are a few metres of partly calcified pebble conglomerate at the base. There is within the dolomite sequence at latitude 21°36′30″, longitude 116°55′10″, a lens of conglomerate which consists mainly of pisoliths derived from the Robe Pisolite and of banded iron-formation and shale clasts from the Marra Mamba Iron Formation.

Over most of the area, the lower 10–15 m of the formation contains layers of illite-nontronite clay, which, in places, make up the entire lower part of the formation; it is green, dark green, blue grey, or yellow, and usually has a waxy appearance and feel.

Veins and bands of silica occur throughout the formation. There are two persistent layers of silcrete, one at an elevation of about 294 m, which is at the present water-table level, and one at about 310 m, which may represent a past water table level.

A layer of limonitic silcrete is generally present in the lower part of the formation, usually at or near the base. The silcrete is mottled, yellow, white, and occasionally greenish, and displays manganese dendrites; it is usually 2–3 m thick, but ranges up to 6 m. Where the limonitic silcrete outcrops near the Robe River, it contains sub-rounded pebbles and cobbles of Robe Pisolite and chert up to 0·15 m in diameter.

Analyses of the formation (Table 3) show that it is dolomite below, and calcareous dolomite above, the water-table. The Proterozoic Wittenoom Dolomite has a similar chemical composition to the dolomite below the water-table, and an analysis of the Wittenoom Dolomite is given in Table 3 for comparison. The analyses of silcrete show a reduction of MgO relative to CaO, indicating that the silica preferentially replaces magnesium carbonate.

Manganese occurs in the dolomite as dendrites or staining; cryptomelane was identified in one sample (lab. no. 17721/76) by the Government Chemical Laboratories.

There are a few surface occurrences of prase, where the silcrete is coloured green and one sample (lab. no. 16941/76) contains 2 000 ppm chromium. The origin of this chrome is unknown. A few samples of bright green and yellow clayey material, occurring as pockets in dolomite, were scanned by scintillometer, but no anomalous levels of radioactivity were detected.

Fragments of organic remains, including ostracod valves, have been recorded in borehole cuttings and samples from bores 3A, 3/75 and 5/75 (Davidson, 1969; Cockbain, 1976). At the western end of the plain (latitude 21°44′25″, longitude 116°42′45″). There are well-preserved gastropods, bivalves, and plant remains including opalized wood. G. W. Kendrick of the Western Australian Museum has identified the gastropods *Plotiopsis* sp. (now known as *Thiara* sp.), which is a fresh-water snail with some tolerance for brackish water; and *Coxiella* cf. *gilesi*, which is a brackish water snail (Cockbain, 1977). The bivalves are probably freshwater mussels. *Thiara* is known from the Miocene onwards, *Coxiella gilesi* from Late Pleistocene to Holocene, but their ranges are not fully known.

The Millstream Dolomite crops out over much of the central and northern part of the Fortescue plain (Fig. 2) and has been shown by drilling to be present in the subsurface in the south-east and east, almost as far as Weelumurra Creek (Fig. 3 sections D–D and E–E).

TABLE 3. CHEMICAL ANALYSES OF MILLSTREAM DOLOMITE AND WITTENOOM DOLOMITE

Laboratory Sample No.	Bore	Interval (m)	Rock Description	Per cent on dry basis				Remarks
				CaO	MgO	Loss on ignition	Acid in-soluble	
17706	1/75	21·5–21·6	Massive dolomite	29·5	22·5	45·8	2·0	Water-table 11·0 m
26289		26·2–26·3	Vuggy dolomite	27·4	20·2	44·3	4·44	
17707		37·0–37·1	Vuggy dolomite	30·8	22·0	46·6	0·6	
17708	2/75	8·4–8·5	Dolomite breccia	31·1	16·0	38·3	13·9	Water-table 21·7 m
17709		20·0–20·1	Marbled dolomite	31·1	15·0	40·1	10·8	
26290		22·8–22·9	Silcrete	12·2	2·45	13·4	71·7	
17710		27·0–27·1	Vuggy dolomite	30·2	21·5	46·0	0·9	
17711	3/75	14·7–14·8	Silcrete	30·3	5·0	28·9	34·9	Water-table 19·4 m
26292		16·6–16·7	Dolomite	27·3	15·9	39·4	14·9	
26293		19·1–19·2	Dolomite	30·1	20·6	45·4	4·23	
26294		20·4–20·5	Dolomite	29·5	20·6	46·6	2·16	
17712		23·9–24·0	Siliceous dolomite	26·6	18·0	39·3	16·5	
17713		28·5–28·6	Dolomite	30·5	20·5	44·7	3·5	
26295		38·2–38·3	Ferruginous silcrete	0·61	0·73	2·9	92·0	
17714		41·5–41·6	Dolomite	30·3	21·5	46·0	1·4	
26296		51·2–51·3	Dolomite	28·3	20·6	45·6	3·07	
26297	4/75	8·7–8·8	Dolomite	27·7	15·9	38·8	17·1	Water-table 23·3 m
17715		20·4–20·5	Siliceous dolomite	22·2	14·0	32·3	31·7	
17720		27·1–27·2	Vuggy dolomite	32·2	21·0	46·9	>0·1	
17716		37·3–37·4	Dolomite	30·1	21·5	45·9	1·7	
17717	5/75	4·6–4·8	Calcified alluvium	25·5	14·5	34·2	21·4	Water-table 23·1 m
17718		6·9–7·0	Silcrete	8·2	1·0	10·0	80·6	
26299		21·6–21·7	Dolomite	49·8	3·65	43·3	2·8	
26300		25·8–25·9	Dolomite	44·5	7·96	42·9	4·24	
17719		37·2–37·3	Dolomite	25·5	21·0	41·5	9·9	
26298	4/75	51·4–51·6	Dolomite	30·2	21·2	46·6	1·22	Wittenoom Dolomite

Analyst: Government Chemical Laboratories

The formation unconformably overlies the Robe Pisolite in much of the area, and onlaps the Marra Mamba Iron Formation to the north, and possibly the Wittenoom Dolomite to the south. In the southeast and east, the upper part of the dolomite passes laterally into the Kangiangi Clay; on the southern side of the plain, the formation is unconformably overlain by the Kumina Conglomerate. Much of the outcrop area is covered by a veneer of clay or gravelly sand that has been omitted from Figure 2.

There are two small outcrops of dolomite in the southeast of the area near bore W6, with underlying beds of gravelly conglomerate; these are probably equivalent to the Millstream Dolomite and Kangiangi Clay.

Sanders (1974) considered that valley calcretes similar to the Millstream Dolomite were formed by precipitated carbonate from groundwater replacing valley-fill deposits. Mann and Horwitz (1979) propose that "groundwater calcretes" have been formed in an arid climate, by the precipitation of carbonate at the water table of alluvial drainages, where the water table was within 5 m of the surface, so that calcium and magnesium ions in the groundwater become concentrated by evapotranspiration. They postulated that progressive deposition of carbonate at the water table displaces the previously formed calcrete upwards to form pods and domes.

The Millstream Dolomite, in the area where gastropods, bivalves, and plant remains are found, is well bedded, with a sharp abutment unconformity against a buried cliff of Marra Mamba Iron Formation. Scattered angular clasts of iron-formation are common within the dolomite close to the cliff, but diminish in number away from it. There is a slight dip away from the cliff, and there are small-scale slump structures. These features indicate a lacustrine origin for the formation. The presence of brackish-water, as well as fresh-water fossils, shows that the salinity of the lake varied seasonally. This indicates that there were pronounced annual wet and dry seasons during the Pleistocene, as is the case at the present time.

The layers of alluvium and conglomerate within the sequence probably represent local accumulations of clastic material derived by episodic flooding, particularly along the north-western margin of the lake near the Nullagine plateau.

In the eastern and southeastern part of the area, the upper section of the Millstream Dolomite passes laterally into the Kangiangi Clay, indicating a facies change to shallower water, or shorter lived lacustrine conditions.

The nodular, veined and brecciated appearance of the dolomite suggests later modification by circulating groundwater. Circular airphoto patterns may indicate the doming process proposed by Mann and Horwitz.

The fact that the formation is more dolomitic below the water table suggests that it has been dolomitized by the groundwater, which is dominantly of magnesium bicarbonate type (Barnett and others, 1977). The Wittenoom Dolomite is the obvious source for the magnesium and calcium carbonate. Secondary silicification has taken place at present and past water-table levels.

Thus, the Millstream Dolomite apparently originated as a sequence of lacustrine limestone and clay, with minor intercalations of alluvium. These original sediments have subsequently undergone extensive diagenetic changes, including dolomitization and silicification.

The age of the Millstream Dolomite is probably Late Tertiary to Pleistocene; the ranges of the fossils found in the formation are insufficiently known to permit a more precise dating.

Kangiangi Clay

This is a newly defined formation, named after Kangiangi Creek, in which it outcrops (latitude 21°41′35″, longitude 117°18′00″). The type section is taken as bore 42A, where the formation reaches its maximum recorded thickness of 47 m. It consists of red-brown and yellow-brown silty clay with interbeds of sand and gravel containing pebbles. The coarser beds are poorly sorted and contain generally subangular to subrounded clasts of chert, banded iron-formation and hematitic shale derived from the Proterozoic rocks. The formation is well bedded; it is cemented by carbonate, iron oxides, and silica; and, in places, stained by manganese. There is usually a basal layer, up to 15 m thick, of pisolitic ironstone gravel in a matrix of clay; an analysis of the basal section is given in Table 4.

TABLE 4. ANALYSIS OF PISOLITIC GRAVEL (KANGIANGI CLAY)

Lab. sample	Bore no.	Percent on dry basis							Remarks
		Fe	Al	Si	P	S	V	Ti	
26304	43A	46·0	6·2	6·7	0·028	<0·001	0·03	1·36	Pisolitic gravel (rotary cuttings)

Analyst: Government Chemical Laboratories

The formation is widespread in the subsurface east and southeast of the area of calcrete outcrop, but it only outcrops in Kangiangi Creek south of bore 33A, and near bores 22N and 24A.

The formation appears to be mainly lacustrine, with alluvial intercalations; the basal, gravelly layer is apparently alluvial, and derived by reworking of Robe Pisolite. The Kangiangi Clay apparently interfingers laterally with the Millstream Dolomite, and represents a facies change to a shallower water environment. It conformably overlies the lower part of the Millstream Dolomite, overlapping the Robe Pisolite in places. It is overlain unconformably by the Kumina Conglomerate, or by a thin veneer of later alluvium and colluvium.

Kumina Conglomerate

This is a newly defined formation, named after Kumina Creek, where the type section (15 m thick) is exposed in a cliff alongside the creek (latitude 21°46′20″, longitude 116°46′05″).

Similar conglomeratic deposits are widespread throughout the northwest of Western Australia, and have been termed Wiluna Hardpan by Bettenay and Churchward (1974). The term *hardpan*, although descriptive of the cemented nature of the deposit, is inappropriate for such a thick alluvial sequence; Kumina Creek Formation is therefore proposed for the deposits in the western Fortescue plain.

The formation is composed of boulders, cobbles, gravel, and sand in a matrix of silty brown clay, usually with a ferruginous section at the base; it includes some lenses of silty clay.

The clasts are generally subrounded to rounded and consist of chert, banded iron-formation, hematite shale, and pisolitic ironstone which were derived from the Proterozoic bedrock and Robe Pisolite. Sorting ranges from very poor to good. Some horizons show traces of rootlets.

The deposits are loosely cemented, mainly by iron oxides, but also by carbonate and silica; where the formation outcrops, the topmost few metres are more strongly cemented by iron oxides. The basal section of the deposit is usually a poorly bedded ferruginous conglomerate, consisting mainly of clasts of Robe Pisolite and Hamersley Group banded iron-formation from the bedrock.

The deposits range up to 120 m thick. The thickest recorded section, in bore 61B, appears to be filling a narrow incised channel, or a collapsed doline structure in the underlying Wittenoom Dolomite. The basal ferruginous section of the Kumina Conglomerate ranges from 5–25 m, but is usually 5–10 m thick.

The formation outcrops at the western end of the Fortescue plain. It is widespread in the subsurface below the southern part of the plain, and to a lesser extent below the northern part. It unconformably overlies Robe Pisolite, Millstream Dolomite, and Kangiangi Clay, and overlaps the Proterozoic rocks along the margins of the plain. Over most of the area, it is overlain by a thin veneer of alluvial fan deposits of Late Pleistocene or Holocene age.

MacLeod (1966) described a ferruginous conglomerate ("canga"), similar to the basal section of the Kumina Conglomerate, as being transitional to Robe Pisolite in the upper Robe River area. In the western Fortescue plain, however, the ferruginous conglomerate is apparently younger than the Robe Pisolite, as the Kumina Conglomerate overlies the Millstream Dolomite.

The Kumina Conglomerate is alluvial, and was deposited mainly as piedmont alluvial fans by creeks debouching vigorously from the Hamersley Range. Some contribution also comes from the Nullagine plateau.

Late Pleistocene to Holocene superficial deposits

Colluvium: Scree deposits flank the Nullagine plateau along the northern end of the plain east of Millstream homestead. They are loosely cemented and poorly sorted; clasts are angular to subangular. They overlie Proterozoic bedrock and Robe Pisolite, and either interfinger with, or overlie, the Kangiangi Clay. Most of the colluvium is probably Pleistocene in age, but some may be Holocene.

Alluvial fan deposits: Younger piedmont alluvium overlies the Kumina Conglomerate and Kangiangi Clay, flanking the Hamersley Range, and the Nullagine plateau east of Millstream. The alluvium has similar lithology to the Kumina Conglomerate, but is uncemented, and has a different pattern on airphotos. These deposits are probably Late Pleistocene to Holocene in age.

Residual clay: Red-brown clay, up to 3 m thick, covers much of the area of outcrop of the Millstream Dolomite; it is omitted from Figure 2. The clay is silty and sandy in places, and often contains loose fragments and blocks of Millstream Dolomite. It dries out at the end of each wet season to form gilgai (a soil with large, deep cracks). The clay is derived mainly by weathering of the Millstream Dolomite, and partly from alluvium at the toe of alluvial fans along the Hamersley Range. It is Late Pleistocene to Holocene in age.

Calcareous silt: A delta of grey calcareous silt has been deposited at the mouth of a tributary creek where it joins the Fortescue River near Millstream homestead (latitude 21°35′05″, longitude 117°04′15″). The silt contains shells of fresh- and brackish-water snails, and layers of calcareous tufa. It is probably about 5 m thick; the surface of the deposit is about 4 m higher in elevation than the present river course. The tributary creek is fed by springs from the Millstream Dolomite, upstream from the delta. The calcareous silt appears to have been laid down in an area of swampy springs when the rainfall was higher than at present, and the spring outflow was consequently greater. The deposit is probably Late Pleistocene to Holocene in age.

Alluvium: Alluvium is being deposited at present along the Fortescue and Robe Rivers and their tributary creeks, following intermittent flooding. It is up to 15 m thick, and consists of banks of sand and gravel, and sheets of red-brown clay and silty clay.

GEOLOGICAL HISTORY

The inferred Phanerozoic geological history of the area is summarized in Table 5.

The ancestral Fortescue River occupied a valley which formed by headward erosion along the strike of the Hamersley Group, and can therefore be regarded as a subsequent river. It has since been captured twice from the northwest, first by the Robe River and then by the lower reaches of the present Fortescue River. The original course of the valley, and the Robe and Fortescue Rivers, are shown on Figure 1.

The original valley was apparently in existence in the Late Jurassic, as indicated by a thick pile of deltaic sediments offshore to the west beneath Barrow Island (Crank, 1973); the sediments are of Late Jurassic to Early Cretaceous age.

The oldest Phanerozoic deposit beneath the Fortescue plain is the Yarraloola Conglomerate, a fluviatile conglomerate deposited along the course of the original valley during the Early Cretaceous. The Hamersley surface may have been forming at this time.

TABLE 5. GEOLOGICAL HISTORY OF WESTERN FORTESCUE PLAIN

Age	Event
Holocene	Capture of Fortescue plain catchment by Fortescue River
	REJUVENATION
Late Tertiary to Pleistocene	Formation of Millstream surface
	EROSION
	Deposition of Kumina Conglomerate Erosion of channel along southern side of Fortescue plain
	REJUVENATION
	Lacustrine deposition of Millstream Dolomite and Kangiangi Clay
?	EROSION
Early-Mid Tertiary	Fluviatile deposition of Robe Pisolite, and duricrust formed on Hamersley surface Capture of Fortescue plain catchment by Robe River
	REJUVENATION
Cretaceous	Regional tilting to northwest Fluviatile deposition of Yarraloola Conglomerate; formation of Hamersley surface
Late Jurassic	Active erosion along strike of Proterozoic rocks Deltaic sediments deposited to west, in Carnarvon Basin

Possibly as a result of regional tilting to the northwest, the original valley was captured by the Robe River, which rejoins the original valley further downstream (Fig. 1). The capture must have occurred before deposition of the Robe Pisolite in the Early to Mid Tertiary, as the pisolite is present along the course of the Robe River downstream from the point of capture. The Robe Pisolite was deposited in a warm pluvial climate, when the landscape was well vegetated. Duricrust on the Hamersley surface apparently formed at the same time.

A period of erosion followed deposition of the Robe Pisolite; after which, in the Late Tertiary and Pleistocene, the Millstream Dolomite and Kangiangi Clay were deposited in a lake within the original valley. The lake dried out seasonally, and the water became brackish, suggesting an arid climate with a pronounced wet and dry season. The dolomite was probably deposited in a deeper part of the lake which was the last area to dry out each year. Periods of more intense rainfall caused sheets of coarser clastic material to be deposited in the lake, particularly at the margins. The lake may have developed because of constriction of the Robe River course by sediment; any such barrier has since been removed by erosion.

A period of rejuvenation followed, and a channel was eroded along the southern side of the Fortescue plain, adjacent to the Hamersley Range. This channel, and its tributaries, then filled with coarse alluvium, the Kumina Conglomerate, which was mainly deposited by creeks from the Hamersley Range.

A further period of erosion resulted in the formation of the Millstream surface, probably near the end of the Pleistocene. The silcrete layer at 310 m above sea level within the Millstream Dolomite may have formed at a water table at about the same time.

At the end of the Pleistocene, or the beginning of the Holocene, the Fortescue plain catchment was again captured from the northwest, by the Fortescue River. Following this capture, the water table within the Millstream Dolomite fell from about 310 m to about 294 m above sea level, because of the lowering of the base level of the Fortescue River, into which the groundwater now discharges by way of springs. The Robe River was also rejuvenated, and the western margin of the plain is now being actively eroded by the Fortescue and Robe Rivers and their tributaries.

As a result of the two episodes of river capture, the watershed between the Robe and Fortescue River Systems now crosses the Fortescue plain.

REFERENCES

Backhouse, J., 1975, Palynology of Weelumurra W6 borehole: West. Australia Geol. Survey Palaeo. Rept 106/1975 (unpublished).

Barnett, J. C., McInnes, D. B., and Waterton, C. A., 1977, Measurement of the specific yield of a Carbonate Aquifer—an unconventional approach: West. Australia Geol. Survey Rec. 1976/23.

Bettenay, E., and Churchward, H. M., 1974, Morphology and stratigraphic relationships of the Wiluna Hardpan in arid Western Australia: Geol. Soc. Australia Jour. v. 21, p. 73–80.

Campana, B., Hughes, F. F., Burns, W. G., Whitcher, I. G., and Muceniekas, E., 1964, Discovery of the Hamersley iron deposits: Australasian Inst. Mining Metall. Proc. 210.

Carlisle, D., 1978, The distribution of calcretes and gypcretes in southwestern United States and their uranium favourability, based on a study of deposits in Western Australia and South West Africa (Namibia): Open file report prepared for US Department of Energy.

Crank, K. A., 1973, Geology of Barrow Island Oil Field: Australian Petrol. Explor. Assoc. Jour v. 13, pt 1, p. 49–57.

Cockbain, A. E., 1976, Calcrete and silcrete samples from Millstream: West. Australia Geol. Survey Palaeo. Rept 34/1975 (unpublished).

——— 1977, Fossils from the Millstream calcrete: West. Australia Geol. Survey Palaeo. Rept 80/77 (unpublished).

Davidson, W. A., 1969, Millstream Hydrogeological investigation: West. Australia Geol. Survey Rec. 1969/3.

Davy, R., 1975, A geochemical study of a dolomite-BIF transition in the lower part of the Hamersley Group: West. Australia Geol. Survey Ann. Rept 1974, p. 88–100.

de la Hunty, L. E., 1965, Mount Bruce, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Harms, J. F., and Morgan, B. D., 1964, Pisolitic limonite deposits in northwest Australia: Australasian Inst. Mining Metall. Proc. 212, p. 91–124.

Hickman, A. H., in press, The Geology of the Pilbara Block and its environs: West. Australia Geol. Survey Bull.

Jutson, J. T., 1950, The Physiography (Geomorphology) of Western Australia: West. Australia Geol. Survey Bull. 95.

Kriewaldt, M., and Ryan, G. R., 1967, Pyramid, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Mann, A. W., and Horwitz, R. C., 1979, Groundwater calcrete deposits in Australia: some observations from Western Australia: Geol. Soc. Australia Jour. v. 26, p. 293–303.

MacLeod, W. N., de la Hunty, L. E., Jones, W. R., and Halligan, R., 1963, A preliminary report on the Hamersley Iron Province, North-West Division: West. Australia Geol. Survey Ann. Rept 1962 p. 44–54.

MacLeod, W. N., 1966, The geology and iron deposits of the Hamersley Range area, Western Australia: West. Australia Geol. Survey Bull. 117.

Sanders, C. C., 1974, Calcrete in Western Australia: West. Australia Geol. Survey Ann. Rept 1973, p. 12–14.

Williams, I. R., 1968, Yarraloola, W.A.: West. Australia Geol. Survey 1:250 000 Series Explan. Notes.

Zimmerman, D. O., Adair, D. L., and Collings, P. S., 1973, Geology of the Upper Robe River Iron Deposits: Australasian Inst. Mining Metall. Ann. Conf., Perth, 1973, Papers p. 143–152.

THE YOGANUP FORMATION AND ASCOT BEDS AS POSSIBLE FACIES EQUIVALENTS

by J. L. Baxter and R. Hamilton*

ABSTRACT

A thin sequence of Pliocene marine sediments unconformably overlies Cretaceous and Eocene-Palaeocene deposits in the Perth Basin. The sequence is a barrier sand with carbonate and siliciclastic facies, which have been referred to as Ascot Beds and Yoganup Formation respectively. The Ascot Beds have been intersected in numerous water boreholes in the central part of the Perth Basin between Cataby and Gosnells. The Yoganup Formation, which occurs along the eastern limit of the Swan Coastal Plain, has been traced discontinuously from Eneabba in the north, to Busselton in the south. Correlation of these formations was first suggested by Kendrick (pers. comm.) and is supported by results of a heavy mineral sand exploration programme at Cooljarloo by Western Mining Corporation. It is suggested that phosphate nodules and phosphatized fossil remains in the Ascot Beds were derived from Cretaceous deposits. However, the presence of both siliciclastic and carbonate sediments as facies equivalents and the preservation of heavy mineral sands and phosphorite in the deposits indicate a shoreline system with little terrigenous and carbonate input.

INTRODUCTION

The known areal distribution of the Ascot Beds, a richly fossiliferous marine limestone, was extended by the discovery of shelly material in drill cuttings from Cooljarloo during heavy mineral sand exploration by Western Mining Corporation (Fig. 1). The molluscan fauna of the Ascot Beds at Cooljarloo is listed by Kendrick (1981), who concluded that it indicates a Pliocene age. Kendrick (pers. comm.) has suggested a correlation of the Ascot Beds with the Yoganup Formation based on comparison of younger transgressive cycles on the Swan Coastal Plain. The proximity of Yoganup Formation and Ascot Beds at Cooljarloo (Fig. 1) has improved the confidence of this correlation.

*Western Mining Corporation

The data reported here have been obtained from samples supplied by Western Mining Corporation from Cooljarloo, and from other samples obtained from bores in the metropolitan area.

STRATIGRAPHY

Quilty (1974a, 1974b), Allen (1976), and Playford and others (1976) have described the Tertiary stratigraphy of the Perth Basin, and, although the individuality of the units was recognized in separate areas, it was not generally appreciated that the Yoganup Formation and Ascot Beds could be correlated.

Ascot Beds

The Ascot Beds are generally less than 2 m thick and rest unconformably on Cretaceous and Palaeocene formations. They contain a diverse fauna with a large number of molluscs. The beds contain nodules which have been found to contain 26·0% P_2O_5, (see table). The phosphate, which is distributed uniformly through the nodule is in the form of phosphorite.

ANALYSES OF PHOSPHORITE NODULES FROM COOLJARLOO

Fe_2O_3	3·9%
P_2O_5	26·0%
S	2·1%
U	55ppm

Analyst: Government Chemical Laboratories

The matrix of the Ascot Beds is a poorly-sorted fine- to medium-grained predominantly bioclastic sandy calcarenite which contains no phosphate. The nodules contain *Inoceramus* prisms, foraminifers and radiolarians of Cretaceous age, and consequently must have been reworked into the Ascot Beds (Cockbain, 1980). The formation is interpreted as a marine calcarenite which was deposited in a sub-littoral inner shelf environment at a time of low supply of terrigenous sediment.

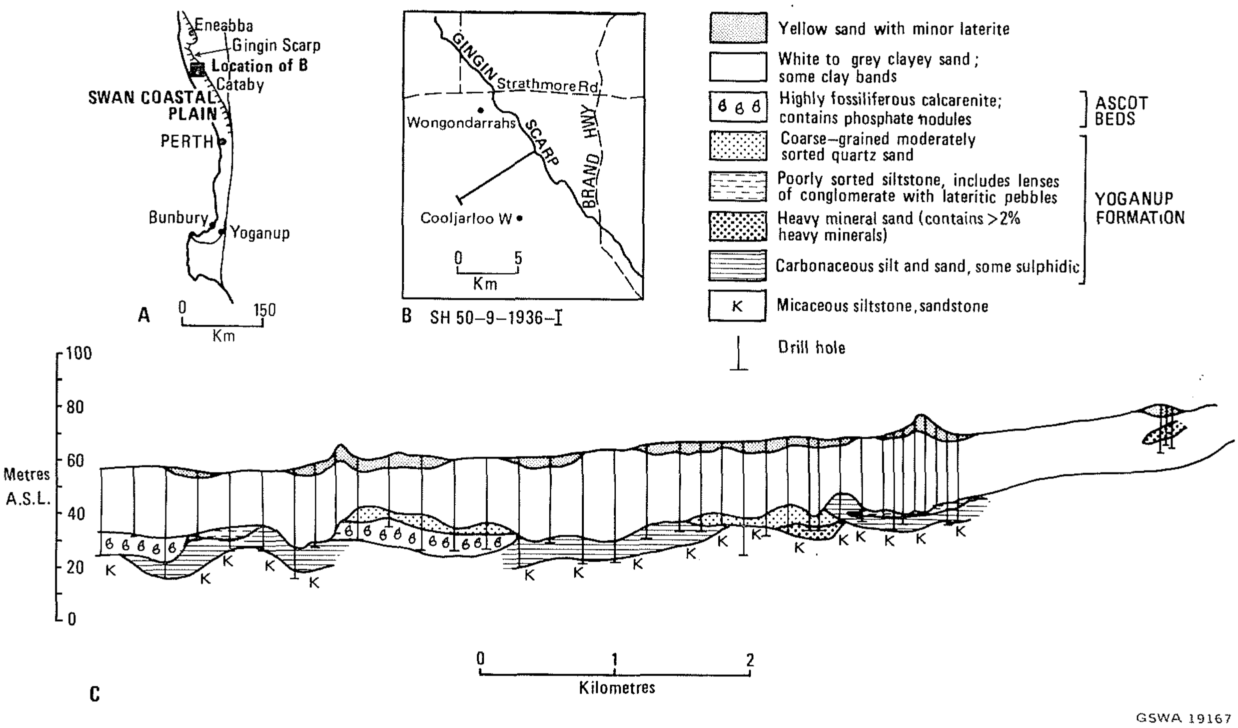


Figure 1 A—Location of the Swan Coastal Plain, Gingin Scarp and the area covered in B; B—Location of the drilled section at the Cooljarloo heavy mineral sand prospect. C—Cross section of a drilled traverse showing the lithologies encountered in Cainozoic units overlying ?Cretaceous sediments and the location of drill holes. Vertical scale exaggerated.

Yoganup Formation

The Yoganup Formation is generally less than 6 m thick and rests unconformably on Cretaceous sediments. It is unconformably overlain by up to 3 m of yellow sand. No fossils have been recorded from the formation. Baxter (1979) correlated all the shoreline deposits at the eastern margin of the Swan Coastal Plain with the Yoganup Formation. The formation consists of parallel, interfingering, lenticular beds of conglomerate, sand and clay. Heavy minerals (ilmenite, zircon, rutile, etc.) which concentrated in the sandy units, have been mined from northern and southern parts of the coastal plain at Eneabba and Yoganup (Baxter, 1977). The Yoganup Formation is interpreted as a paralic sequence, the sandy units being barrier sheets whereas the clay beds may represent interdunal or estuarine deposits (Baxter, 1981). The unit contains ferruginous cemented "coffee rock" layers which reflect past water-table fluctuations.

CORRELATION OF THE UNITS

The drilled section at Cooljarloo has demonstrated the complex facies variation that develops at the base of the Cainozoic in the Perth Basin (Fig. 1). The highly fossiliferous calcarenite is correlated with the Ascot Beds because it contains a similar fauna (Kendrick, 1981) and is of comparable lithology. The remaining units at the base of the sequence are correlated with the Yoganup Formation: the coarse-grained quartz sand and the heavy mineral sand representing barrier sands; and the siltstone and carbonaceous beds representing lagoonal and estuarine deposits. The overlying clayey sand and yellow sand are probably of terrestrial origin. Considering the vertical exaggeration of the section it is apparent that the Ascot Beds and Yoganup Formation are in juxtaposition and are reasonably interpreted as facies equivalents. The entire sequence is at the foot of the Gingin Scarp and thus compares geomorphically with the position of the Yoganup Formation in the southern part of the Basin.

ORIGIN OF THE PHOSPHATE

The restriction of phosphate to nodules containing *Inoceramus* etc., indicates that the phosphatization occurred in the Cretaceous prior to development of the Ascot Beds. Phosphorite has previously been recorded from the Cretaceous Coolyeena Group (Matheson, 1948).

The most probable interpretation of the palaeoenvironment is that coarse-grained material forming barrier sands (nodules, pebbles and sand) was swept eastward on a transgressive shoreline (Warren and others, 1981), ultimately being deposited in the Ascot Beds between the shallow inner shelf zone and the shoreline. Subsequent regressive and transgressive cycles do not appear to have brought phosphatic material onshore as there are no nodules in the Yoganup Formation. This may be because the preserved heavy-mineral-bearing sequence was deposited during later transgressive cycles.

REFERENCES

Allen, A. D., 1976, Outline of the hydrogeology of the superficial formations of the Swan Coastal Plain: West. Australia Geol. Survey Ann. Rept 1975, p. 35–41.

Baxter, J. L., 1977, Heavy mineral sand deposits of Western Australia: West. Australia Geol. Survey Min. Resources Bull. 10.

——— 1979, Mineral sands, *in* Prider, R. T., (ed.), Mining in Western Australia: Univ. West. Australia Press.

——— 1981, Geology of mineral sand deposits in Western Australia, *in* Selective Reference Papers for Mineral-Sand Mining: Western Australia School of Mines, WAIT-AID Ltd, Perth.

Cockbain, A. E., 1980, Cretaceous fossils in phosphatic nodules from the Ascot Beds: West. Australia Geol. Survey Palaeontological Rept 44/1980 (unpublished).

Kendrick, G. W., 1981, Molluscs from the Ascot Beds from the Cooljarloo heavy mineral deposit, Western Australia: West. Australia Geol. Survey Ann. Rept 1980, p. 44.

Matheson, R. S., 1948, The Dandaragan Phosphate Deposits: West. Australia Geol. Survey Min. Resources Bull. 4.

Playford, P. E., Cockbain, A. E., and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull. 124.

Quilty, P. G., 1974a, Tertiary stratigraphy of Western Australia: Jour. Geol. Soc. Australia, v. 21, p. 301–318.

——— 1974b, Cainozoic stratigraphy of the Perth area: Royal Soc. West. Australia Jour., v. 57, p. 16–31.

Warren, J., Hocking, R. M., and Baxter, J. L., 1981, Barrier Island hydro-sedimentary genesis for heavy mineral sands of southern and western Australia, *in* Selective Reference Papers for Mineral-Sand Mining: Western Australia School of Mines, WAIT-AID Ltd, Perth.

MOLLUSCS FROM THE ASCOT BEDS FROM THE COOLJARLOO HEAVY MINERAL DEPOSIT, WESTERN AUSTRALIA

by George W. Kendrick*

Fossils have been collected by R. Hamilton of Western Mining Corporation from an exploratory drill hole in the Cooljarloo heavy mineral sand prospect. The material was obtained from a calcarenite with intercalated carbonaceous sediment intersected from 10·5 to 12·0 m in a bore (R.L. about 60 m ASL) located on the Western Mining Corporation grid at 25 000N and 7 200E. The grid is 50 m south of Strathmore Road and 14·35 km west of the junction with the Brand Highway (latitude 30°33′S, longitude 115°18′E). This calcarenite is in a similar stratigraphic position to fossiliferous calcarenite (described by Baxter and Hamilton, 1981) from a section 10 km to the south, assigned to the Ascot Beds. The fossils discussed in this report are stored in the palaeontological collections of the Western Australia Museum (WAM) under catalogue numbers 80.1039 to 80.1095 and P.80.4.

Forty-four mollusc species (23 bivalves, 1 scaphopod, and 20 gastropods) have been identified; the sample also includes bryozoans, brachiopods, echinoderms and fragments of fossil wood, the latter being probably reworked from the Cretaceous. The sample is a small one and unlikely to be fully representative of the fauna. Shells are mostly well-preserved but have been damaged during recovery. The species present are typical of the shallow, sandy, inner shelf on an open coast, with well-circulated water of normal marine salinity. The bivalves are mostly infaunal filter feeders; the gastropods include herbivores, parasites, scavengers and carnivores.

Species in the list below marked with an asterisk are those which, in the Perth Basin, are at present known only from the Ascot Beds and are possibly charasteristic of that formation. At least 14 species, (*Limopsis beaumariensis*, *Cuna* sp., *Donax* sp., *Dosinia* sp., *Placamen* sp., *Tawera* spp., *Corbula* sp., *Gadila infans*, *Bankivia* (*Leiopyrga*) sp., *Bittium subgranarium*, *Hartungia* sp., *Nassarius* sp. and *Acteocina aptycha*) appear to be extinct and, in most cases, also undescribed. The *Hartungia*, represented only by fragments, is probably *H. dennanti chavani* Ludbrook described from the Roe Calcarenite of the Eucla Basin (Ludbrook, 1978). The assemblage compares well with material from other bores on the Swan Coastal Plain which is considered to be derived from the Ascot Beds. Of these bores, the most informative are Rando's 1 and 2 bores (WAM collection), Thornlie, from which the arcoid bivalve *Cucullaea* has been recovered. The presence of this genus in the Ascot Beds is considered to be of significance in the age determination of the formation; it occurs in Eocene to Pliocene deposits throughout southern Australia, but is unrecorded there from post-Pliocene strata (T. A. Darragh, pers. comm.). At least seven of the species (*Lissarca rubricata*, *Divalucina cumingi*, *Kellia australis*, "*Bornia*" *trigonale*, *Saltocuna obliquissima*, *Gomphina undulosa* and *Alaba fragilis*) are extant and a further four possibly belong to living species.

*Western Australian Museum

The molluscs of the Ascot Beds form a distinctive assemblage, which, on present knowledge, cannot be correlated readily with other better-known faunas of broadly comparable age in southern Australia. Though sharing many common species, the Ascot Beds fauna is nevertheless quite distinct from that of the "Jandakot beds" of the Perth Basin; fewer living species and a higher proportion of extinct species distinguish the Ascot Beds fauna from the other, younger fauna. A substantial proportion of both faunas remains unidentified and there seems no point at present in attempting any detailed Lyellian assessment of the two. Indications are that the Ascot Beds are likely to be of Pliocene age. This conclusion will be substantiated more fully in another contribution now in preparation.

MOLLUSCS FROM THE ASCOT BEDS AT COOLJARLOO

Bivalves: *Nuculana* (*Scaeoleda*) sp. (fragments), *Limopsis beaumariensis* Chapman*, *Lissarca rubricata* (Tate), *Glycymeris* sp. (juveniles), *Divalucina cumingi* (A. Adams and Angas), *Mysella* sp., *Kellia australis* (Lamarck), "*Bornia*" *trigonale* (Tate), *Saltocuna* (*Propecuna*) *obliquissima* (Tate), *Cyclocardia* (*Scalaricardita*) sp. (fragments), *Cuna* sp. cf. *C. edentata* Verco, *Cuna* sp.*, cardiid fragments cf. *Fulvia tenuicostata* (Lamarck), *Mactra* sp. (fragment), *Mactra* (*Electomactra*?) sp.*, *Abra*? sp.*, *Donax* sp.*, *Dosinia* sp.*, *Gomphina undulosa* (Lamarck), *Placamen* sp. aff. *P. subroborata* (Tate)*, *Tawera* sp. cf. *T. pernitida* (Woods)*, *Tawera* sp., *Corbula* sp*.

Scaphopod: *Gadila infans* (Tate)*.

Gastropods: *Amblychilepas* sp. (juvenile), *Bankivia* (*Leiopyrga*) sp. cf. *B.* (*L.*) *octona* (Tate), *Bankivia* (*Leiopyrga*) sp.*, *Botelloides* sp., *Rissoina* sp., vitrinellid, genus and species undetermined, *Alaba* sp. cf. *A. fragilis* (Thiele), *Bittium subgranarium* Ludbrook*, *Hartungia* sp.* (fragments), *Polinices* (*Conuber*) sp. (juveniles), *Nassarius* (*Niotha*) sp., *Marginella* (*Austroginella*) *johnstoni* Petterd (new subspecies), *Cystiscus* sp.*, *Mangelia* sp. (juvenile), *Pervicacia* sp., *Odostomia* sp., *Syrnola* sp., *Ringicula* sp. cf. *R. tatei* Cossmann, *Acteocina aptycha* (Cossmann), *Acteocina* (?) sp.

REFERENCES

Baxter, J. L., and Hamilton, R., 1981, The Yoganup Formation and Ascot Beds as possible facies equivalents: West. Australia Geol. Survey Ann. Rept 1980, p. 42–43.

Ludbrook, N. H., 1978, Quaternary molluscs of the western part of the Eucla Basin: West. Australia Geol. Survey Bull. 125.

ON THE AGE OF THE MERLINLEIGH SANDSTONE, CARNARVON BASIN

by A. E. Cockbain

ABSTRACT

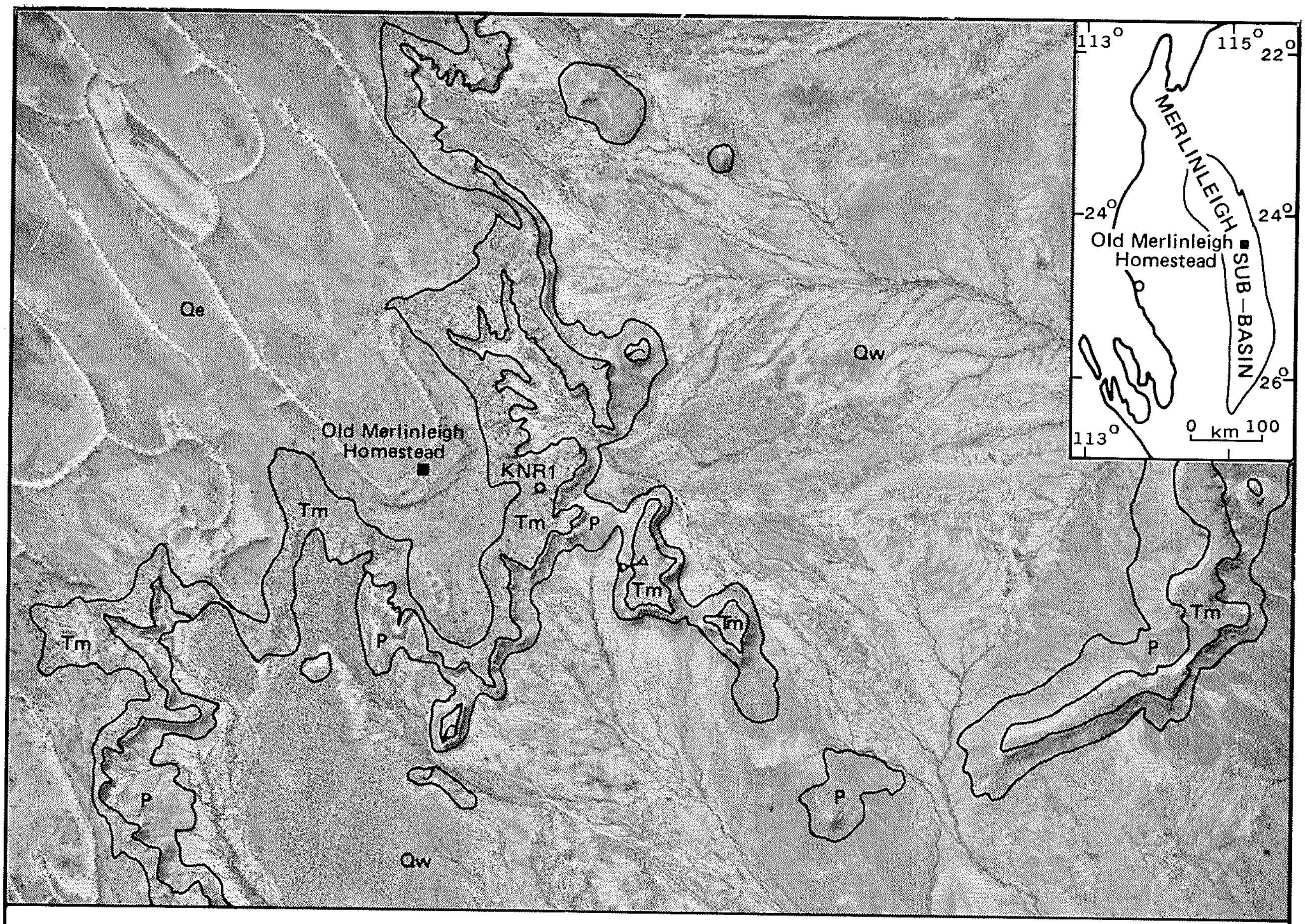
The foraminifers *Maslinella chapmani*, *Crespinina kingscotensis*, *Operculina* sp. and *Rotalia* sp. occur in a sample of Merlinleigh Sandstone collected near the type section. *M. chapmani* and *C. kingscotensis* suggest that the unit is Middle and Late Eocene in age, more probably the latter.

INTRODUCTION

The Merlinleigh Sandstone is a unit of quartz sandstone which outcrops intermittently in the Merlinleigh Sub-basin. It contains ". . . silicified wood and a rich fauna of bivalves, gastropods, echinoids, foraminifers, corals and nautiloids" (Playford and others, 1975, p. 301). To this should be added hydrozoans (Pulley, 1959) and bryozoans (herein). Of these fossils only the coelenterates *Millepora*, *Cyphastrea* and *Duncanopsammia* (Pulley, 1959) and the nautiloid *Aturia clarkei* (Teichert, 1944) have been figured and described.

The age of the formation has been deduced from the molluscs. Teichert (1944) erected the species *Aturia clarkei*, the holotype and paratypes of which came from the Merlinleigh Sandstone in the Kennedy Range. The species also occurs in the Pallinup Siltstone (Plantagenet Group) which Teichert (1944), following Chapman and Crespin (1934), considered to be of Early Miocene age and consequently ". . . a Miocene age can, therefore, also be assumed for the *Aturia* beds of the Kennedy Range" (Teichert, 1944, p. 79). Subsequently Glaessner (1953) suggested that the Plantagenet Group was probably of the same age as Late Eocene beds containing *A. clarkei* (Tortachilla Limestone, Blanche Point Marl) in South Australia. Glenister and others (1956, p. 495) in discussing the age of the Merlinleigh Sandstone remarked that "Recent detailed field work has revealed the presence of a large fauna of pelecypods, gastropods, and echinoids, which R. O. Brunnschweiler (pers. comm.) believes to be Lutetian" (Middle Eocene). Accordingly the unit is now considered to be of Middle and Late Eocene age.

However, Pulley (1959) in describing corals from the formation stated that, while Brunnschweiler and Dickins regarded the shelly fauna as late Middle Eocene, the corals appeared to be younger; *Cyphastrea* does not occur before the Miocene in the East Indies and *Duncanopsammia axifuga* is known only from living reefs in northern Australia. More recently, molluscs have been collected by personnel from the Western Australian Museum and the National Museum of Victoria.



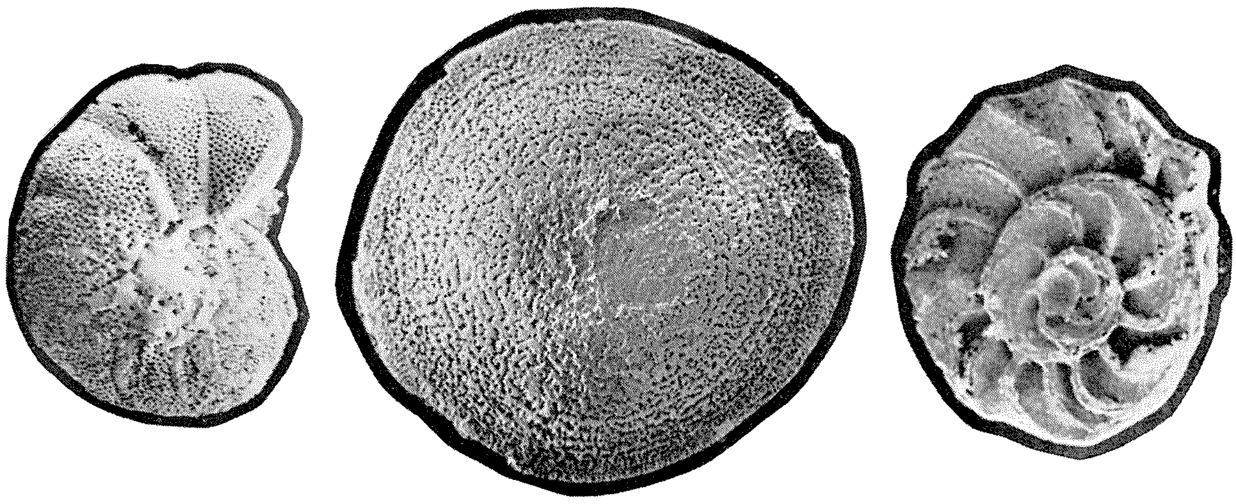
Qw	Wash
Qe	Sand Plateau
Tm	MERLINLEIGH SANDSTONE
P	PERMIAN ROCKS

⊳⊲ Merlinleigh Sandstone type section
KNR1 Fossil locality
■ Homestead

0 1km

Figure 1 : Locality Map (Kennedy Range, WA 862, run 6, photo 5144)

GSWA 19205



A B C

Figure 2 : Photographs of specimens
A – *Maslinella chapmani* (x 30)
B – *Crespinina kingscotensis* (x 30)
C – *Operculina* s p. (x 30)
All from sample F11293 collected from fossil locality KNR1

GSWA 19206

T. A. Darragh (pers. comm., 1980) considers that ". . . the [mollusc] fauna is not diverse enough to allow any precise correlation . . . [It] looks quite modern in aspect . . .".

In order to see whether any independent evidence for the age of Merlinleigh Sandstone could be obtained, a bryozoan-rich sample was examined for foraminifers with the following results.

FORAMINIFERS

The sample was collected by K. J. McNamara and G. W. Kendrick of the Western Australian Museum and bears the number WAM 79.2877/87 of that institution; a portion has been retained by the Geological Survey and given the registered fossil number F11293. The material came from a breakaway in the Kennedy Range, 1 km east of Old Merlinleigh homestead (Fig. 1) and is consequently from slightly to the northwest of the type section (GSWA fossil locality No. KNR1). Lithologically it is a sandstone with silicified bryozoa, molluscs and foraminifers. Foraminifers are quite common in the sample although only a few species are present (Fig. 2). Preservation is variable but there is no reason to suspect reworking. The following taxa have been identified (r = less than 10 specimens, c = 10–100 specimens):

Maslinella chapmani Glaessner and Wade	c
Crespinina kingscotensis Wade	r
Operculina sp.	c
Rotalia sp.	r

The critical species for age determination are *M. chapmani* and *C. kingscotensis*. *Maslinella chapmani* was originally described as being confined to Upper Eocene strata (Glaessner and Wade, 1959, p. 202), but Ludbrook (1963) recorded the species from the middle Eocene part of the Wilson Bluff Limestone. It ranges no higher than the Late Eocene in South Australia (Lindsay, 1969, p. 23). Western Australian occurrences are:

(1) Wilson Bluff Limestone (see Lowry, 1972 plate 4).

(2) Toolinna Limestone (see Lowry, 1973 plate 4).

(3) Werilup Formation (Quilty, 1968; Backhouse, 1970).

(4) Giralia Calcarenite (Glaessner and Wade, 1959, p. 202 (their record from Rough Range South 1, 1170–1175 ft is from this formation); Condon and others 1956, p. 47 (record what is probably this species as *Crespinella* sp. 1); Cockbain, 1967, p. 68).

Crespinina kingscotensis was described from South Australia (Wade, 1955) where it ranges no higher than the Upper Eocene (Lindsay, 1969, p. 23). Ludbrook (1963) records the species from the Upper Eocene, but not from the Middle Eocene. Western Australian records are:

(1) Werilup Formation (Quilty *in* Hodgson and others, 1962).

(2) Norseman Limestone (Cockbain, 1968).

The southern Australian occurences of these two species are important since they are associated there with planktonic foraminifers. Details are documented by Ludbrook (1963) and Lindsay (1967, 1969) and may be summarised as suggesting that *M. chapmani* is Middle and Late Eocene in age and *C. kingscotensis* is probably confined to the Late Eocene.

CONCLUSIONS

The foraminifers from the Merlinleigh Sandstone suggest that the unit is Late Eocene in age with a possibility that it ranges into the Middle Eocene. The Giralia Calcarenite is of Middle and Late Eocene age and contains several fossils in common with the Merlinleigh Sandstone, namely *Maslinella chapmani*, *Operculina* sp. and *Aturia* (*A. australis* in the Merlinleigh Sandstone, *A.* cf. *australis* in the Giralia Calcarenite; Glenister and others, 1956). The two formations were deposited at the same time, the Merlinleigh Sandstone being laid down near the shoreline and the Giralia Calcarenite deposited under more open marine conditions.

REFERENCES

Backhouse, J., 1970, Foraminifera from the Plantagenet Group east of Esperance, Western Australia: West. Australia Geol. Survey Ann. Rept 1969, p. 40–42.

Chapman, F. M. and Crespin, I., 1934, The palaeontology of the Plantagenet Beds of Western Australia: Royal Soc. West. Australia Jour., v. 20, p. 103–136.

Cockbain, A. E., 1967, *Asterocyclina* from the Plantagenet Beds near Esperance, W.A.: Australian Jour. Sci., v.30, p. 68.

Cockbain, A. E., 1968, Eocene Foraminifera from the Norseman Limestone of Lake Cowan, Western Australia: West. Australia Geol. Survey Ann. Rept. 1967, p. 59–60.

Condon, M. A., Johnstone, D., Pritchard, C. E. and Johnstone, M. H., 1956, The Giralia and Marilla anticline, North West Division, Western Australia: Australia Bur. Mineral Resources Bull. 25.

Glaessner, M. F., 1953, Conditions of Tertiary sedimentation in southern Australia: Royal Soc. South Australia Trans., v. 76, p. 141–146.

Glaessner, M. F. and Wade, M., 1959, Revision of the foraminiferal family Victoriellidae: Micropaleontology, v. 5, p. 193–212.

Glenister, B. F., Miller, A. K. and Furnish, W. M., 1956, Upper Cretaceous and early Tertiary nautiloids from Western Australia: Jour. Paleontology, v. 30, p. 492–503.

Hodgson, E. A., Quilty, P. J. G. and Rutledge, D. I., 1962, The geology of the south coast in the vicinity of Cheyne Bay, W.A.: Univ. West. Australia Sci. Hons. thesis (unpublished).

Lindsay, J. M., 1967, Foraminifera and stratigraphy of the type section of Port Willunga Beds, Aldinga Bay, South Australia: Royal Soc. South Australia Trans., v. 91, p. 93–110.

Lindsay, J. M., 1969, Cainozoic Foraminifera and stratigraphy of the Adelaide Plains Sub-basin, South Australia: South Australia Geol. Survey Bull. 42.

Lowry, D. C., 1970, (published, 1972), The geology of the Western Australian part of the Eucla Basin: West. Australia Geol. Survey Bull. 122.

Ludbrook, N. H., 1963, Correlation of the Tertiary rocks of South Australia: Royal Soc. South Australia Trans., v. 87, p. 5–15.

Playford, P. E., Cope, R. N., Cockbain, A. E., Low, G. H. and Lowry, D. C., 1975, Phanerozoic, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 233–433.

Pulley, J. M., 1959, Corals from the Merlinleigh Sandstone of the Carnarvon Basin, Western Australia: Australia Bur. Mineral Resources Rept 38, p. 113–118.

Quilty, P. J. G., 1968, Studies in Tertiary Foraminifera, Part 1 Upper Eocene Foraminifera from the Plantagenet Beds southwestern Western Australia: Univ. Tasmania Ph.D. thesis (unpublished).

Teichert, C., 1944, The genus *Aturia* in the Tertiary of Western Australia: Jour. Palaeontology, v. 18, p. 73–82.

Wade, M., 1955, A new genus of the Chapmanininae from southern Australia: Cushman Foundation, Foraminiferal Res. Contrib., v. 6, p. 45–49.

PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1980

by K. A. Crank

ABSTRACT

There was a significant increase in petroleum exploration in Western Australia in 1980, continuing the upward trend started in 1976. In 1980, 32 exploration wells were completed compared with 17 in 1979, and 6 were drilling ahead at the end of the year, for a total penetration of 91 733 m, an increase of 25 305 m, or 38%, compared with the previous year. Expressed in rig months, the increase was 63% compared with 1979. Drilling activity in 1980 would have been considerably higher but for a severe shortage of offshore drilling rigs. Six development wells were completed in the Barrow Island Oil Field and two in the Dongara Gas Field in 1980.

Highlights of the year included the discovery of gas at Woodada in the northern Perth Basin; and a significant gas show at Phoenix 1, the first such discovery in the offshore Canning Basin. Hydrocarbon shows were encountered in several other wells.

There was a considerable increase in onshore seismic surveys, from 909 km to 4 898 km. However, there was a small decrease in marine seismic activity, which declined by 27% compared with 1979, and totalled 19 089 km.

INTRODUCTION

Exploratory drilling for petroleum in Western Australia over the past two years is illustrated in the following tables:

Type of well	Wells completed		Wells drilling on 31 December	
	1979	1980	1979	1980
New field wildcats	15	21	4	4
New pool wildcats	1	11	0	0
Extension tests	1	0	0	2
Total	17	32	4	6

Basin	Metres drilled—by Basin			
	1979 Onshore	1979 Offshore	1980 Onshore	1980 Offshore
Bonaparte Gulf	0	2 863	0	3 589
Browse	....	6 474	....	13 058
Canning	6 940	0	5 447	4 880
Carnarvon	796	20 232	11 554	11 845
"Exmouth Plateau"	....	29 123	....	16 284
Perth	0	0	18 383	0
Eucla	0	0	0	2 573
Officer	0	....	4 120	....
Totals	7 736	58 692	39 504	52 229
	66 428		91 733	

One gas discovery was made in 1980, at Woodada, in the northern part of the Perth Basin, and excellent gas shows were reported in the Phoenix 1 well, the first such discovery in the offshore Canning Basin. At Mount Horner 3 a small oil pool was discovered; this oil had previously been thought to be non-commercial when originally encountered by West Australian Petroleum Pty Ltd in 1965. Several new small pools of oil were also delineated on Barrow Island within the Barrow Island Oil Field.

Figure 1 summarizes seismic activity since 1968. Geophysical survey activity in 1979 and 1980 is shown below:

Type of survey	Line km	
	1979	1980
Land seismic	909	4 898
Marine seismic	26 312	19 089
Land gravity	0	226
Marine gravity	9 626	1 328
Marine magnetic	4 903	3 587

DRILLING

DRILLING OPERATIONS

Expressed in rig months, overall exploration operations increased by 63% to 73·2 rig months in 1980, compared with 44·8 rig months in 1979. Offshore operations increased by 18% compared with 1979 (47·3 compared with 40·0 rig months), but the big increase was in onshore activity (25·9 compared with 4·8 rig months). In addition, 6·2 rig months were spent on development drilling in the Barrow Island and Dongara fields, compared with 11·0 rig months in 1979.

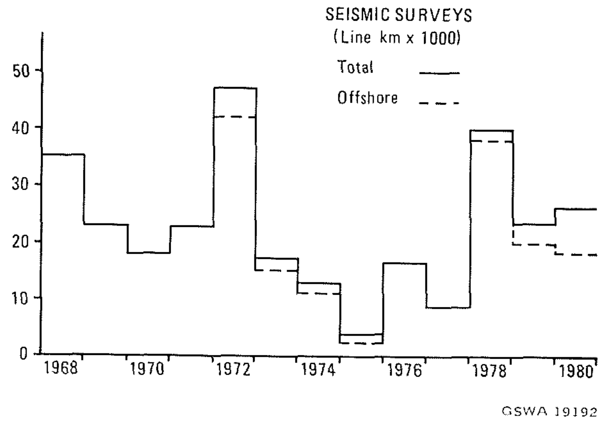


Figure 1 Seismic surveys since 1968

A total of 13 rigs, six offshore and seven onshore, operated in Western Australia. A shortage of drilling rigs in 1980 reduced considerably the expected increase in offshore operations. After drilling Barcoo 1 and Sirius 1 respectively, the drill-ships Sedco 445 and Sedco 472 left Western Australian waters. The semi-submersible Ocean Digger was not utilized prior to drilling Phoenix 1 and, after this well, it also left Western Australian waters. Other details of rig deployment are shown in Figure 2.

Four tropical cyclones interrupted drilling operations in January and February. A total of 55 rig days were lost due to cyclones "Amy", "Brian", "Dean" and "Enid". The wells affected were Buffon 1 (14 days), Vinck 1 (9 days), Barcoo 1 (20 days) and Parker 1 (12 days).

Figure 3 is a summary comparison of drilling operations for the 13-year period 1968–1980.

WELLS COMPLETED IN 1980

The locations of wells drilled for petroleum exploration in Western Australia during 1980 are shown in Figure 4. Details relating to wells drilled during the year are given in Table 1. All petroleum wells drilled in Western Australia up to the end of 1980 are listed in the Geological Survey Record 1981/1 (Crank, 1981). A summary follows of the principal results of drilling in each basin during the year.

Bonaparte Gulf Basin

Only one well was completed in the Bonaparte Gulf Basin in 1980, Lesueur 1, drilled by Australian Aquitaine Petroleum Pty Ltd in Exploration Permit WA–18–P. This was drilled on an anticlinal structure, 169 km north of the town of Wyndham and 57 km north of the coast. The main objectives were sandstones of Permian age and Early Carboniferous carbonates and sandstones, but only minor gas shows were encountered and the well was plugged and abandoned in Early Carboniferous rocks at a total depth of 3 589 m.

Browse Basin

Woodside Petroleum Development Pty Ltd completed three wells in the Browse Basin: Barcoo 1, Buffon 1 and Brewster 1A.

Barcoo 1 was drilled in WA–32–P in 720 m of water on a large anticline in the southwest part of the basin, about 100 km west of Lombardina 1 and 80 km northwest of Lynher 1. The objectives were Late Triassic and Early to Middle Jurassic sandstones, and although good porosities and permeabilities were encountered, only very low gas readings were detected. The well was plugged and abandoned at 5 109 m in Upper Triassic rocks.

Buffon 1, in WA–37–P, in 720 m of water, was drilled on an anticlinal structure in the northern part of the basin, 100 km north-northwest of Scott Reef 1. Objectives were Middle to Late Jurassic and Triassic Sandstones. The Triassic was not reached and Middle Jurassic volcanics were encountered between 3 825 and the total depth. Good gas shows occurred

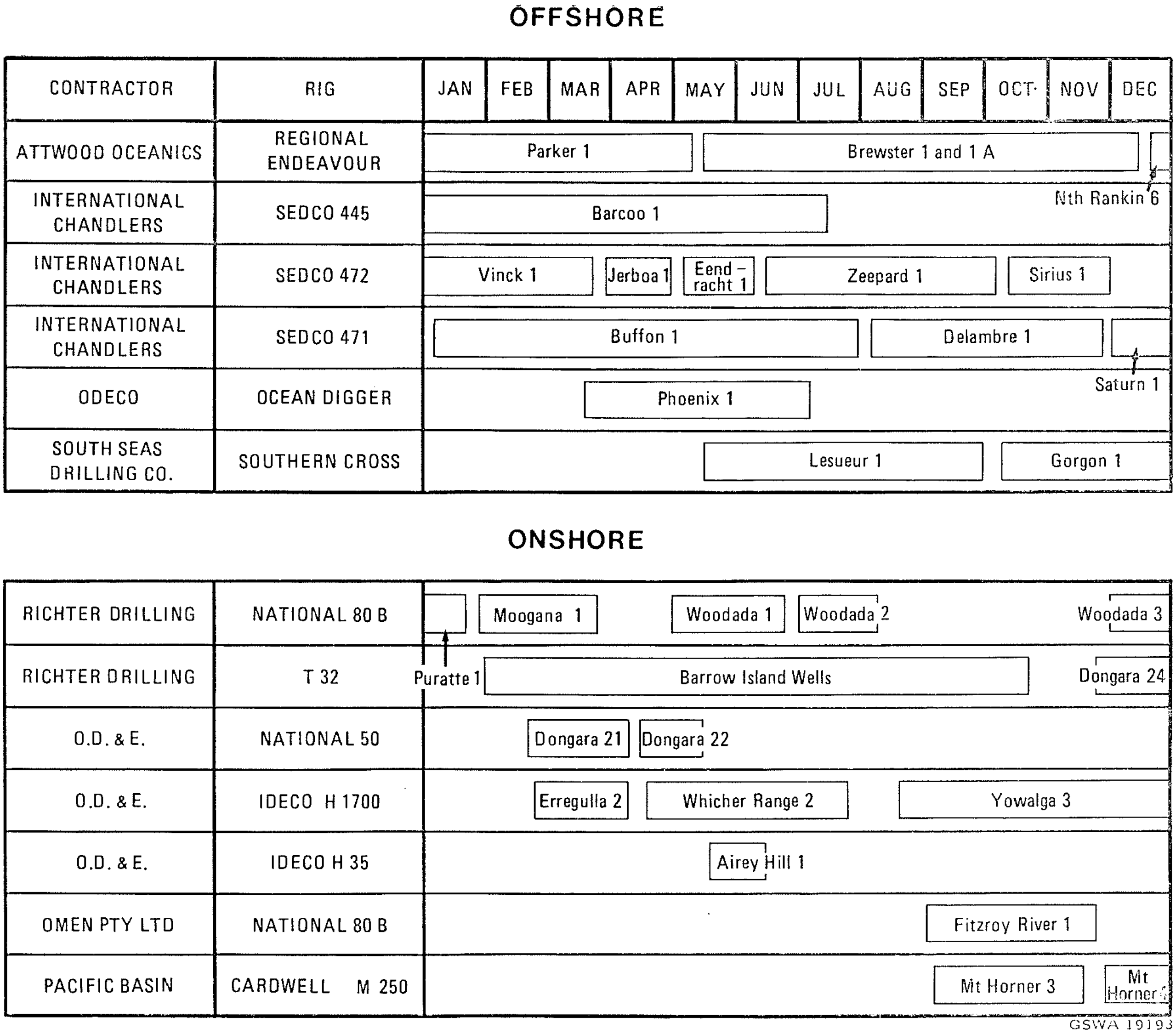


Figure 2 Rig utilization, 1980

in the volcanic section but a drillstem test of the interval 3 739 m to 4 246 m yielded only salt water and a trace of gas. The well was plugged and abandoned at the total depth, 4 757 m.

Brewster 1A was drilled in 250 m of water, in WA–35–P, in the northern part of the basin on a low-relief anticlinal structure. Objectives were sandstones of Lower Jurassic to Lower Cretaceous (Neocomian) age. Brewster 1 was abandoned at 633 m because of mechanical problems. The 1A well also encountered Jurassic volcanics (between 4 565 m and 4 630 m), and gas shows were seen in sandstones below 3 942 m but porosities were low. The drill pipe became stuck after drilling to 4 464 m and it was necessary to drill a sidetrack hole to the total depth of 4 703 m, after which the well was plugged and abandoned.

Canning Basin

In the Canning Basin one offshore and three onshore wells were completed in 1980. One of these, Puratte 1, reached its total depth at the end of 1979 but was completed as a dry hole early in January 1980. This well, drilled by Esso Australia Ltd in EP–104, was sited to test an integrated Devonian pinnacle reef, but no reef rock was encountered and there were no significant shows.

Esso drilled a second well in EP–104 in the onshore Canning Basin, Moogana 1, to test Devonian carbonates in a tilted fault block. Only thin carbonates were penetrated, and there were no shows. Total depth was 2 213 m, in Precambrian graphitic shale and dolerite.

The third onshore well, Fitzroy River 1, was put down by Amax Iron Ore Corporation in EP–97. Total depth was 3 134 m in probable Early Carboniferous rocks, although the main objective had been Devonian carbonates. Only very minor gas shows were encountered, and thin sandstone beds between 2 743 m and 2 800 m tested gas flows too small to measure. The well was plugged and abandoned.

The offshore well, Phoenix 1, was drilled by BP Petroleum Development Australia Pty Ltd on a large elongate anticline in the central part of the offshore basin in Exploration Permit WA–62–P. The main objective in Phoenix 1 was middle to Late Triassic sandstones, and thick sandstones below 4 113 m yielded significant gas shows. At the total depth (4 880 m) gas shows were still being encountered in Middle Triassic sandstones, but the well had to be suspended because it was considered unsafe to continue operations with available pressure-control equipment. BP hopes to return to this location later.

Carnarvon Basin

Two exploration wells offshore were completed by Woodside during the year. Onshore, one new field wildcat and eleven new pool wildcats were completed. Two offshore exploration wells drilling at the end of 1980 were Gorgon 1, a new field wildcat put down by West Australian Petroleum Pty Ltd, and North Rankin 6, an extension test in the North Rankin Field.

Woodside's first well was Parker 1, commenced near the end of 1979 in WA–28–P, located to test a tilted fault block on the southern part of the Kendrew Terrace, south of the productive Rankin Trend. Objectives were sandstones in the Jurassic and Late Triassic, but the Triassic was not reached and the well had to be abandoned at 4 737 m due to mechanical problems.

TABLE 1. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1980

Basin	Well	Concession	Operating Company	Type	Position		Elevation and water depth (m)			Dates			Total depth (or depth reached) (m)	Bottomed in	Status on 31 Dec.
					Latitude South	Longitude East	GL	RT	WD	Commenced	Reached TD	Rig released			
Bonaparte Gulf	Lesueur 1	WA-18-P	Aquitaine	NFW	13°57′09″	128°07′33″	....	22	37	16/5/80	22/8/80	30/9/80	3 589	Carboniferous	Gas shows, P & A
Browse	Barcoo 1	WA-32-P	Woodside	NFW	15°20′37″	120°38′12″	....	11	720	14/12/79	29/6/80	12/7/80	5 109	U. Triassic	Dry, P & A
	Buffon 1	WA-37-P	Woodside	NFW	13°23′38″	122°11′00″	....	10	533	4/1/80	18/6/80	3/8/80	4 787	L. Jurassic	Gas shows, P & A
	Brewster 1	WA-35-P	Woodside	NFW	13°54′47″	123°15′29″	....	8	253	13/5/80	16/5/80	23/5/80	633	Tertiary	Mechanical problems, P & A
	Brewster 1A	WA-35-P	Woodside	NFW	13°54′49″	123°15′28″	....	8	250	23/5/80	8/12/80	19/12/80	4 703	Jurassic	Gas shows, suspended
Canning	Puratte 1	EP-104	Esso	NFW	17°05′16″	123°14′17″	27	33	....	4/11/79	2/1/80	17/1/80	3 750	?U. Devonian	Dry, P & A
	Moogana 1	EP-104	Esso	NFW	16°56′17″	122°41′27″	32	38	....	27/1/80	8/3/80	17/3/80	2 313	Precambrian	Dry, P & A
	Phoenix 1	WA-62-P	BP	NFW	18°38′07″	118°47′07″	....	30	139	22/3/80	18/6/80	10/7/80	4 880	M. Triassic	Gas shows, suspended
	Fitzroy River 1	EP-97	Amax	NFW	18°29′39″	124°52′50″	76	81	....	29/8/80	14/11/80	23/11/80	3 134	?L. Carboniferous	Dry, P & A
Carnarvon	Parker 1	WA-28-P	Woodside	NFW	20°00′08″	115°40′08″	....	8	80	26/11/79	1/4/80	4/5/80	4 737*	L. Jurassic	Gas shows, P & A
	Barrow R38	PL1H	WAPET	NPW	20°46′50″	115°22′07″	23	27	....	3/2/80	10/2/80	15/2/80	1 037	L. Cretaceous	Oil well
	Barrow T12	PL1H	WAPET	NPW	20°44′43″	115°23′33″	42	46	....	17/2/80	23/2/80	27/2/80	1 190	L. Cretaceous	Shut-in gas well
	Barrow F48	PL1H	WAPET	NPW	20°50′38″	115°23′58″	12	16	....	29/2/80	4/3/80	7/3/80	901	L. Cretaceous	Shut-in
	Barrow L45M	PL1H	WAPET	NPW	20°48′55″	115°23′21″	52	56	....	22/4/80	9/5/80	11/5/80	976	L. Cretaceous	Oil well
	Barrow Y24M	PL1H	WAPET	NPW	20°43′08″	115°26′56″	29	33	....	17/5/80	23/5/80	29/5/80	1 250	L. Cretaceous	Oil well
	Airey Hill 1	EP-166	Monarch	NFW	23°04′02″	113°52′20″	68	72	....	23/5/80	6/6/80	11/6/80	1 037	L. Permian	Dry, released as water well
	Barrow J46	PL1H	WAPET	NPW	20°48′42″	115°19′51″	14	18	....	4/7/80	8/7/80	10/7/80	783	L. Cretaceous	Oil well
	Barrow R36	PL1H	WAPET	NPW	20°46′50″	115°21′35″	11	15	....	12/7/80	18/7/80	19/7/80	774	L. Cretaceous	Oil well
	Barrow R28	PL1H	WAPET	NPW	20°46′37″	115°22′07″	26	30	....	15/8/80	20/8/80	22/8/80	789	L. Cretaceous	Oil well
	Delambre 1	WA-90-P	Woodside	NFW	18°31′05″	116°41′48″	....	10	884	6/8/80	17/11/80	28/11/80	5 495	Triassic	Dry, P & A
	Barrow T24	PL1H	WAPET	NPW	20°44′48″	115°23′57″	41	45	....	23/8/80	28/8/80	30/8/80	820	L. Cretaceous	Under test
	Barrow Q46M	PL1H	WAPET	NPW	20°47′08″	115°23′31″	56	60	....	2/9/80	20/9/80	23/9/80	1 052	L. Cretaceous	Oil well
	Barrow E31M	PL1H	WAPET	NPW	20°50′22″	115°24′10″	17	21	....	24/9/80	6/10/80	8/10/80	945	L. Cretaceous	Under test
	Gorgon 1	WA-25-P	WAPET	NFW	20°34′43″	114°46′22″	....	21	259	11/10/80	....	....	4 231	....	Drilling
	North Rankin 6	WA-1-L	Woodside	EXT	19°32′46″	116°08′27″	....	8	124	24/12/80	....	....	460	....	Drilling
"Exmouth Plateau"	Vinck 1	WA-97-P	Esso	NFW	20°35′04″	112°11′34″	....	10	1 362	20/12/79	17/3/80	25/3/80	4 600	U. Triassic	Gas shows, P & A
	Eendracht 1	WA-96-P	Esso	NFW	19°54′26″	112°14′09″	....	10	1 353	8/5/80	30/5/80	5/6/80	3 410	U. Triassic	Gas shows, P & A
	Zeepard 1	WA-96-P	Esso	NFW	20°44′14″	114°25′22″	....	10	740	8/6/80	10/10/80	16/10/80	4 215*	U. Triassic	Gas shows, P & A
	Sirius 1	WA-97-P	Esso	NFW	20°55′04″	112°41′21″	....	10	1 176	18/10/80	26/11/80	2/12/80	3 500	U. Triassic	Gas shows, P & A
	Saturn 1	WA-84-P	Phillips	NFW	19°54′36″	114°56′41″	....	10	1 177	1/12/80	....	....	3 074	....	Drilling
Perth	Erregulla 2	EP-23	Mesa	NFW	29°22′31″	115°23′51″	241	248	....	20/2/80	10/4/80	13/4/80	3 577	M. Triassic	Dry, P. & A
	Whicher Range 2	EP-130	Mesa	NFW	33°50′31″	115°22′56″	150	157	....	25/4/80	24/6/80	27/7/80	4 330	U. Permian	Gas shows, P & A
	Woodada 1	EP-100	Hughes	NFW	29°47′44″	115°08′21″	35	40	....	29/4/80	12/6/80	21/6/80	2 546	L. Permian	Gas well
	Woodada 2	EP-100	Hughes	NFW	29°47′43″	115°09′07″	37	42	....	28/6/80	26/7/80	3/8/80	2 468	L. Permian	Gas well
	Mt Horner 3	EP-96	XLX	NFW	29°07′42″	115°05′00″	195	198	....	3/9/80	5/11/80	19/11/80	1 558	L. Permian	Oil well
	Mt Horner 4	EP-96	XLX	NFW	29°07′49″	115°05′24″	215	218	....	28/11/80	....	....	1 470	....	Drilling
	Woodada 3	EP-100	Hughes	EXT	29°45′16″	115°09′21″	42	43	....	9/12/80	....	....	2 434	....	Drilling
Eucla	Jerboa 1	WA-126-P	Esso	NFW	33°30′15″	127°36′03″	....	10	771	2/4/80	24/4/80	29/4/80	2 573	Precambrian	Dry, P & A
Officer	Yowalga 3	EP-178	Shell	NFW	29°08′58″	125°55′00″	476	483	....	19/8/80	....	....	4 120	....	Drilling

* Does not include sidetracked hole

Aquitaine: Australian Aquitaine Petroleum Pty Ltd
Woodside: Woodside Petroleum Development Pty Ltd
Esso: Esso Exploration and Production Aust. Inc.
BP: BP Petroleum Development Aust Pty Ltd
Amax: Amax Iron Ore Corporation
WAPET: West Australian Petroleum Pty Ltd
Monarch: Monarch Petroleum N.L.
Phillips: Phillips Australian Oil Co.
Mesa: Mesa Australia Ltd
Hughes: Hughes & Hughes
XLX: XLX N.L.
Shell: The Shell Co. of Austraiia Ltd

NFW: New field wildcat well
NPW: New pool wildcat well
EXT: Extension test well
P & A: Plugged and abandoned
GL: Ground level
RT: Rotary table
WD: Water depth

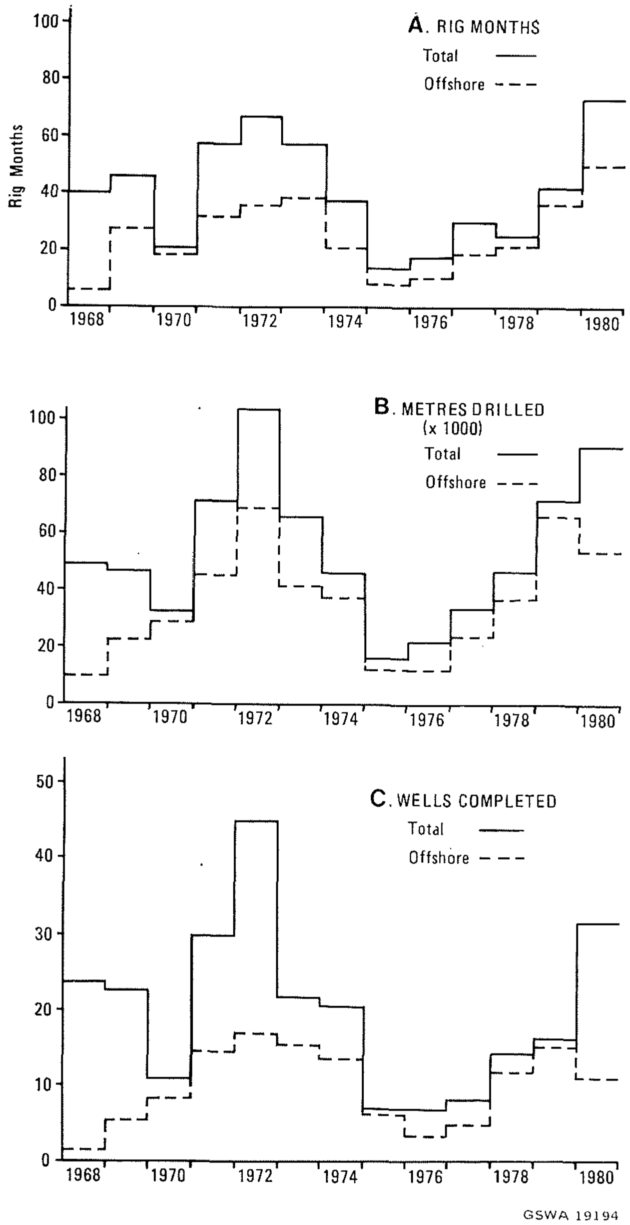


Figure 3 Drilling operations since 1968

The second well completed by Woodside was Delambre 1 in WA–90–P, drilled in the extreme northern part of the Carnarvon Basin. Objectives were Triassic and Jurassic sandstones. The well was abandoned as a dry hole at 5 495 m after the objective sands were found to be water-bearing.

Onshore, a shallow test was drilled by Monarch Petroleum NL in EP–166, about 100 km south of Learmonth. The objective was Cretaceous Birdrong Sandstone, but no hydrocarbon shows were encountered, and after reaching 1 037 m in Early Permian rocks it was released as a water well.

West Australian Petroleum Pty Ltd (WAPET) drilled a total of eleven wells classed as new pool wildcats within the area of the Barrow Island Oil Field. Seven of these were producing oil, two were shut in, and two were under test at the end of the year. The status of these wells at the end of 1980 is shown in Table 2.

Barrow Island development wells

During 1980 six development wells were drilled by WAPET within the Barrow Island Oil Field. One of these, L63 was classed as a water-source well. In the field, 4 513 m of development drilling were completed. The status of these wells at the end of the year is also shown in Table 2.

Exmouth Plateau area

Four wells were completed by Esso in the Exmouth Plateau area in water depths from 740 m to 1 362 m. At the end of the year Phillips Australian Oil Company was drilling Saturn 1 in WA–84–P.

TABLE 2. STATUS OF BARROW ISLAND WELLS

Well name	Total depth (m)	Status
		New Pool wildcats
R38	1 037	Oil producer—Windalia
T12	1 190	Shut-in gas well—Windalia
F48	901	Shut-in
L45M....	976	Oil producer—Munderong
Y24M	1 250	Oil producer—Munderong
J46	783	Oil producer—Windalia
R36	774	Oil producer—Windalia
R28	789	Oil producer—Windalia
T24	820	Under test
Q46M	1 052	Oil producer—Barrow
E31M....	945	Under test
		Development Wells
F64	857	Shut-in observation well
B16B	713	Oil producer—Windalia
J78	789	Under test
J88	792	Oil producer—Windalia
L63	1 372	Water-source well
L14	754	Oil producer—Windalia

Vinck 1, commenced late in 1979, was drilled in WA–97–P about 250 km northwest of North West Cape. The water depth was 1 362 m. Objectives in this well were Triassic sandstones and Late Jurassic-Early Neocomian deltaic sandstones. Minor gas and condensate were recovered from formation interval tests and the well was plugged and abandoned as non-commercial at a total depth of 4 600 m.

Esso's second well was Eendracht 1 in WA–96–P about 80 km north-northeast of Vinck 1. Water depth was 1 353 m. In this well the objective was Late Triassic sandstones in a large fault block closure. Formation interval tests yielded both gas and condensate between 2 467 and 2 652 m but the well was plugged and abandoned as non-commercial at 3 410 m.

Zeepard 1 was drilled in WA–96–P about 90 km west of Barrow Island, close to the northern margin of the Exmouth Sub-basin. The hole was drilled in 740 m of water and the main objectives were Late Triassic sandstones and Early Neocomian sandstones. Gas was encountered in several thin sandstones between 4 011 m and 4 164 m. One month was lost on fishing and sidetracking before the well was abandoned.

Sirius 1 was located about 65 km southeast of Vinck 1 in 1 176 m of water in WA–97–P. The plays here were for Late Triassic and Jurassic/Cretaceous deltaic sandstones but only thin gas/condensate-bearing sandstones were penetrated. The well was plugged and abandoned as a dry hole at 3 500 m.

Perth Basin

There was no offshore drilling in the Perth Basin, but five onshore wells were completed and two were drilling at the end of the year.

Mesa Australia Ltd drilled two wells, Erregulla 2 and Whicher Range 2, both follow-up wells to earlier WAPET exploration efforts. Erregulla 2 was located 200 m north of Erregulla 1, which was drilled in 1966 in EP–23 and which had encountered excellent hydrocarbon shows in the Early Jurassic and Permian. Attempts to produce commercial oil from the first well had failed and the second well was drilled nearer the crest of the structure. However, no significant hydrocarbon shows were encountered and the well was plugged and abandoned.

Mesa's second well, Which Range 2, in EP–130 in the southern part of the Perth Basin, was also a follow-up to an earlier WAPET well (1968). It was drilled to re-evaluate the potential of Permian sandstones in a structurally higher position than in the original well. Results were disappointing in that the Permian produced only minor amounts of gas. Four drillstem tests were run in Permian rocks, and, although fairly high flow rates were reported (up to 155 750 m^3/day), rapid decline occurred in each case. Of significance was the occurrence of 200 m of intrusive dolerite in the Triassic; this was not present in the No. 1 well.

Hughes and Hughes, on behalf of Strata Oil NL, completed two wells and was drilling a third at the end of the year, on the Woodada structure in EP–100 in the northern Perth Basin. The main objective of the Woodada 1 well was Early Permian Carynginia Formation sandstone which had flowed gas in 1965 at Arrowsmith 1, 25 km to the northeast. However, the well encountered a limestone section within the Carynginia Formation which was considerably thicker than at any other location in the Perth Basin. A drillstem test of the interval 2 297 m to 2 345 m yielded gas at a rate of 233·7 x $10^3 m^3$/day apparently from fracture porosity in the limestone. Woodada 2 penetrated a similar section with good gas flows from the limestone section, i.e. flow rates of up to 920 x $10^3 m^3$/day. Both these wells have been classified as gas producers.

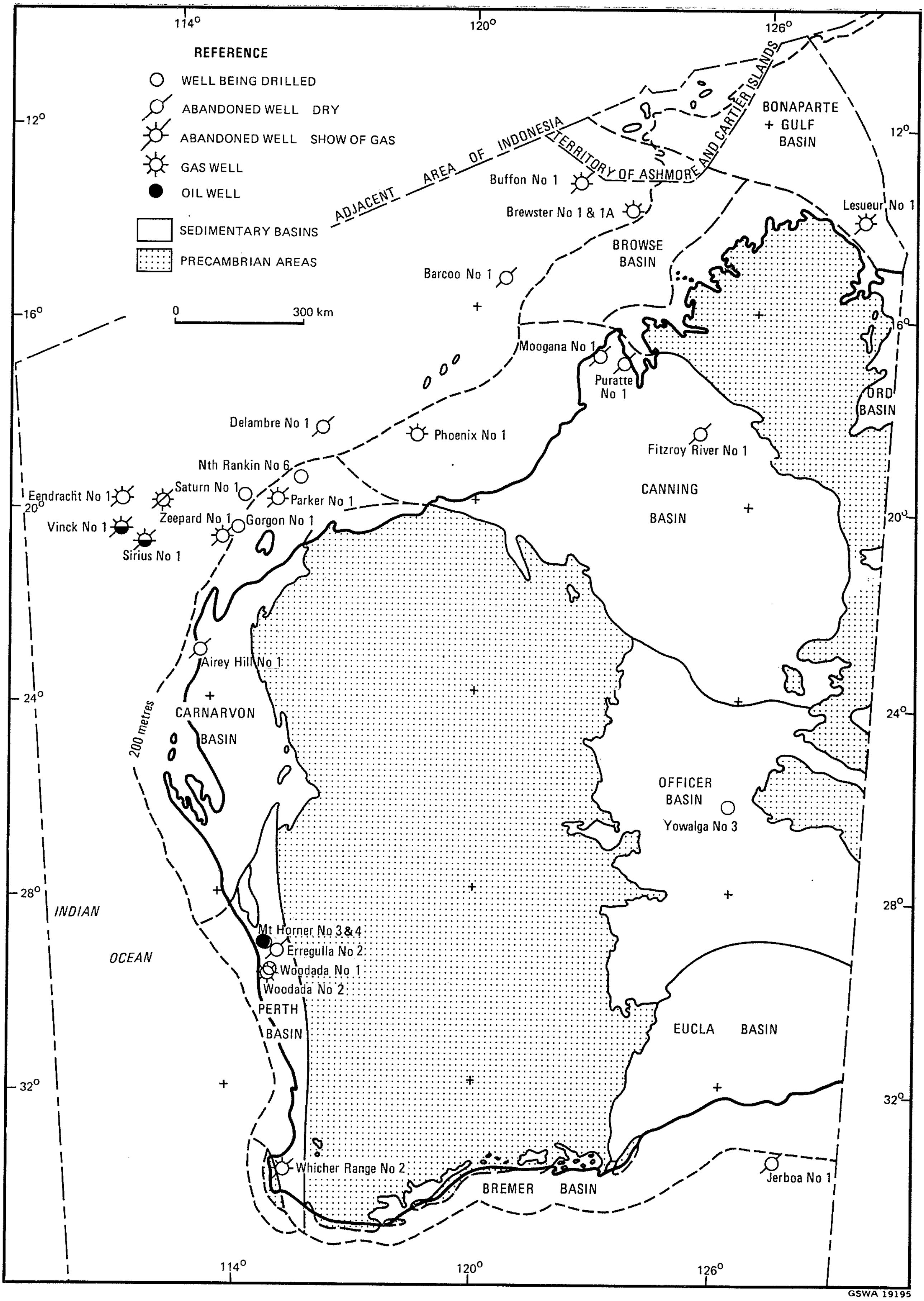


Figure 4 Map showing wells drilled for petroleum in Western Australia during 1980.

In EP–96 in the northern Perth Basin, XLX NL completed one well (Mount Horner 3) and was drilling a second (Mount Horner 4) at the end of the year. Mount Horner 3 was drilled about 195 m from Mount Horner 1 (drilled by WAPET in 1965). The primary objectives were basal triassic sandstones which have produced some oil in the Dongara and Yardarino fields; and minor sands in the Early Triassic, from which some oil was pumped in the No. 1 well during a production test by WAPET. Mount Horner 3 was completed as an oil producer with a production rate of 52 barrels of oil per day from a sand in the Early Triassic. The No. 4 location is about 500 m east of the No. 3 well.

Dongara Field development wells

Within the Dongara Field, two development wells were completed and one was drilling at the end of 1980, for a total of 5 454 m of drilling. Details are shown below:

STATUS OF DONGARA FIELD DEVELOPMENT WELLS

Well name	Total depth (m)	Status	Completed on
Dongara 21	1 889	Shut-in	10/4/80
Dongara 22	1 800	Shut-in water disposal well	14/5/80
Dongara 23	....	Drilling, at 1 765 m	....

Eucla Basin

Esso Australia Ltd drilled one well in Exploration Permit WA–126–P in the offshore Eucla Basin, the first well to be drilled off the south coast of Western Australia. The well, Jerboa 1, located about 250 km southwest of Eucla, was drilled to a total depth of 2 573 m, bottoming in the Precambrian. The objective was to test Neocomian sandstones draped over a titled basement block, but although porous sandstones were penetrated, no shows of oil or gas were encountered and the well was abandoned as a dry hole.

Officer Basin

The Shell Company of Australia Ltd, at the end of 1980, was drilling Yowalga 3, the first exploration well to be drilled in the remote Officer Basin since 1966.

GEOPHYSICAL SURVEYS

Geophysical surveys carried out during the year consisted mainly of seismic work. In line-kilometrage, seismic surveys decreased by about 12 per cent on the 1979 figure. However, there was a considerable increase in the expensive onshore surveys, from 909 km to 4 898 km, mainly due to increased activity in the Perth and Canning Basins.

Other geophysical activities were marine gravity and magnetic surveys, largely in conjunction with seismic surveys. A gravity survey was conducted in the onshore Bonaparte Gulf Basin by Australian Aquitaine Petroleum Pty Ltd.

SEISMIC

During 1980, offshore seismic surveys were conducted in the Perth Basin (1 681 km), Carnarvon Basin (7 395 km), Canning Basin (4 580 km), Browse Basin (1 015 km), Bonaparte Gulf Basin (3 028 km), and in the Exmouth Plateau area (1 390 km). Onshore seismic surveys were conducted in the Perth Basin (551 km), Carnarvon Basin (20 km), Canning Basin (3 733 km) Bonaparte Gulf Basin (209 km) and the Officer Basin (385 km). Details are as follows:

SEISMIC SURVEYS—ONSHORE

Basin	Tenement	Company	Line km
Officer	EP–178–180	The Shell Co. of Aust. Ltd.	385
Perth	EP–100	Hughes & Hughes	100
	EP–105	Mesa Australia Ltd.	60
	EP–111	Jervois Sulphates (N.T.) Ltd.	12
	EP–111	Pancontinental Mining Co.	57
	EP–130	Mesa Australia Ltd.	322
Carnarvon	EP–169	Mergui Holdings Ltd.	20
Canning	EP–104	Esso Exploration & Production Aust. Inc.	842
	EP–107	Era Western Australia Inc.	150
	EP–129	Home Oil Australia Ltd.	863
	EP–134	Mobil Oil Australia Ltd.	797
	EP–175	Getty Oil Development Co. Ltd.	1 081
Bonaparte Gulf	EP–126	Australian Aquitaine Petroleum Pty. Ltd.	209
Total			4 898

SEISMIC SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Perth	WA–59–P	Western Mining Corp. Ltd.	833
	WA–113–P	Haoma Gold Mines NL	130
	WA–115–P	Geometals Oil Exploration Pty. Ltd.	304
	WA–135–P	Wainoco International Inc.	414
Carnarvon	WA–1–P	Woodside Petroleum Development Pty. Ltd.	449
	WA–3–L	Woodside Petroleum Development Pty. Ltd.	265
	WA–4–L	Woodside Petroleum Development Pty. Ltd.	22
	WA–24–P	West Australian Petroleum Pty. Ltd.	8
	WA–25–P	West Australian Petroleum Pty. Ltd.	657
	Vacant	West Australian Petroleum Pty. Ltd.	15
	WA–28–P	Woodside Petroleum Development Pty. Ltd.	1 168
	WA–28–P	West Australian Petroleum Pty. Ltd.	42
	WA–58–P	Hudbay Oil (Australia) Ltd.	1 331
	WA–64–P	Offshore Oil N.L.	529
	WA–64–P	West Australian Petroleum Pty. Ltd.	21
	WA–80–P	Otter Exploration N.L.	212
	WA–81–P	Continental Oil Company of Aust. Ltd.	1 275
	Vacant	Esso Exploration & Production Aust. Inc.	297
	WA–102–P	Canada North West Land Ltd.	577
	WA–110–P	CNW Oil (Australia) Pty. Ltd.	527
Canning	WA–58–P	Western Energy Pty. Ltd.	226
	WA–109–P	Esso Exploration & Production Aust. Inc.	1 137
	WA–114–P	Era South Pacific Pty. Ltd.	261
	WA–117–P	Pursuit Exploration Pty. Ltd,	513
	WA–119–P	Weaver Oil & Gas Corp., Australia	1 013
	WA–120–P	Weaver Oil & Gas Corp., Australia	876
	WA–137–P	B.P. Petroleum Development (Aust.) Pty. Ltd.	554
Browse	WA–104–P	Brunswick Oil N.L.	851
	WA–68–P	Oxoco International Inc.	164
Bonapatre Gulf	WA–18–P	Australian Aquitaine Petroleum Pty. Ltd.	665
	WA–74–P	Mesa Australia Ltd.	367
	Vacant	Mesa Australia Ltd.	49
	WA–77–P	Magnet Metals Ltd.	619
	WA–103–P	Lennard Oil N.L.	641
	WA–128–P	CNW Oil (Australia) Pty. Ltd.	687
Exmouth Plateau	WA–90–P	Woodside Petroleum Development Pty. Ltd.	679
	WA–93–P	Hudbay Oil (Australia) Ltd.	560
	WA–96–P	Esso Exploration & Production Aust. Inc.	52
	WA–97–P	Esso Exploration & Production Aust. Inc.	99
Total			19 089

GRAVITY

One gravity survey was conducted in the onshore Bonaparte Gulf Basin by Aquitaine. Other surveys were carried out in conjunction with marine seismic surveys, as follows:

GRAVITY SURVEYS—ONSHORE

Basin	Tenement	Company	Line km
Bonaparte Gulf	EP–126	Australian Aquitaine Petroleum Pty. Ltd.	226

GRAVITY SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Bonaparte Gulf	WA–103–P	Lennard Oil N.L.	641
	WA–128–P	CNW Oil (Australia) Pty. Ltd.	687
Total			1 328

MAGNETIC

Magnetic surveys were carried out in conjunction with marine seismic surveys as follows:

MAGNETIC SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Canning	WA–117–P	Pursuit Exploration Pty. Ltd.	370
	WA–119–P	Weaver Oil & Gas Corp. Australia	1 013
	WA–120–P	Weaver Oil & Gas Corp. Australia	876
Bonaparte Gulf	WA–103–P	Lennard Oil N.L.	641
	WA–128–P	CNW Oil (Australia) Pty. Ltd.	687
Total			3 587

REFERENCE

Crank, K. A., 1981, Wells drilled for petroleum exploration in W.A. to the end of 1980: West. Australia Geol. Survey Rec. 1981/1.

THE TUMBLAGOODA SANDSTONE, WESTERN AUSTRALIA
ITS TYPE SECTION AND SEDIMENTOLOGY

by R. M. Hocking

ABSTRACT

The Tumblagooda Sandstone is a thick Silurian sequence which was deposited in fluviatile, tidal and coastal environments. The type section is in the lower Murchison River gorge and consists of a number of partial sections, correlation between which is achieved by interpretation of aerial photographs, lithological similarities, or physical tracing of marker horizons. It is unrealistic to construct a single composite vertical section from these partial sections, because the type section is 70 km long and is cut by three faults; but used as a fence diagram, the type section allows palaeogeographic reconstructions for the Tumblagooda Sandstone in the type area. In the east, sedimentation commenced in a low-sinuousity sheet-braided fluviatile environment, with a south-eastern source. Marine influence increased to the northwest. In time, supply lessened and the dominant environment changed to a shallow, largely tidal, marine environment. Fluviatile sands were probably still being deposited to the east. A second sheet-braided phase followed, possibly as a result of a relatively abrupt rejuvenation of the source area. This phase shows indications of waning at the very top of the type section.

INTRODUCTION

BACKGROUND

The type section of the Tumblagooda Sandstone extends down the gorge of the Murchison River from the Hardabut Anticline to Second Gully, a distance of approximately 70 km (Fig. 1). The section was measured twice previously, in 1954 and 1957, and the results recorded by Johnstone and Playford (1955) and Condon (1965) respectively. As the sandstone dips westwards at angles less than 5°, it is neither practicable nor possible to measure a single continuous section. Therefore, partial vertical sections were measured on cliffs with good exposure, and aerial photographs were used to correlate between them. Bedding shows very clearly on photographs, so this provides a generally reliable method of correlation.

It proved necessary to remeasure the type section in 1980 for three reasons:

(1) At least two faults cut the section and invalidate previous correlations.

(2) The interpretation of the sedimentology of the Tumblagooda Sandstone in the type section needed more systematic revision than was done by Mandyczewsky (1973) or Hocking (1979).

(3) Previously, the type section was presented as a single, composite, vertical section, which is not a realistic manner of presentation when the lateral extent and probable lateral facies variations within the section are considered.

TECHNIQUES

As was the practice of previous authors (Condon, 1965; Johnstone and Playford, 1955), individual sections (22 total, of which 19 are presented here) were measured after detailed interpretation of 1:40 000 aerial photographs. Section locations (Fig. 1) differ in part from those used previously because of access, exposure, and potential for correlation. Final correlation of sections was partly from aerial photographs, partly from lithology (such as facies boundaries, thickness of individual facies units, or sets of fining-upwards cycles), and partly by tracing marker horizons on the ground. Three faults were recognized, all with a probable movement of less

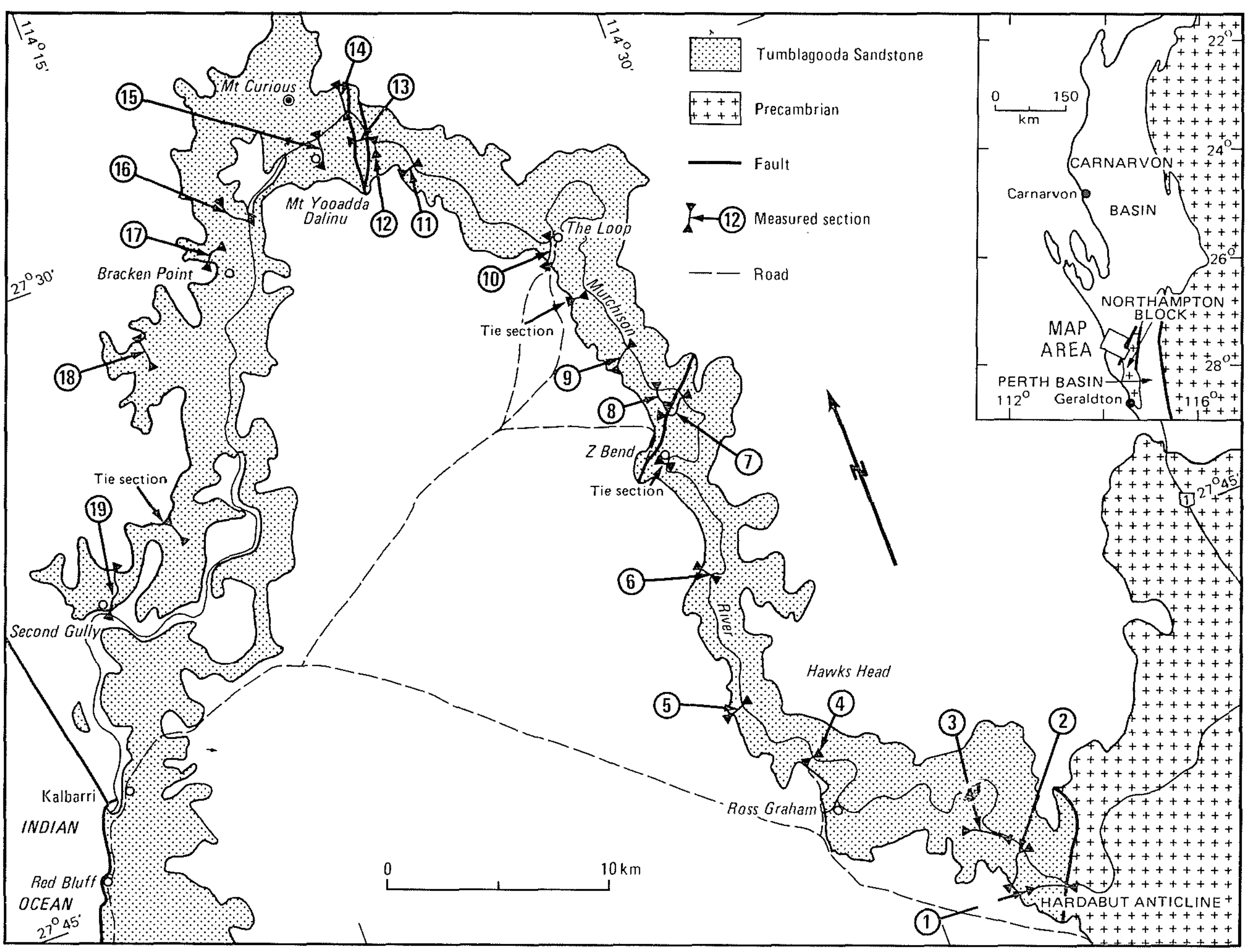
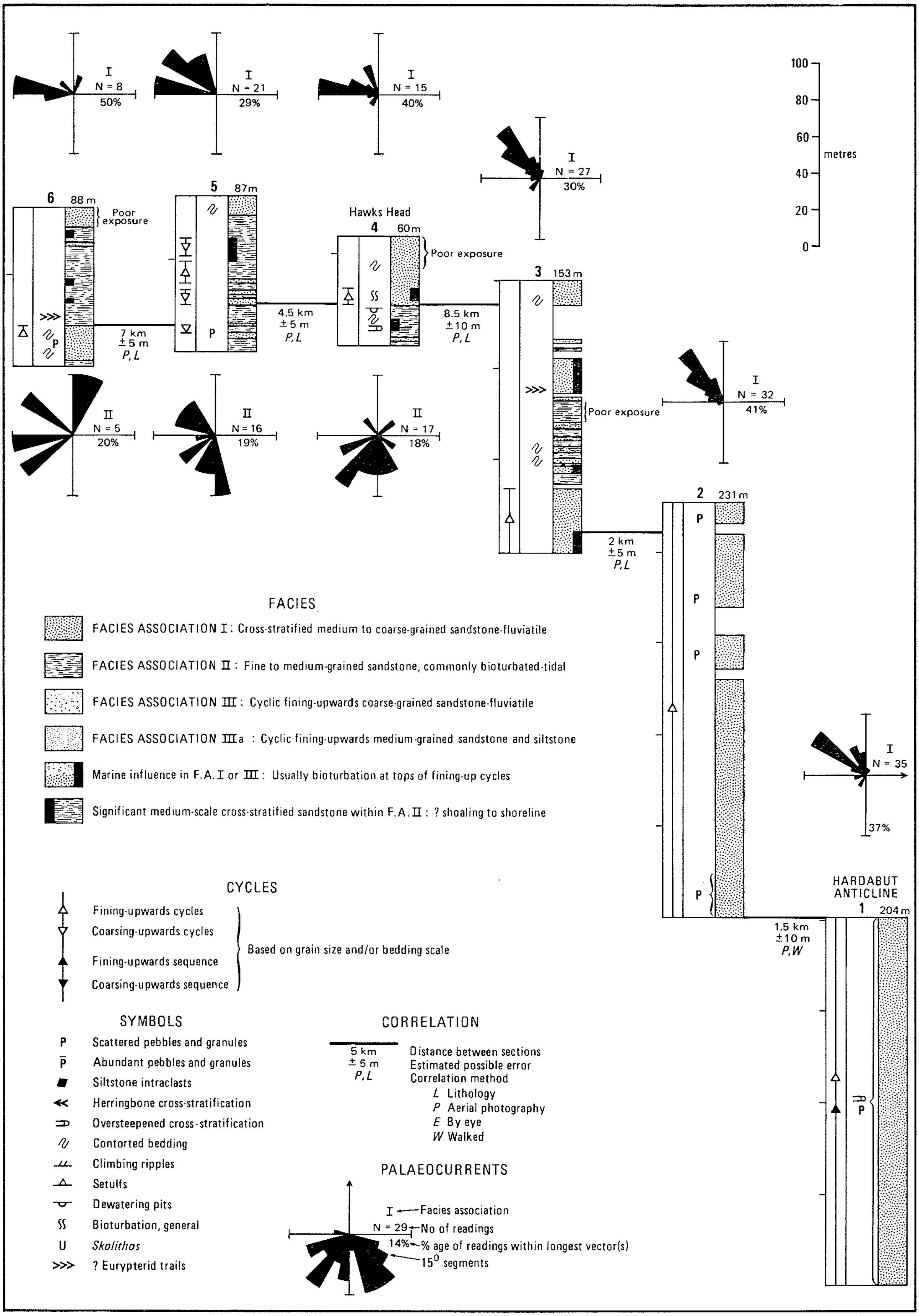


Figure 1 The Tumblagooda Sandstone type section, showing locations of faults cutting the section. Numbers refer to measured partial sections which are represented in Figures 2 and 3.



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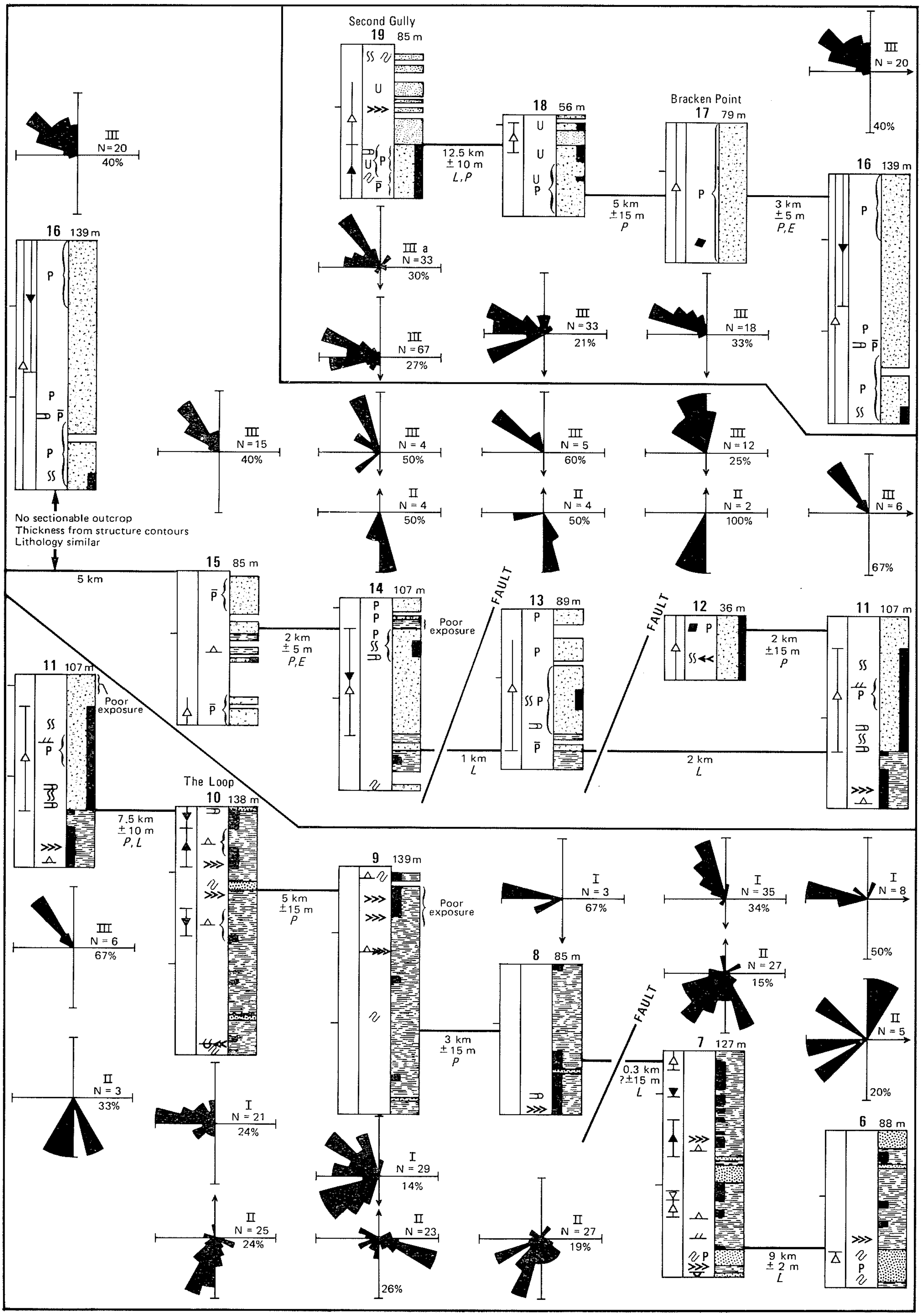
Figures 2 and 3 Partial sections for the Tumblagooda Sandstone type section. Palaeocurrent roses are total palaeocurrents for each facies association within each section. For section locations, see Figure 1.


Second Gully
19 85 m
18 56 m
Bracken Point
17 79 m
16 139 m
12.5 km
± 10 m
L, P
5 km
±15 m
P
3 km
± 5 m
P, E
III
N = 20
40%
III a
N = 33
30%
III
N = 67
27%
III
N = 33
21%
III
N = 18
33%
III
N = 15
40%
III
N = 4
50%
III
N = 5
60%
III
N = 12
25%
II
N = 4
50%
II
N = 4
50%
II
N = 2
100%
III
N = 6
67%
No sectionable outcrop
Thickness from structure contours
Lithology similar
5 km
15 85 m
14 107 m
Poor exposure
2 km
± 5 m
P, E
FAULT
13 89 m
FAULT
12 36 m
2 km
±15 m
P
11 107 m
1 km
L
2 km
L
11 107 m
Poor exposure
The Loop
10 138 m
7.5 km
± 10 m
P, L
9 139 m
5 km
±15 m
P
Poor exposure
III
N = 6
67%
I
N = 3
67%
I
N = 35
34%
I
N = 8
50%
8 85 m
3 km
± 15 m
P
II
N = 27
15%
FAULT
II
N = 5
20%
7 127 m
0.3 km
?±15 m
L
II
N = 3
33%
I
N = 21
24%
I
N = 29
14%
6 88 m
II
N = 25
24%
II
N = 23
26%
II
N = 27
19%
9 km
± 2 m
L
GSWA 19186

than 100 m. Correlation over these faults is therefore possible, and was made by means of cycle thicknesses and facies boundaries. The distance between sections, probable maximum error in correlation, and methods of correlation are shown on sections in Figures 2 and 3.

PRESENTATION

The sections are presented in a simplified format using broad facies associations in Figures 2 and 3. Only a single correlation line is shown, although in some cases correlation is based on several datum lines. Detailed representative sections of each facies association are shown in Figure 4, together with total palaeocurrent measurements for each association. Only palaeocurrents measured in 1980 are shown. A detailed version of the type section (GSWA 19200), at 1:500 scale, is in the Geological Survey plan collection.

FACIES ASSOCIATIONS

Three broad facies associations have been recognized in the type section. These are based on grain-size variation, bedding type and scale, and evidence of bioturbation.

FACIES ASSOCIATION I (F.A. I)

Trough cross-stratified, medium- to coarse-grained sandstone and subordinate planar-bedded sandstone outcrop in the eastern, or lower part, of the section, and correspond to Facies 1 of Hocking (1979). The sandstone falls primarily into lithofacies *St* of Miall (1977), with subordinate *Sh* and minor *Sp* (Table 1). Sorting is poor in some more easterly outcrops, but improves markedly to the north and west, or higher in the sequence. Pebbles and granules are present, either scattered through the rock or concentrated in lags and stringers. Fining-upwards cycles, 2 to 10 m thick, can be distinguished in most places. Parabolic recumbent cross-stratification is common (Doe and Dott, 1980), and contorted bedding is locally present. A representative portion of the association, from Section 2, is shown in Figure 4.

Locally poor sortings, sporadic pebbles, and the unimodal palaeocurrent distribution suggests F.A.I. is a fluviatile deposit, whose source was to the southeast. Further, the small scatter of palaeocurrents in each section, together with the absence of clear, incised channels or abandoned-channel deposits, suggests a low-sinuosity sheet-braided depositional environment (Miall, 1980).

FACIES ASSOCIATION II (F.A. II)

Thin-bedded, fine- to medium-grained sandstone, commonly bioturbated, outcrops in the central part of the type section, and corresponds to Facies 2 of Hocking (1979). Bedding is characteristically planar to ripple laminated (Fig. 5A, B), but in many places grades into low- to very low-angle cross-stratification. Megaripples are common, and locally coalesce to form medium-scale cross-stratified units, which are distinguished on the sections where significant. Intensely bioturbated beds characterize the association, and locally develop into laminated-to-burrowed alternations in which the couplets are up to 60 cm thick (Fig. 5C). Tracks and trails attributed to trilobites and eurypterids (Fig. 6A) and collapsed burrows attributed to trilobites (Fig. 5B), as well as non-specific tracks, trails and burrows, are present. *Skolithos* has not been found within this facies association in the type section. Sedimentary structures, such as climbing ripples (Fig. 5D), flat-topped ripples, setulfs (Fig. 6B) (Friedman and Sanders, 1974, 1978), herringbone cross-stratification, contorted bedding (Fig. 7A) and marine trace fossils, suggest that F.A. II was deposited in tidal to very shallow subtidal environments. This is supported by the intimate and repeated association of F.A. I (or F.A. III) and F.A. II sediments, and the mixture of wave and current ripples. Clay-draped surfaces, granule lags (Fig. 7D) and washed-out tracks indicate temporary cessations of supply. Because little basal scouring is present, cross-stratified sand bodies may be tidal sand-ridges (Elliot, 1978a) and shoreline barriers, produced by reworking of fluviatile sands (Elliot, 1978b), rather than channel sand as suggested by Hocking (1979). Figure 4 shows a portion of the association from Section 4 at Hawks Head.

FACIES ASSOCIATION III (F.A. III)

Facies Association III consists of fining-upwards cycles of coarse-grained sandstone and is present in the western part of the type section. Cyclicity is more pronounced than in F.A. I: fining-upwards cycles are 10 to 15 m thick, and sandstones are texturally less mature. In Miall's (1977) classification, the facies present are *St* (Fig. 6G, 7B), *Ss*, and minor *Gt* and *Sp*. Bioturbation and typical F.A. II sediments are present at the top of some fining-upwards cycles (Fig. 7C), and *Skolithos* is sporadically present throughout cycles (Figs. 6D, 8). Parabolic recumbent bedding is present but uncommon, and contorted bedding is known only from the Second Gully area.

Cycles grading upwards from medium- or coarse-grained sandstone to red siltstone (Fig. 8) constitute a subdivision within F.A. III, distinguished as Facies Association IIIa (F.A. IIIa). In Miall's classification (Table 1), they are primarily lithofacies *St* and *Fl*, with minor *Sp*. This association is the "Yalthoo Member" of Johnstone and Playford (1955) and appears to be a low-energy variant of F.A. III rather than a separate association.

Facies Association III, like F.A. I, was deposited in low-sinuousity, sheet-braided fluviatile environments. The energy level, as reflected by grain size, sorting and cycle thickness, was higher than for F.A. I, but waned during deposition of F.A. IIIa. Marine influence in F.A. III is more widespread than in F.A. I, and indicates that deposition was partly in a shoreline setting, where marine processes at times dominated during low energy stages of the braided system. This concept is similar to that of the depositional model for the Eregunda Sandstone Member from the Flinders Ranges, South Australia (Moore, 1980), in which fan-deltas debouched into a shallow epicontinental sea. This produced a sequence in which current-laid sandstones alternated with low-energy tidal deposits.

DEPOSITIONAL HISTORY

The following additions and modifications to the palaeogeography and geological history suggested by Hocking (1979) are now proposed. Three phases of deposition took place, and these are reflected in three facies associations. In the type section, deposition commenced in a fluviatile environment. A marine-dominated phase followed. The change was not abrupt, because sections show a gradual transition upwards and westwards from the fluviatile first phase. The westwards change from fluviatile to marine deposition (see Sections 3 to 7) suggests that in eastern areas, above the stratigraphic level which is now preserved in the type section, fluviatile deposition may have continued; and that in western areas, now below the level of outcrop, the fluviatile first phase may have graded laterally into marine deposition. The marine-dominated, second phase of deposition was followed by an upper, fluviatile-dominated phase, which shows signs of waning in the Second Gully area. This change from marine to fluviatile was relatively abrupt, indicating a sudden increase in energy levels.

Cyclicity in the section can be distinguished on two scales. Fining-upwards cycles in both the fluviatile phases are autocyclic (Miall, 1980), and formed by lateral shifting of sediment bars and lobes. No external influences, such as tectonic movement are necessary. However, two fining-upwards cycles

TABLE 1. LITHOFACIES, SEDIMENTARY STRUCTURES AND ENVIRONMENTAL INTERPRETATION OF BRAIDED STREAM DEPOSITS BY MIALL (1977)

Facies Code	Lithofacies	Sedimentary Structures	Interpretation
Gm	Gravel, massive or crudely bedded; minor sand, silt or clay lenses	Ripple marks; crossbeds in sand units; gravel imbrication	Longitudinal bars; channel-lag deposits
Gt*	Stratified gravel	Broad, shallow trough crossbeds; imbrication	Minor channel fills
Gp	Stratified gravel	Planar crossbeds	Linguoid bars or deltaic growths from older bar remnants
St*	Medium to very coarse sand, may be pebbly	Solitary (theta) or grouped (pi) trough crossbeds	Dunes (lower flow regime)
Sp*	Medium to very coarse sand, may be pebbly	Solitary (alpha) or grouped (omicron) planar crossbeds	Linguoid bars, sand waves (upper and lower flow regime)
Sr*	Very fine to coarse sand	Ripple marks of all types, including climbing ripples	Ripples (lower flow regime)
Sh*	Very fine to very coarse sand, may be pebbly	Horizontal lamination, parting or streaming lineation	Planar bed flow (lower and upper flow regime)
Ss	Fine to coarse sand, may be pebbly	Broad, shallow scours (including eta cross-stratification)	Minor channels or scour hollows
Fl*	Sand (very fine), silt, mud, interbedded	Ripple marks, undulatory bedding, bioturbation	Deposits of waning floods, overbank deposits

* Present in Tumblagooda Sandstone (see Figure 4).

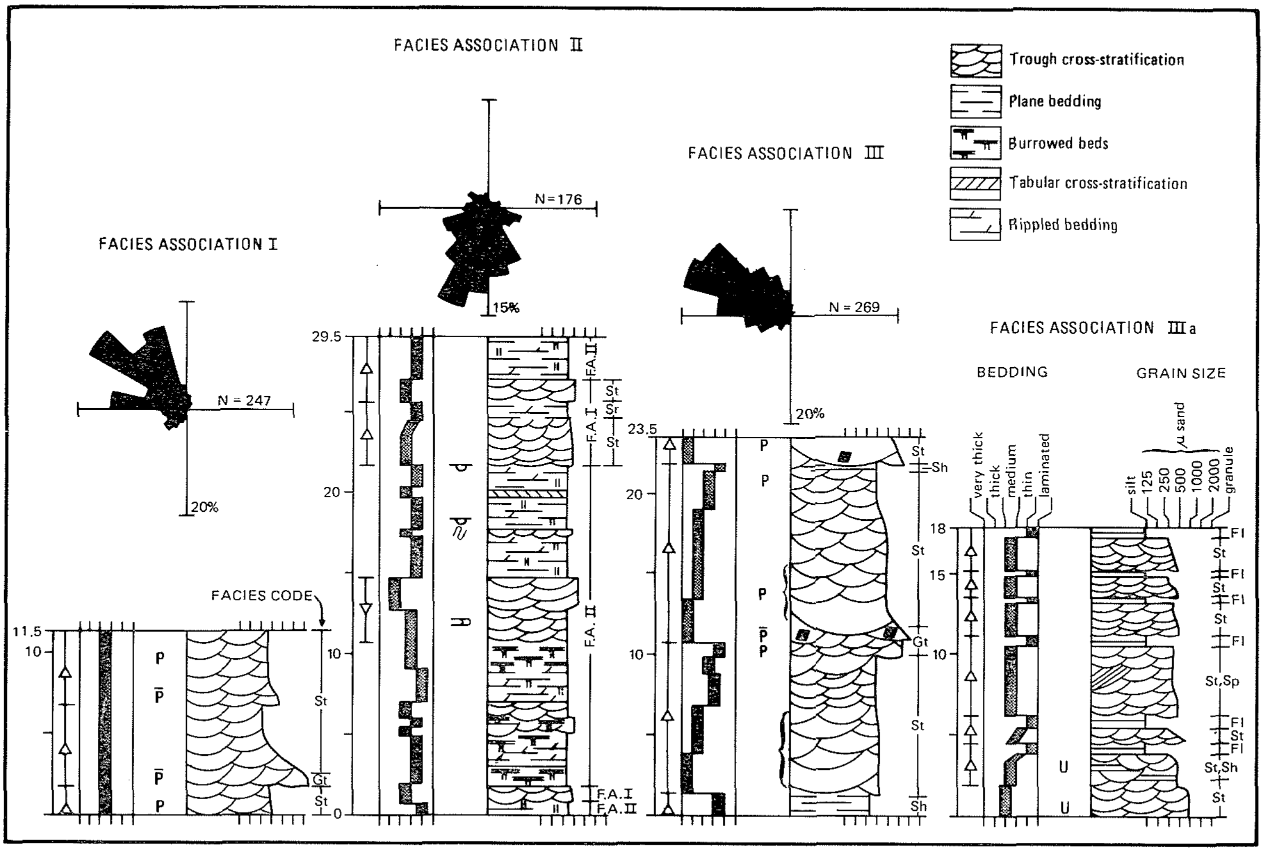


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Figure 4 Representative sections of each facies association. Palaeocurrents are total measured palaeocurrents for each facies association. For F.A.IIIa palaeocurrents, see Figure 2, Section 19. Location of sections: F.A.I.—Section 2; F.A.II—Section 4, Hawks Head; F.A.III—Section 17, Bracken Point; F.A.IIIa—Section 19, Second Gully. For explanation of symbols, see Figure 3.

of far greater magnitude can be discerned by pairing F.A. I and F.A. II, and also F.A. III and F.A. IIIa. The size of these two pairs indicates that they were controlled by external influences. The nature of these influences can be deduced from the sharp boundary between the marine depositional phase and the second fluviatile phase. Basinal downwarping would not produce this sharp change, but abrupt upwards movement on a basin-bounding fault (in this case, the Darling Fault) with the basin remaining relatively stable, would. The abrupt uplift was followed by infilling and gentle subsidence in the basin until another major fault movement would again bring in a return to fluviatile deposition.

LIMITATIONS OF THE TYPE SECTION

The type section of the Tumblagooda Sandstone offers a great deal of sedimentological detail, but there are several reasons why it is unrealistic to present only a single composite section as the type section:

(1) The length of the section along the gorge is more than 70 km, which is equivalent to approximately 50 km down the palaeoslope. This is a greater width than that of many coastal plains and continental shelves combined (Glaeser, 1978). This must be considered in any reconstruction of the Tumblagooda Sandstone because significant lateral changes should occur over this distance, especially in a coastal setting.

(2) Alternative correlations between sections (for example, taking the bases of fluviatile lenses rather than the top), can give a significantly different total thickness.

(3) Correlations across faults have been suggested here but it is quite possible that movement on the faults is greater than the depth of the gorge, and the correlation is thus fortuitous and invalid.

Therefore, the type section should be used as an indicator of trends in sedimentation, rather than a single sedimentary section.

REFERENCES CITED

Bryhni, I., 1976, Patterned cones and pits from the Hornelen district, Norway (Old Red Sandstone): Jour. Sedimentary Petrology, v. 46, p. 616–619.

Condon, M. A., 1965, The Geology of the Carnarvon Basin, Part 1: pre-Permian stratigraphy: Australia Bur. Mineral Resources Bull. 77.

Doe, T. W., and Dott, R. H., Jnr, 1980, Genetic significance of deformed cross bedding—with examples from the Navajo and Weber Sandstones of Utah: Jour. Sedimentary Petrology, v. 50, p. 793–812.

Elliot, T., 1978a, Clastic shorelines *in* Reading, H. G. (ed.), Sedimentary environments and facies: Blackwell, Sci. Pub., London.

——— 1978b, Deltas, *in* Reading, H. G. (ed.), Sedimentary environments and facies: Blackwell, Sci. Pub., London.

Friedman, G. R., and Sanders, J. E., 1974, Positive relief bedforms on modern tidal flats that resemble molds of flutes and grooves: implications for geopetal criteria and for origin and classification of bedforms: Jour. Sedimentary Petrology, v. 44, p. 181–189.

Friedman, G. R., and Sanders, J. E., 1978, Principles of Sedimentology: John Wiley & Sons, New York, 792 pp.

Glaeser, J. D., 1978, Global distribution of barrier islands in terms of tectonic setting: Jour. Geology, v. 86, p. 283–297.

Hocking, R. M., 1979, Sedimentology of the Tumblagooda Sandstone (Silurian) in the lower Murchison River area, Western Australia: a preliminary interpretation: West. Australia Geol. Survey Ann. Rept 1978, p. 40–44.

Johnstone, D., and Playford, P. E., 1955, Geology of the Shark Bay-Murchison area, Carnarvon Basin: West Australian Petroleum Pty Ltd Report (unpublished).

Levell, B. K., 1980, Evidence for currents associated with waves in Late Precambrian shelf deposits from Finmark, North Norway: Sedimentology, v. 27, p. 153–166.

Mandyczewsky, A., 1973, Stratigraphy and sedimentology of the Tumblagooda Sandstone, lower Murchison River, Western Australia: Univ. Western Australia Hons. Thesis (unpublished).

Miall, A. D., 1977, A review of the braided river depositional environment: Earth Science Reviews, v. 13, p. 1–62.

——— 1980, Cyclicity and the facies model concept in fluvial deposits: Bull. Canadian Petroleum Geology, v. 28, p. 59–80.

Moore, P. S., 1980, Deltaic sedimentation—Cambrian of South Australia: Jour. Sedimentary Petrology, v. 49, p. 1229–1244.

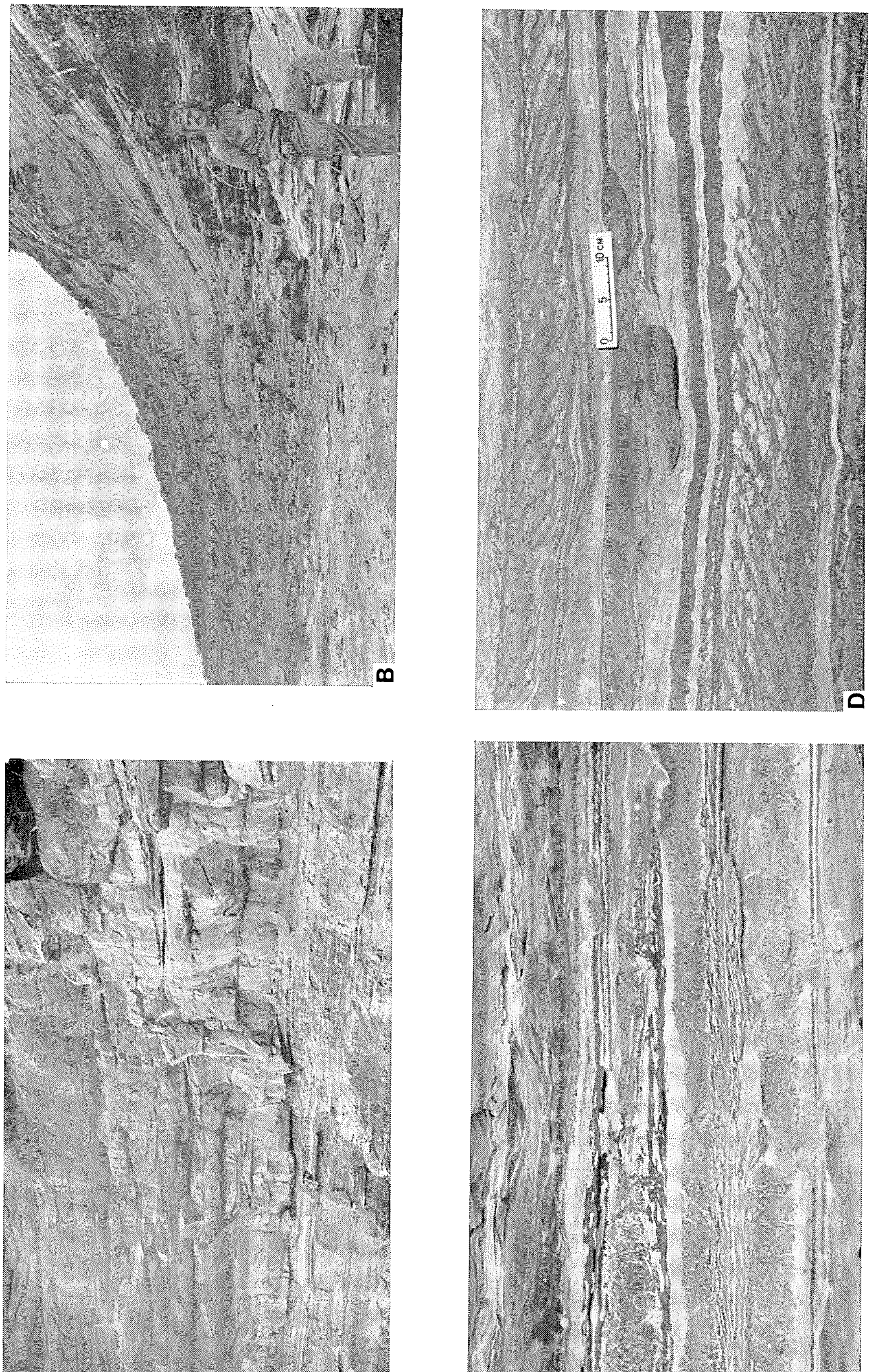

Figure 5 (a) Contact of medium-scale trough cross-stratified sandstone of Facies Association I with thin bedded Facies Association II (below). Hawks Head immediately below lookout.
(b) Typical thin-bedded F.A.II. The Loop.
(c) Intensely bioturbated beds, F.A.II. Lamination between burrowed intervals only poorly shown. The Loop.
(d) Climbing ripples with opposing current directions. F.A.II, base of The Loop.

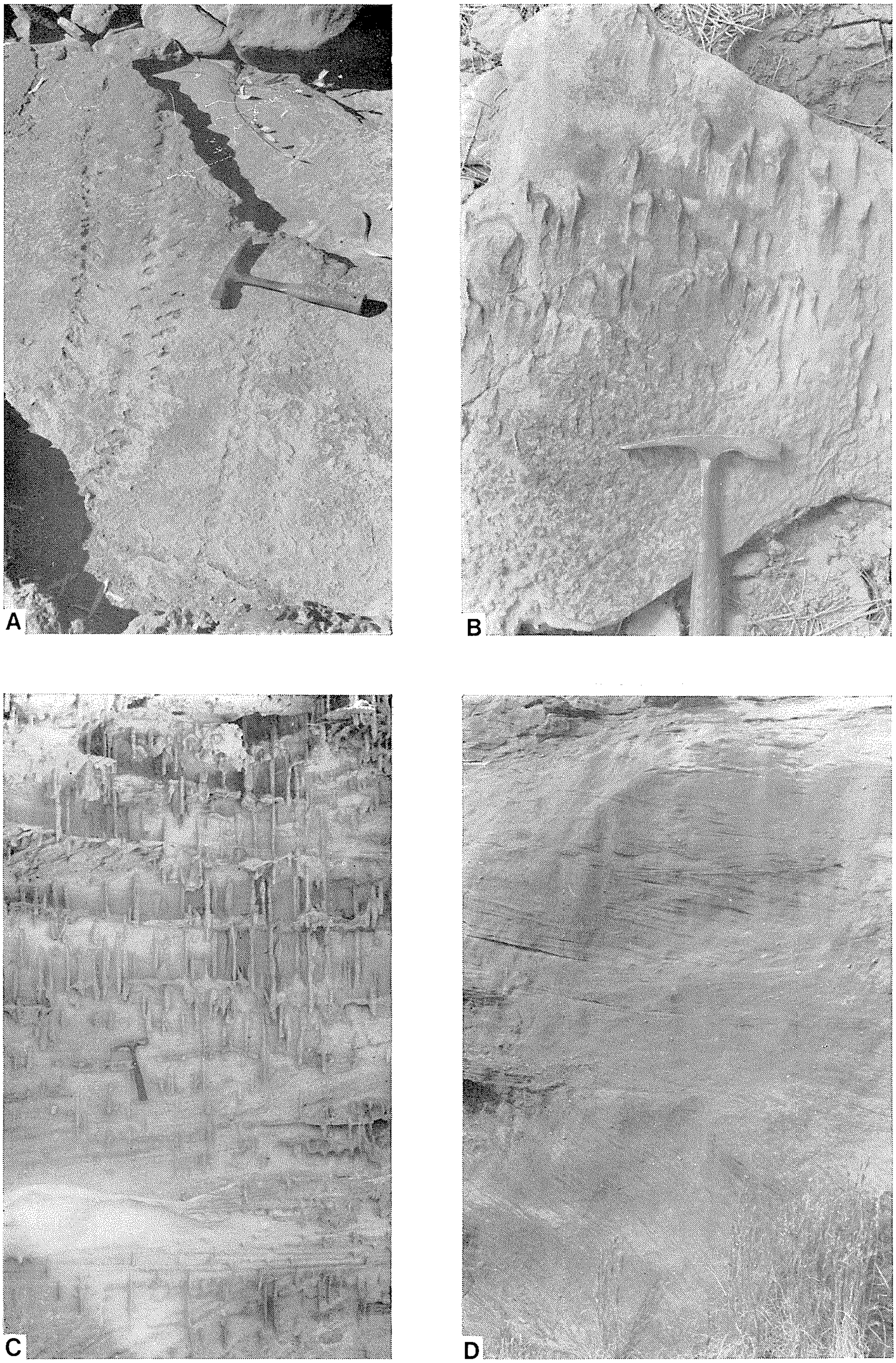

Figure 6 (a) Three sets of eurypterid tracks, one set showing imprint of legs from one side of body only. F.A.II, base of Section 8.
(b) Large setulfs in medium-grained F.A.II sandstone, grading into dimpled surface of uncertain origin (?foam markings). Current down page. The Loop.
(c) *Skolithos* in medium-grained sandstone, F.A.III, south of Kalbarri. Note length of tubes.
(d) Fining-upwards cycle in medium and coarse-grained sandstone with scattered pebbles, F.A.III, 5 km south of Bracken Point. Large-scale cross-stratification at base, overlain by medium-scale cross-stratification, with small scale cross-stratification at top. Top of cycle not shown. Grass on right hand side is 1 m high.

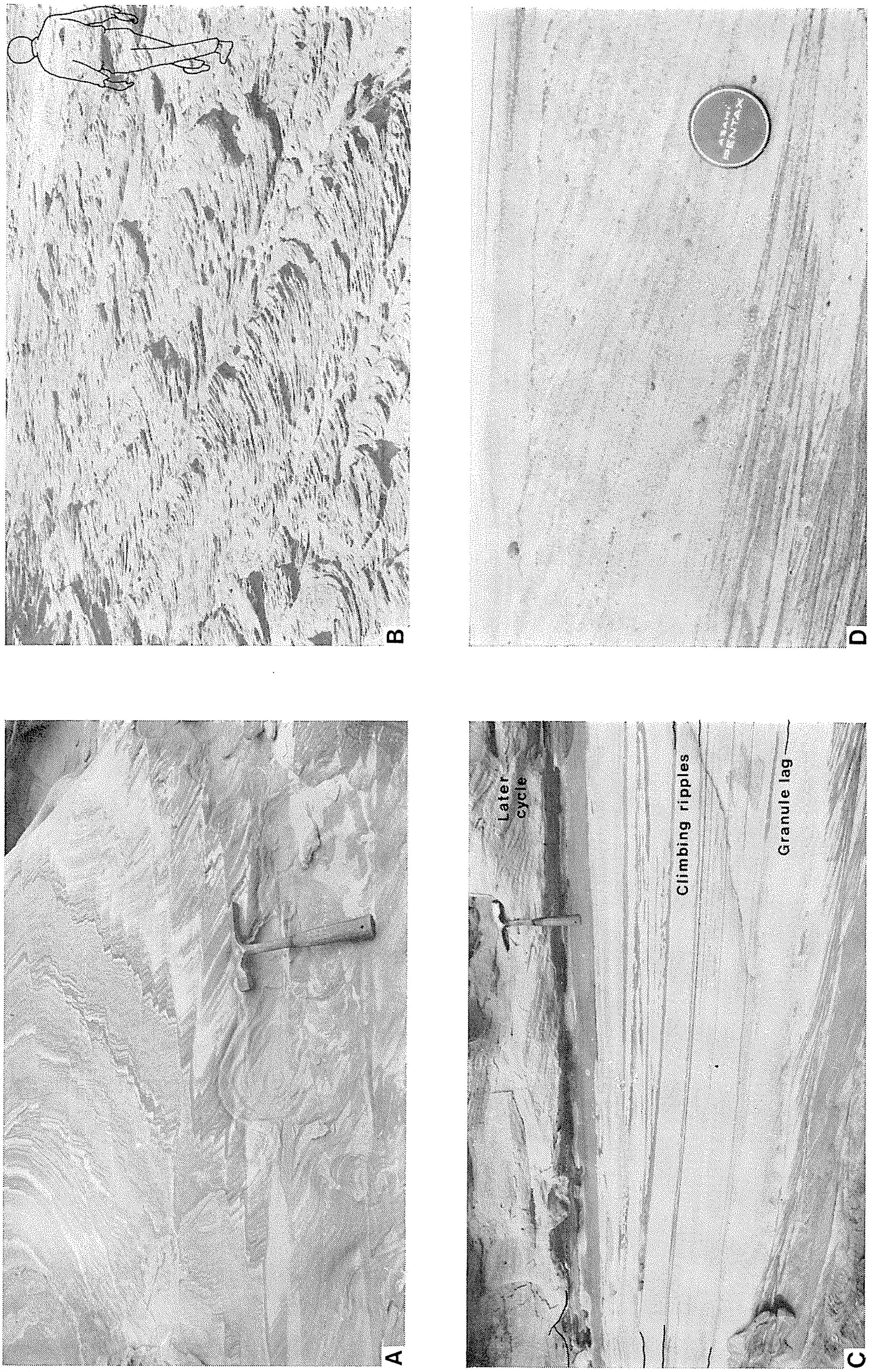

Figure 7 (a) Contorted bedding in 3 m-thick zone, showing recumbent fold with axial-plane faulting. The zone of contortion extends laterally for more than 200 m, in a cliff-face exposure. F.A.II, Section 9.
(b) Medium-scale trough cross-stratification in pebbly, coarse-grained sandstone. F.A.III, Red Bluff.
(c) Top of cycle, F.A.III, Section 11. Northwestwards directed trough cross-stratification at base, truncated by granule lag. Typical F.A.II bedding overlies this, with plane bedding, eastwards-climbing ripples and very low-angle cross-stratification. Geological hammer is balanced in coarse-grained sandstone of the next cycle.
(d) Detail of Figure 7c. Pebbly and granuley cross-stratified sandstone overlain by granule and small-pebble lag. Plane bedded sandstone overlying the lag is of marine origin.

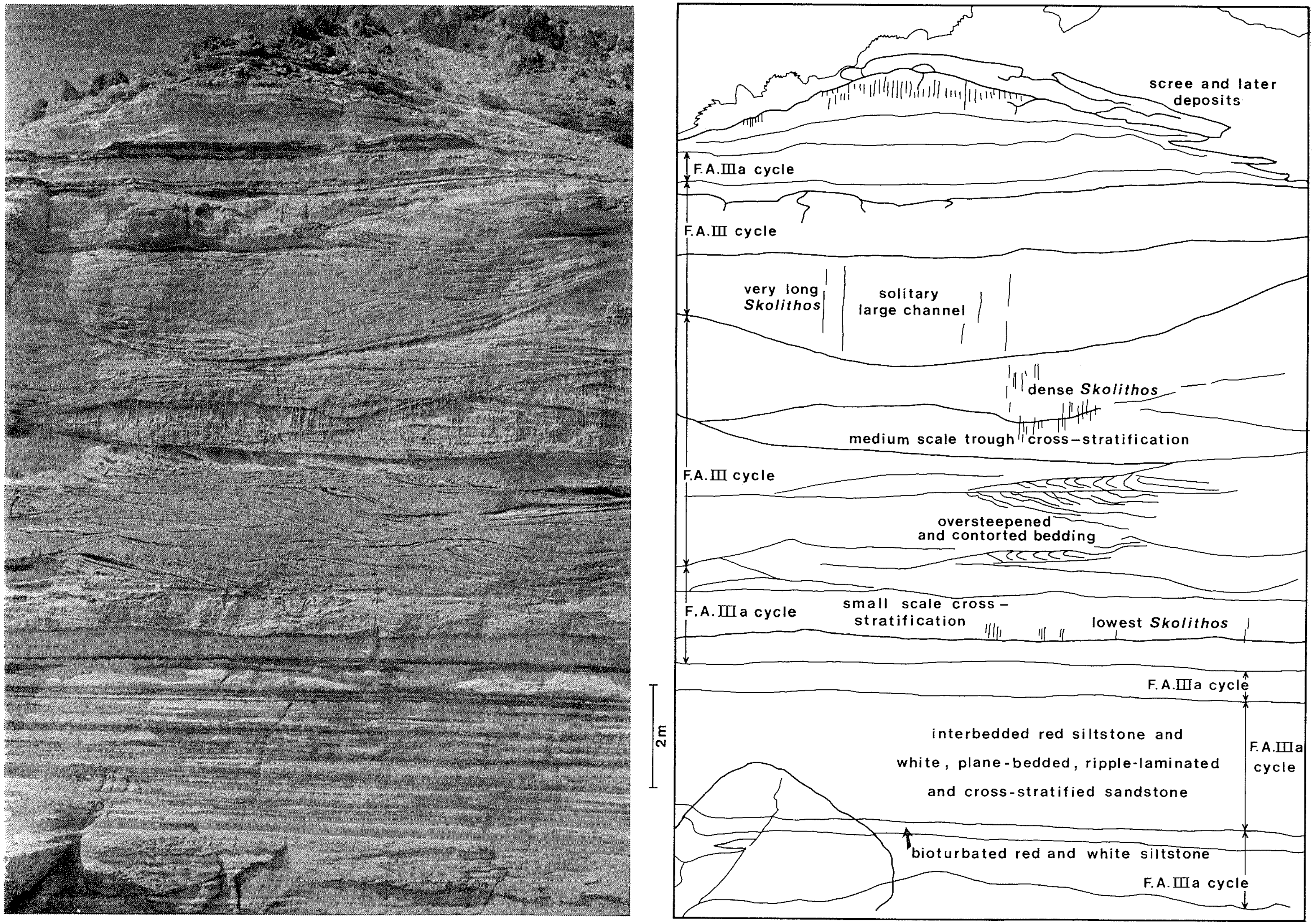

Figure 8 Face of Red Bluff showing F.A.III and F.A.IIIa cycles, oversteepening, *Skolithos*, cross-stratification, and solitary large channel.

AN ALLUVIAL FAN–FLUVIAL PLAIN DEPOSITIONAL MODEL FOR THE DEVONIAN WILLARADDIE FORMATION AND MUNABIA SANDSTONE OF THE CARNARVON BASIN, W.A.

by H. T. Moors

ABSTRACT

From their constituent rock types and field relationships, it is clear that the Munabia Sandstone and Willaraddie Formation are genetically related. Earlier workers regarded both formations as marine sediments, but current field work has shown that the bulk of the two formations are in fact terrestrial deposits.

Though the base of the Munabia Sandstone is clearly marine, and restricted marine incursions occur elsewhere in the section, the bulk of the sequence consists of fining-upwards cycles of sand, with erosional bases, completely devoid of trace or body fossils except for plant fragments. This sequence of beds with their internal organization suggests a fluvial origin. The Willaraddie Formation is typified by coarse sediments of low maturity and poor sedimentary organization, typical of a mid to distal alluvial fan deposit. An alluvial fan model suited to the Willaraddie Formation and a fluvial model suited to the Munabia Sandstone are described.

From palaeocurrent measurements in the formations and their field relationships a reconstruction of the basin of deposition as a wide, northerly-plunging graben with a faulted eastern margin of high relief can be postulated. The central portion of the graben was occupied by a braided fluvial system, while at the base of the fault scarp, alluvial fans accumulated and periodically prograded over the fluvial system. This reconstruction makes the Munabia Sandstone more extensive than previously thought, upgrading its importance as a potential petroleum reservoir.

INTRODUCTION

The Carnarvon Basin underwent a substantial change in shape in the Devonian with the world-wide rise of sea level (North, 1980). The initial deposit, the Nannyarra Sandstone, represents the reworking of the deep soil which had accumulated over a long period on the Precambrian craton. When this was exhausted clear water sedimentation commenced and the dominantly carbonate Gneudna Formation was deposited. This formation extends over a huge area, being recognized in bores from Carnarvon (Pelican Hill) northwards (Cape Cuvier 1) to near Exmouth Gulf (Pendock 1).

This phase of deposition was brought to an end by the reactivation of faults to the east of the present margin of the basin, again providing vast amounts of siliciclastic detritus from the continental block. These sediments have been subdivided into two formations: the dominantly clean sandstone of the Munabia Sandstone, and the Willaraddie Formation consisting of immature sandstone and conglomerate with minor clean sandstone. As the elevation of the source area was reduced, a period of non-deposition took place until a later sea-level rise in the Carboniferous started a new depositional cycle (Fig. 1).

The Devonian sediments outcrop in three meridional, westerly-dipping belts, the largest running from near Mount Sandiman homestead in the south to north of Williambury homestead, a distance of 95 km. The northern third is repeated by faulting west of the main belt and the southern third is preserved on a series of higher fault blocks east of the main belt (Fig. 1).

Probably because of the proximity of the obviously marine Gneudna Formation to the arenaceous formations, Condon (1965) assigned a marine depositional environment to the Munabia Sandstone and Willaraddie Formation. "The Munabia Sandstone was deposited in shallow sea water on a very slowly subsiding bottom; the terrigenous sediment was subjected to the action of waves and currents and a clean quartz sandstone was deposited in cross-laminated beds . . . the change of lithology into the Willaraddie Formation most probably indicates deeper water and a more rapidly subsiding floor." (Condon, 1965, p. 54). The purpose of this paper is to emphasize the depositional textural characteristics of the sediments, which enables a greater confidence in the interpretation of their depositional environment. Though marine sediments are present in the Munabia Sandstone, especially near the base, sedimentary textures indicate the bulk is of fluvial facies. For the Willaraddie Formation, textural criteria suggest an alluvial fan environment is most likely.

It is here suggested that the Munabia Sandstone and Willaraddie Formation are part of the one depositional event, the Willaraddie Formation is an alluvial fan and the Munabia Sandstone is the fluvially reworked distal equivalent.

ALLUVIAL FAN MODEL

Alluvial fans develop only adjacent to areas of high relief, commonly fault induced, where sediment is available in large quantities (Collinson, 1979). They have a radial symmetry in plan and can be subdivided into three main areas with distinctive morphology and sedimentary deposits, distributed in concentric zones. These are the proximal-fan, mid-fan and distal-fan zones (Fig. 2). The relative proportions of these zones varies from fan to fan, and are strongly influenced by climate and the state of vegetation of the landmass. In an arid climate the proximal and mid fan are strongly developed, whereas in a humid climate the proximal zone is insignificant but mid and distal zones are expanded (Collinson, 1979).

The proximal fan occurs near the point where the process of sediment transport becomes ineffectual and sediment is deposited. The flow is confined to deep channels by effective levees (Fig. 2). Proximal deposits are the coarsest in the fan and are typified by erosional bases and sedimentary features indicative of traction transportation processes (Collinson, 1979; Heward, 1978).

On the mid fan the levees are not as well developed so that channels anastomose and overbank deposits become important. Each channel is flanked by lobes of sediment separated by interlobe areas. The sediments of the depositional lobes contain both channel and overbank deposits ranging from debris flows to turbulent flows similar to channel deposits. The build-up of lobes also is an inducement for the abandonment of a channel and not only do channels migrate but they also tend to split into "tributaries". Overbank deposits usually are more abundant than channel sediments. The overall grain size in the mid fan is finer than in the proximal fan so that conglomerate becomes less significant and sand more important. The interlobe areas are sediment-starved and may accumulate fine-grained sediment of substantial lateral extent (Fig. 2). The proportion of lobe areas to interlobe areas varies largely from fan to fan (Collinson, 1979; Heward, 1978).

The distal fan is characterized by the presence of numerous channels which are free to migrate laterally. These sediments are therefore characterized by channel deposits of low sinuosity and may merge imperceptibly into adjacent fluvial deposits (Fig. 2), (Collinson, 1979; Heward, 1978).

FLUVIAL MODEL

Fluvial deposits are readily separated from the fan deposits on the criteria of grain size and maturity. Conglomerate is virtually absent, any that is present being of lag type. Sand shows greater maturity in content of labile grains, degree of sorting, and grain roundness (Figs 5a, b, c). Of the two major subdivisions of fluvial environments, a braided river environment appears to fit the Munabia Sandstone better than a meandering river environment. The lack of fine overbank deposits, the tendency for vertical rather than lateral accretion and the sedimentary structures present are better explained by braided stream deposition.

The principal factor controlling a braided stream is that the confining influences to the channel are low. Thus the channel has little permanency, which inhibits the development of large features such as point bars. Any overbank deposits which might have been deposited also have a low preservation potential because of large-scale lateral movement of the channels. A braided-river bed contains channels, which concentrate the flow of water, separated by a variety of bars and sand flats (Cant and Walker, 1978). For a greater part, erosion takes place in the channels, and aggradation on the bars and flats. Sand moves down the channels and across the bars as sand dunes, waves and ripples, and at times of falling flow may be left behind. Straight-crested dunes result in planar or cross-bedded strata, while those with curved crests produce trough cross-bedding. The falling flow regime also results in a vertical decrease in size of the structures and component sand grains of the deposited sediments (Cant and Walker, 1978; Coleman, 1969).

WILLARADDIE FORMATION

The Willaraddie Formation consists of three rock types in almost equal proportions; the dominant lithology is immature lithic wacke (Fig. 5A), pebbly sandstone is the next most abundant lithology (Fig. 5D), and more mature arenite (Fig. 5B) is the least common. Claystone is the only other lithology to have been deposited, but is usually only found as clasts in sandstone indicating its local presence.

The lithic wackes grade imperceptibly into the pebbly sandstones by an increase in grain size. Both lithologies are very immature texturally and mineralogically. The component grains are poorly size-sorted, and, except where larger grains have a better roundness, are angular in shape. Sphericity is also low, with length-width ratios of quartz grains up to 4:1 (Fig. 5A). The high content of heavy minerals scattered throughout the sand (Edwards, 1952) also indicates poor hydrological separation of grains. In the pebbly sandstones the clasts are always matrix-supported and rarely range up to 30 per cent of the rock in vertical section and 50 per cent in plan view. All the lithologies present as clasts in the conglomerate are present as grains in the wacke indicating a single continuum of supply.

Bedding features are poorly developed and beds are commonly massive. The conglomerate beds frequently show fining-upwards textures but occasionally coarsening-upwards textures are seen, though always only as a minor portion of the bed. Fining-upwards cycles continue from the pebbly sandstone into the sandstone (Fig. 5D), and can be detected when closely examined with a size comparator. Planar cross-bedding is found in both conglomerate and sandstone, but

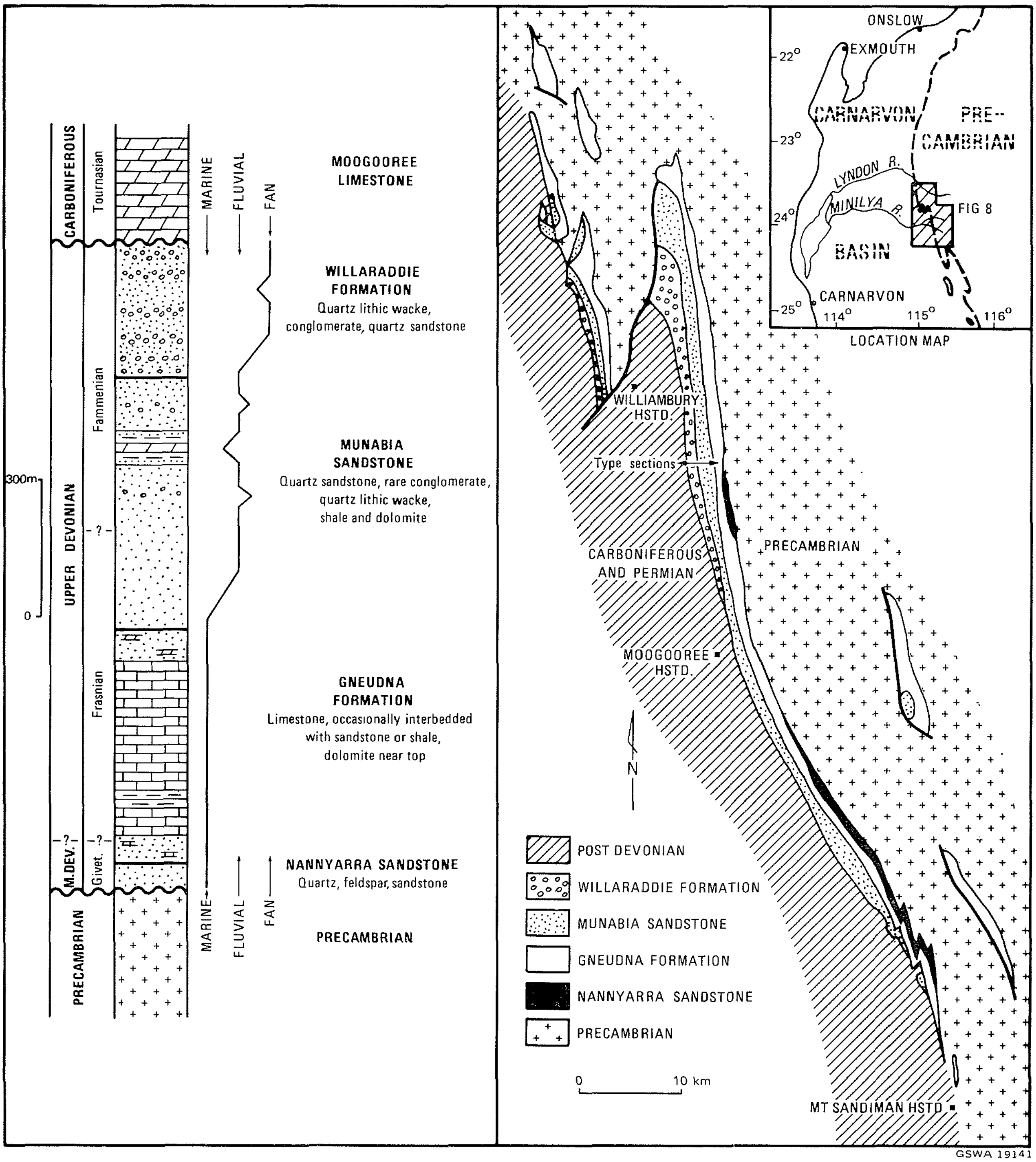

Figure 1 Distribution map of Devonian formations in the Carnarvon Basin, showing location of study area. A stratigraphic column shows the relative positions, age, environment, general lithology and thicknesses of the formations in their type section.

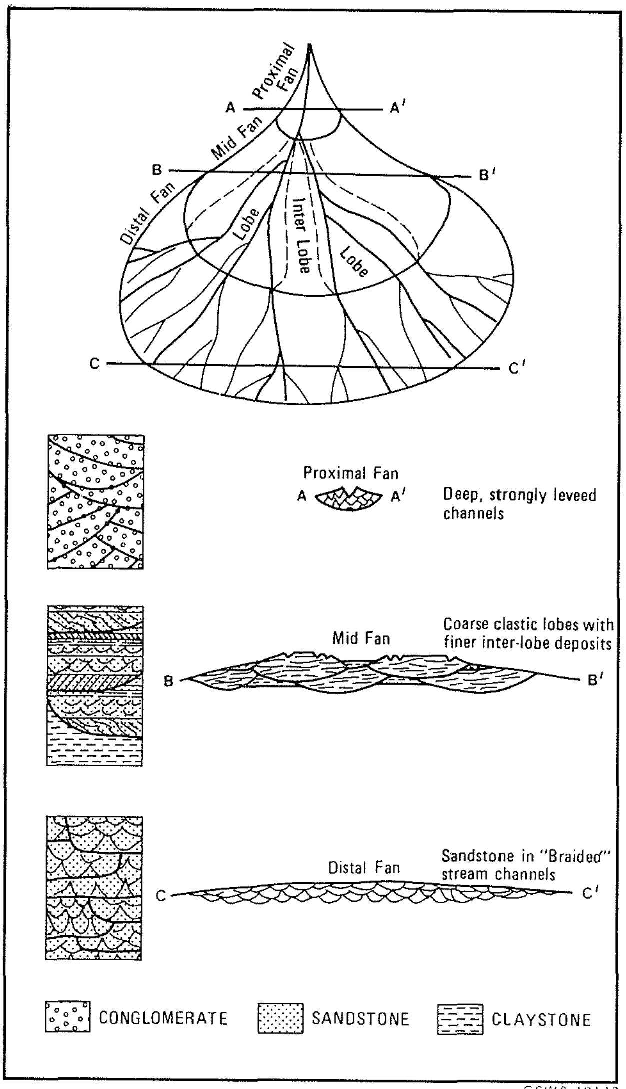

Figure 2 Alluvial fan model. Fan divisible into three zones—proximal, mid and distal. Sediments in proximal fan are the coarsest and were deposited chaotically in deep leveed channels. Mid fan is divided into: sediment lobes surrounding channels built up by overbank sheet-flood or debris flows; and interlobe areas where only fine overbank sediments are deposited in low swamps or lakes. In the distal fan anastomosing of streams has caused dissipation of energy to such a degree that only finest sediments are deposited in an almost fluvial environment. Cross-sections indicate relationships of depositional sequences. Columns represent typical cycles within sequences in respective parts of fan.

trough cross-bedding occurs in the sandstone only. Cross-bedding in the conglomerate beds may be outlined solely by flat clast orientation or strings of clasts, but it is usually obvious in the sandstone beds. Well-developed planar bedding is only present occasionally in the sandstone. No typical vertical sequence can be recognized and beds show a great variation in thickness. Conglomerate beds are usually less than 0·5 m in thickness, rarely passing 1 m, and sandstone beds are usually over 1 m but may also be thin units.

The presence of matrix-supported pebbly sandstones eliminates both traction and suspension as methods of transport of the sediments, and suggests some form of debris-flow mechanism. Though the bases of most coarse beds are sharp, erosion is minimal and the absence of any coarser lag deposit also suggests a temporary sheet flood rather than prolonged channel occupation. Such conditions occur in the mid-fan region of an alluvial fan, where most aggradation occurs, as lobes surrounding channels. True conglomerates are rapidly deposited, while progressively more clast-poor sediments and sands showing upper flow regime structures are indicative of more distal situations (Collinson, 1979). The Willaraddie Formation appears to be in such a distal mid-fan position, where debris flows begin to turn into sheet flood deposits of a more aqueous nature.

The cleaner sandstone, which forms the remainder of the formation, has different characteristics from those already described. It shows much better maturity, reflected in a reduction of labile components, better size sorting and rounding of grains, and shows clearer evidence of transportation by traction currents (Fig. 5B). Bedding is more prominent and becomes organized in a similar way to braided-stream deposits. Grain size decreases upwards and the amplitude of trough cross-bedding becomes smaller upwards, giving way to planar beds. The base may be erosional, though only mildly, but lag deposits of autochthonous clay clasts suggest some permanency of occupation of the channel. These cleaner sandstones represent either channel deposits on the mid fan, or distal fan deposits associated with a decrease in activity of the alluvial fan.

MUNABIA SANDSTONE

This formation is almost entirely sandstone; claystone and conglomerate occur only in minor amounts, and carbonate (dolomite) only occurs as a number of metre-thick beds at specific horizons. The sands themselves are divisible into two classes, those of marine origin and those of fluvial origin. The marine sand is thinly bedded and bedding is generally planar, though small scale planar cross-bedding (often in herringbone sets) occurs, and flaser to linsen fabric is also present. Apart from scarce conodonts, body fossils are absent, but trace fossils (living, resting and feeding traces) can commonly be found. Evidence of emergence in the form of impressions of desiccation flakes of claystone in sandstone also exists. In the field the marine sand is easily distinguished by its brown colour, terrestrial sand being a red colour.

On the other hand, the terrestrial sand contains no body or trace fossils except for rare plant impressions, is much more thickly bedded, and is usually clearly organized into vertical sequences of changing structures and decreasing size of structures and component grains. Typical cycles are illustrated in Figure 3. Usually the base is gently erosive, indicative of channel deposition, but this may only be obvious if there is a substantial grain size contrast across the contact. The initial bed may be a completely massive sand unit a few decimetres thick representing an unstructured lag deposit, but more commonly the lowermost unit is a single, planar to slightly curved cross-bedded set from 0·5 m to 2 m thick. This is interpreted as the result of the down-stream migration of a channel bar. Commonly the cross-bedding shows pronounced

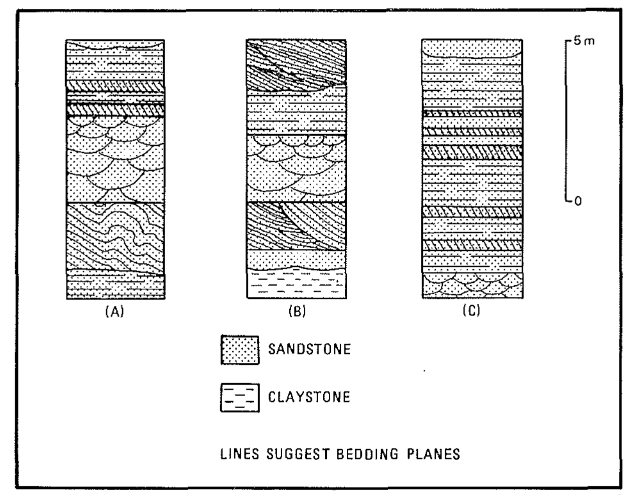

Figure 3 Typical cycles in the Munabia Sandstone, showing different structures present, their variation in size and relationship to each other, and variation in thickness.

(A) initial, thick, planar cross-bedding showing slumping, overlain by trough cross-bedding decreasing in size upwards, overlain by planar and small-scale planar bedding.

(B) coarse massive bed overlain by trough cross-bedding which may be either single or multiple, overlain by, upwardly-decreasing trough cross-bedding and thin planar bedding.

(C) alternations of thin planar bedding and small-scale planar cross-bedding.

distortion: gravity-sliding down the cross-beds resulting in crumpled, isoclinally folded and even overthrust laminae. Coleman (1969) suggested this could be due to increased shear stress accompanying a sudden increase in turbulence across the bar, or by the emergence of the depositing surface and increased hydrological head (see also Bluck, 1980). Rarely, the single cross-bed set may be subdivided into two or more smaller sets. Overlying this zone of planar cross-bedding is a zone of trough cross-bedding 1 m to 3 m in thickness formed when lunate mega-ripples are left behind by the falling water stage (Coleman, 1969). The fall in water-level stage is indicated by a decrease in the size of the sets and a decrease in constituent grain size vertically. The final component of the cycle is dominantly flat-bedded fine sand with occasional decimetre-high cross-bedded units which formed as lower flow regime units on emerging channel bars (Fig. 3C). The cross-bedding is produced by the migration of small-scale straight crested dunes. Rippling appears to be entirely absent.

These cycles range in thickness from 2 m to over 10 m. The internal zones also show a large range in the thickness and in the proportions of each. This is a function of the variation in size of bars in the river and also of the exact part of the bar exposed in outcrop.

Occasionally, the cycles are completed by a bed of silty claystone which may reach over a metre in thickness. The general absence of claystone is probably more a matter of preservation, as clasts of this lithology are frequently found as lag deposits or scattered on cross-bed laminations in some beds. The clay was deposited in temporarily abandoned channels from where it was rapidly eroded during re-occupation.

Zones 10 m to 20 m thick of dirty sand and pebbly sandstone occur occasionally in the formation. In the upper part of the type section a marine incursion is documented by the presence of a thick unit of greenish shale with a number of thin, yellow dolomite beds.

RELATIONSHIP OF WILLARADDIE FORMATION AND MUNABIA SANDSTONE

In all field occurrences, the Willaraddie Formation overlies the Munabia Sandstone. The contact is gradual with lithologies common to both sides, showing that the two formations are intimately related. However, from a study of the depositional environments, it seems plausible that they are coeval facies of the one depositional cycle, and that the overlying relationship is merely a reflection of the eventual progradation of the Willaraddie Formation into this part of the basin. Within the Munabia Sandstone type section, fine conglomerate beds with sheet-flood characteristics occur in association with quartz wacke (not mentioned in text by Condon, 1965, but indicated on his measured section, Fig. 22), and these represent earlier progradations of the edge of the Willaraddie alluvial fan into this area. These incursions were probably due to tectonic activity rejuvenating the provenance of the Willaraddie complex.

Figure 4 shows the three-dimensional relationship of the two formations in a block diagram. A segment has been removed for clarity, the corner of which represents approximately the type sections of the formations. A major fault with variation in throw bounds the basin and creates an upland to the east which provides large amounts of coarse detritus for the basin. Where each fluvial system emerged from the upthrown block an alluvial fan was built up and gradually prograded onto the fluvial plain. Because of the greater throw on the fault plane in the north, the more northerly fans may have prograded directly into the sea, as suggested by the presence of some poorly preserved marine fossils in the Willaraddie Formation (Condon, 1965). Where the fans were close together they may have interfered with each other or overlapped. The main fluvial plain contains a braided river system building up a widespread ribbon of sandstone parallel to the basin margin. When the build-up became too high, the whole river system moved laterally to commence building a new pile of sediment. Periodically, either because of a eustatic rise of sea level or activation

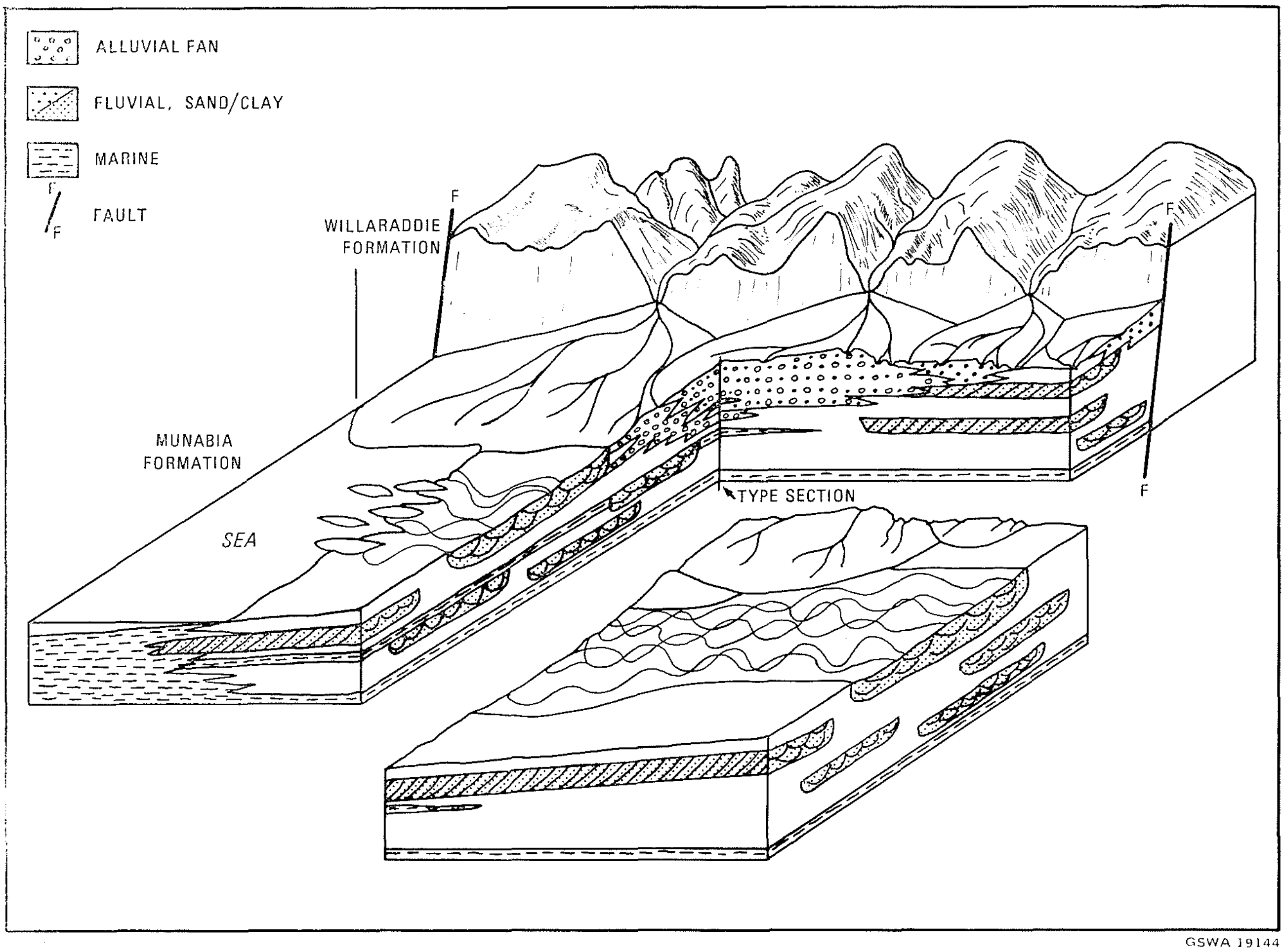

Figure 4 Three dimensional diagram of environment of deposition, and relationship of Munabia Sandstone and Willaraddie Formation. Bounding-fault creates elevated hinterland providing large amounts of sediment. Alluvial fans accumulate at the base of the fault (Willaraddie Formation) and prograde over fluvial plain. On the fluvial plain a braided river channel moves backwards and forwards depositing Munabia Sandstone. Either because of eustatic or tectonic sea-level rise, the shoreline encroaches periodically onto the fluvial plain or fan.

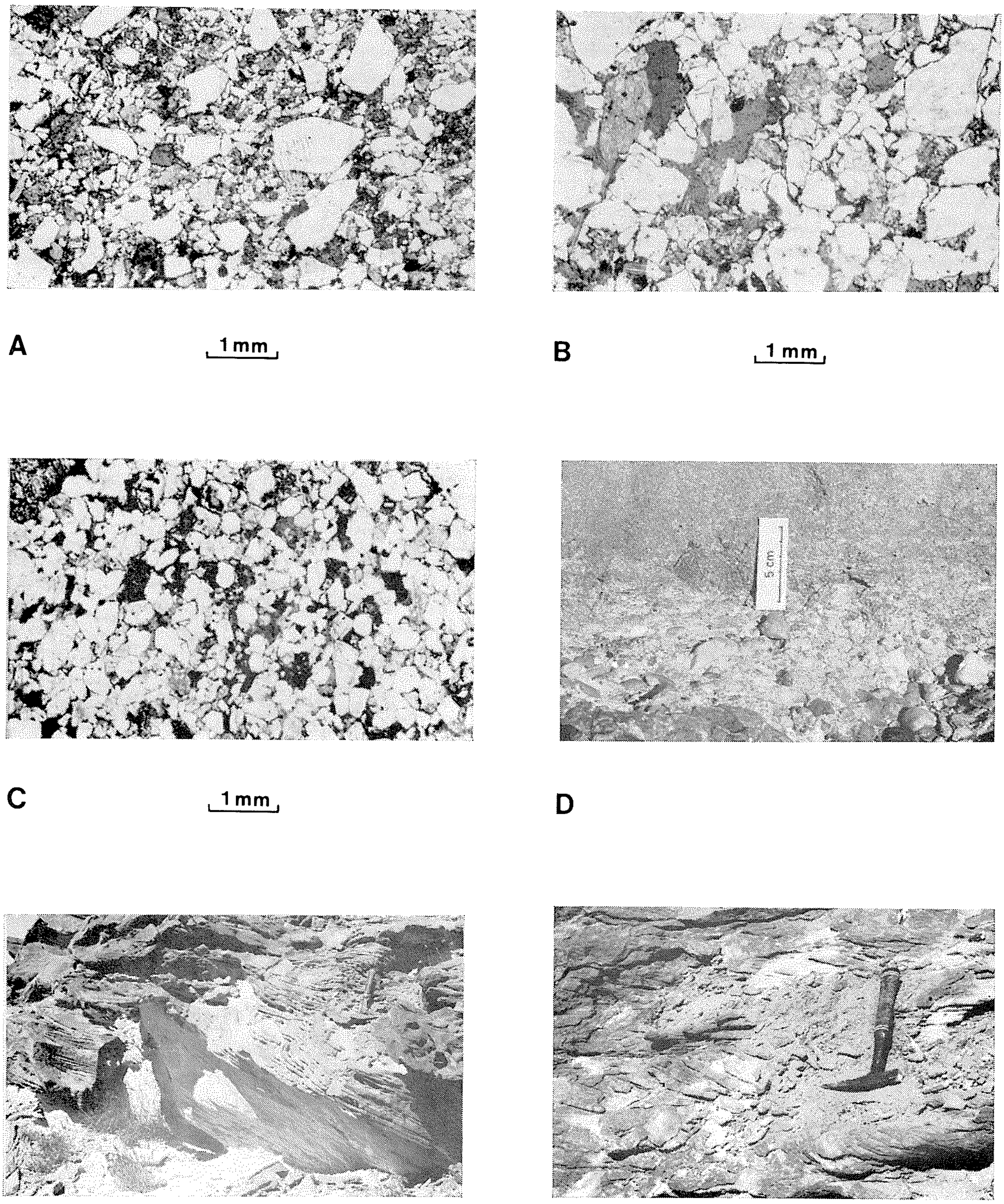

Figure 5 (A) Typical alluvial fan sand showing poor rounding, poor sorting and a high proportion and variation of lithic grains (Willaraddie Formation).

(B) Distal fan sediment showing improved rounding and sorting but great abundance of lithics (Munabia Sandstone).

(C) Typical fluvial sandstone showing relatively good sorting and rounding but still high lithic content, large scale cross-bedding (Munabia Sandstone).

(D) Unusually clast-rich and well-organised pebbly sandstone (Willaraddie Formation). Size of 'grains' decreases upwards with a sympathetic increase in matrix.

(E) Basal unit of fluvial cycle (Munabia Sandstone). Large scale cross-bedding shows strong gravity sliding. Note single cross-bed set replaced by two smaller sets to left.

Thin, pianar bedding and small scale cross-bedding typical of upper part of cycle (Munabia Sandstone).

of the bounding fault, the sea transgressed onto the land and carbonates and reworked sands were deposited. In this scheme sediments associated with the alluvial fans would be ascribed to the Willaraddie Formation, and those associated with the fluvial plain to the Munabia Sandstone.

The only part of the Willaraddie Formation which outcrops, represents a distal portion of the alluvial fan. Mid-fan and proximal-fan deposits with different characteristics would have been deposited originally but have since been removed by erosion. The Munabia Sandstone fluvial plain sediments are entirely sandy, either no overbank deposits accumulated or they were removed by erosion during re-establishment of the new river bed. The only shale and carbonate found in the unit are associated with marine conditions at the base of the formation, or related to a period of marine transgression in the upper part.

A large number of palaeocurrent directions were measured from cross-bedding in the Munabia Sandstone. Though varying in detail from location to location, all distributions showed a dominant current flow to the north-northwest. Because of the bad outcrop and poorly developed bedding, palaeocurrent data were less abundant in the Willaraddie Formation. Nevertheless, data from the type section confirmed the tectonic model, with transportation coming from the highland and along the fluvial plain in a north-northwest direction.

CONCLUSIONS

Towards the end of the Frasnian (Upper Devonian) the Carnarvon Basin underwent a phase of tectonism and the eastern margin became strongly faulted. A braided fluvial system flowing northwards became established on the down-thrown plain. At the same time the elevation of the Precambrian rocks created a prolific source of coarse material, and alluvial fans were built out from the base of the fault scarp on to the plain. From the field evidence, conglomeratic sediments associated with the fans have been included in the Willaraddie Formation, while the fluvial sands are placed in the Munabia Sandstone.

The effect of climate and rudimentary vegetation cover on the sediments requires more detailed examination. The probable poor stabilization of the soil by vegetation would have encouraged braided rather than meandering river morphology (Miall, 1980), but braiding could also have been in response to steep slopes or a large variation in river flow which was climatically controlled (Collinson, 1979). The present day red and white colouration of the sediments could be due to oxidation during the Holocene deep weathering profile or to the originally oxidizing conditions of deposition.

Condon (1965) downgraded the potential of the Munabia Sandstone as a reservoir by believing that the formation was a marine deposit fringing the basin. This thin ribbon of sand would have had little continuity down dip (westwards), changing rapidly to basinal clay. In this new interpretation, though the western boundary is still unknown, the Munabia Sandstone is expected to have substantial westerly extent, with no rapid deterioration of reservoir quality, and thus could be an important exploration target.

REFERENCES

Bluck, B. J., 1980, Structure, generation and preservation of upward fining, braided stream cycles in the Old Red Sandstone of Scotland: Trans. Roy. Soc. Edinburgh: Earth Sci. v. 71, p. 29–46.

Cant, D. J. and Walker, R. G., 1978, Fluvial processes and facies sequences in the sandy braided South Saskatchewan River, Canada: Sedimentology v. 25(5), p. 625–648.

Coleman, J. M., 1969, Brahmaputra River: channel processes and sedimentation: Sedimentary Geology v. 3, p. 129–239.

Collinson, J. D., 1979, Alluvial sediments, *in* Reading, H. G. (ed.), Sedimentary environments and facies: Blackwell, London, p. 15–60.

Condon, M. A., 1965, The geology of the Carnarvon Basin, Western Australia, Part I, pre-Permian stratigraphy: Australia Bur. Mineral Resources Bull. 77.

Edwards, A. B., 1952, Sandstones from the North West Basin: Mineragraphic Investigations No. 498: Australia Sci. and Industrial Research Organization, Melb.

Heward, A. P., 1978, Alluvial fan and lacustrine sediments from the Stephanian A and B (La Magdalena, Cinera-Matallana and Sabero) coalfields, northern Spain: Sedimentology v. 25, p. 451–488.

Miall, A. D., 1980, Cyclicity and the facies model concept in fluvial deposits: Canadian Petroleum Geol. Bull. v. 28(1), p. 59–80.

North, F. K., 1980, Episodes of source-sediment deposition, 2 The episodes in individual close-up: Jour. Petroleum Geol. v. 2(3), p. 323–338.

ESTIMATED PRESSURE AND TEMPERATURE CONDITIONS FROM SOME WESTERN AUSTRALIAN PRECAMBRIAN METAMORPHIC TERRAINS

by D. F. Blight and M. E. Barley

ABSTRACT

The pelitic mineral assemblage, garnet + cordierite + sillimanite + quartz, can be used to estimate pressure and temperature conditions during metamorphism. Comparison of preliminary results from Archaean and Proterozoic medium-to high-grade metamorphic terrains in Western Australia suggests that this assemblage equilibrated at similar temperatures, but consistently lower pressure in the Archaean terrains.

INTRODUCTION

Only broad generalizations about metamorphic conditions can be obtained from most studies of regional metamorphism in Precambrian terrains. However, recent experimental determinations of the stability fields and compositions of co-existing minerals (see review by Green, 1977) provide the potential for estimating the actual pressures and temperatures at which co-existing minerals equilibrated during metamorphism. In this study we have used thermo-chemical considerations and experimental data for the mineral assemblage, garnet + cordierite + sillimanite + quartz, to estimate pressure and temperature conditions for Precambrian metamorphic terrains in Western Australia. This assemblage occurs in pelitic gneisses in both the Archaean Yilgarn Block and the surrounding Proterozoic mobile belts, and is placed in the upper amphibolite to lower granulite facies (Binns, 1964; Winkler, 1975).

THEORY

The assemblage, garnet + cordierite + sillimanite + qua results from the reaction

3(Fe-Mg) cordierite = 2(Mg-Fe) garnet + 4 sillimanite + 5 quartz.

At equilibrium this may be considered as an exchange reaction thus:

(Fe) garnet + (Mg) cordierite = (Mg) garnet + (Fe) cordierite.

The distribution coefficient, Kd, can be calculated from the following equation:

$$Kd = \left(\frac{X_{Mg}^{cord}}{1-X_{Mg}^{cord}}\right)\left(\frac{X_{Fe}^{gnt}}{1-X_{Fe}^{gnt}}\right)$$

where X_a^b is the mole fraction of component 'a' in phase 'b'

For the above reaction Kd will be dependent upon the pressure and temperature of equilibrium. Using known thermo-chemical data and laboratory experiments it is possible to calibrate this reaction and use it to estimate the pressure and temperature at which natural assemblages equilibrated. Calibrations have been published by Currie (1971), Hensen and

Green (1973), Hutcheon and others (1974) and Wells (1979). The calibrations of Hensen and Green, and Hutcheon and others are considered unsuitable and have been rejected, chiefly because when applied to natural assemblages they give results which fall outside the stability field of sillimanite, an integral component of the equilibrium reaction. For a more detailed discussion see Blight and Oliver (in press).

SAMPLES ANALYSED

Figure 1 is a simplified geological map of part of Gondwana which now comprises southwestern Australia and part of Antarctica. The locations of analysed samples are plotted on this map showing their geological environment. Precise locations and petrographic details of the samples are presented in the Appendix. All samples are pelitic gneisses.

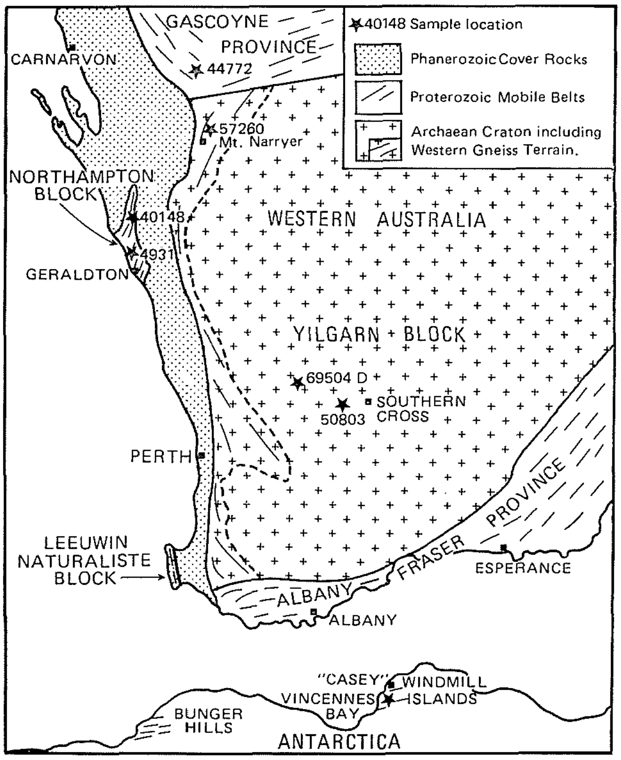

Figure 1 Sample locations shown on a simplified geological map of southwestern Australia and part of Antarctica using the "pre-drift" reconstruction of Norton and Molnar (1977).

Samples 4931, 40148 and 44772 are from Proterozoic mobile belts which surround the Yilgarn Block. Samples 4931 and 40148 are from sequences of pelitic gneisses with intercalated quartzites and mafic granulites within the Northampton Block. Compston and Arriens (1968) considered that these rocks were metamorphosed approximately 1 000 m.y. ago. Sample 44772 is from a sequence of pelitic and quartzofeldspathic gneisses in the Gascoyne Province. It is considered that this sequence is part of the Archaean Western Gneiss Terrain, which has experienced high-grade metamorphism during a major early Proterozoic tectonothermal event (S. J. Williams, pers. comm.). Data obtained from pelitic gneisses from the Windmill Islands, Antarctica (Blight and Oliver, in press) have been included in this study for comparison with the Western Australian data. According to the most favoured pre-drift continental reconstruction, it is considered that the Proterozoic metamorphic terrain in the Windmill Islands is an extension of the Albany-Fraser Province mobile belt (Fig. 1). This view was supported by Oliver (1971) who noted the geological similarity of the Windmill Islands and the Albany-Fraser Province. Thus the pressure-temperature estimates from the Windmill Islands (Table 2) contribute to the circum-Yilgarn data.

Samples 50803, 57260 and 69504D are from the Archaean Yilgarn Block. Sample 57260 is from a sequence of pelitic and quartzofeldspathic gneisses in the Western Gneiss Terrain of Gee and others (in press), near Mount Narryer. Whole-rock Rb-Sr isotopic data indicate that this sequence was metamorphosed approximately 3 350 m.y. ago (de Laeter and others, 1981). Samples 50803 and 69504D are from sequences of medium- to high-grade metamorphosed sedimentary and igneous rocks in small greenstone belts in the granitoid-greenstone terrain, adjacent to its boundary with the Western Gneiss Terrain. It is considered that these samples were metamorphosed during the major tectonothermal event which affected the Southern Cross Province 2 600–2 700 m.y. ago (Chapman and others, in press).

RESULTS

The compositions of the coexisting cordierite and garnet were determined using a MAC electron microprobe. Compositions were determined a number of times using both crystal spectrometers and an energy-dispersive multichannel analyser. Garnets were checked for zoning either by scans across the grains (Fig. 2) or by spot analyses of both the cores and rims of single grains. No zoning was found. Analytical results are listed in Table 1. Elemental concentrations given are mean values of a number of determinations. Analyses of four cordierite-garnet pairs from sample 69504D indicate that the range in estimated pressure and temperature values is $\pm$ 10 MPa and $\pm$ 15°C for either calibration.

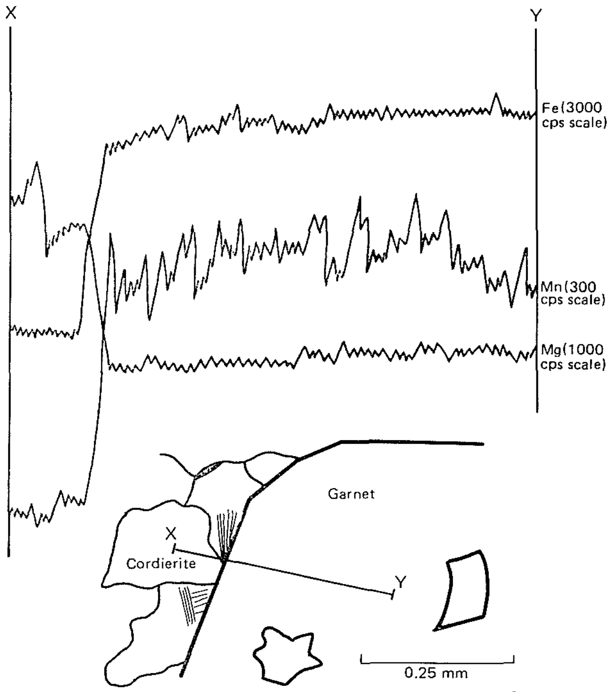

Figure 2 Graphical readout of counts per second of Fe, Mn and Mg wavelength spectrometers, during a traverse from a cordierite grain across an abutting garnet grain in sample 50803, as shown in the accompanying sketch.

When applying the calibrations of Currie (1971) and Wells (1979) to natural assemblages the following conditions should be satisfied:

(1) attainment of equilibrium, at least with regard to partitioning between iron and magnesium;

(2) reasonable freedom of the cordierite and garnet from cations which would complete with Fe^{2+} and Mg for lattice positions; and

(3) besides garnet and cordierite the investigated assemblages must also contain sillimanite and quartz.

Only rocks satisfying condition (3) were chosen for this study. Condition (1) is more difficult to determine. The absence of disequilibrium textures (with the possible exception of 44772) and the lack of zoning within the garnets suggest that equilibrium has been reached.

The only major cation in these minerals which would compete with Fe^{2+} and Mg for site occupancy is Mn. The effect of Mn has not been studied in any great detail; however, Weisbrod (1973) has shown that the presence of 25 mole per cent spessartite in garnet could reduce the equilibrium pressure by about 100 MPa. As most of these samples contain less than 5 mole per cent spessartite the influence of Mn on their equilibrium position is probably minimal. Samples 57260 and 69504D contain slightly more Mn, approximately 10 and 15 mole per cent spessartite respectively, so that Mn may have some influence on their equilibrium position. This influence is unlikely to be very large, perhaps in the order of 50 MPa.

TABLE 1. ANALYSES OF CO-EXISTING GARNET AND CORDIERITE ASSEMBLAGES FROM ARCHAEAN AND PROTEROZOIC METAMORPHIC TERRAINS IN WESTERN AUSTRALIA, AND CALCULATED PRESSURE AND TEMPERATURE ESTIMATES.

Sample	4931		40148		44772		50803		57260		69504D	
Mineral	gnt	cord	gnt	cord	gnt	cord	gnt	cord	gnt	cord	gnt	cord
SiO_2	36·05	48·35	37·02	49·45	36·73	49·36	36·48	47·74	35·55	47·77	36·65	48·72
Al_2O_3	21·47	33·85	21·70	34·15	21·39	34·30	21·35	32·59	21·05	33·56	20·28	32·65
FeO	36·05	9·68	33·16	6·70	34·04	6·10	38·40	14·15	37·85	11·68	36·56	12·51
MnO	0·85	....	0·84	....	1·11	....	1·25	0·16	2·05	0·10	3·11	0·30
MgO	4·49	8·01	6·32	9·65	5·69	10·24	1·75	4·75	2·66	6·69	1·94	5·78
CaO	0·96	....	0·93	....	0·96	....	0·60	0·02	0·60	....	1·33	....
Total	99·86	99·89	99·93	99·95	99·92	100·00	99·83	99·42	99·76	99·80	99·87	99·96
Kd*	6·813		7·552		10·047		7·400		8·203		8·747	
P–T estimates: A. Using method of Currie (1971)												
P (MPa)	570		630		650		460		510		480	
T (°C)	741		765		838		760		785		800	
P–T estimates: B. Using method of Wells (1979)												
P (MPa)	630		700		660		520		550		530	
T(°C)	677		603		562		657		622		607	

* Kd: distribution coefficient

Results of the application of the calibrations of Currie (1971) and Wells (1979) are given in Table 1 and displayed on Figure 3. Data from the Windmill Islands, Antarctica are given in Table 2 and also shown on Figure 3.

DISCUSSION

As can be seen from Figure 3 the estimates of pressure obtained using the calibration of Wells (1979) are approximately the same as those obtained using the calibration of Currie (1971). However, temperatures obtained from the Wells calibration are significantly lower than those obtained from the Currie calibration. This results from the fact that different relationships between the distribution co-efficient (Kd) of Fe^{2+} and Mg between cordierite and garnet, and temperature have been reported for the various sets of experimental data on which these calibrations are based. Other mineralogical data (discussed below) do not indicate clearly which is the more realistic calibration. However, while further experimental work is required to establish the correct relationship between Kd and temperature, it is significant that there are only minor differences in the range of pressure-temperature gradients indicated (Fig. 3).

With the exception of sample 44772, the Proterozoic samples we have studied form a cluster of points on Figure 3, indicating pressures of 560–650 MPa and temperatures between 740 and 800°C (using the calibration of Currie, 1971) or 600–700 MPa and 600–680°C (using the calibration of Wells, 1979). The absence of muscovite and the occurrence of anatectic phenomena in felsic gneisses in the Northampton Block (Playford and others, 1970, p. 11 and 12), restrict pressure and temperature

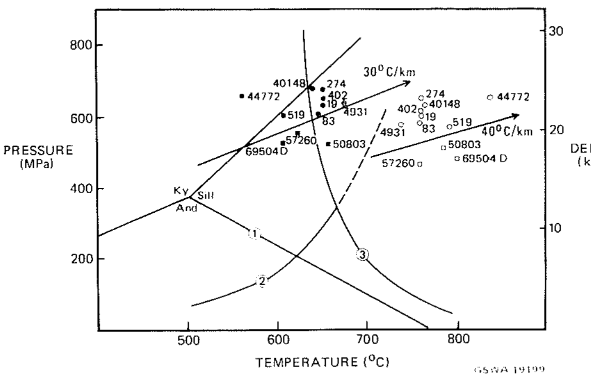

Figure 3 Plot of calculated pressure-temperature conditions of Archaean (squares) and Proterozioc (circles) garnet-cordierite pairs using the calibrations of Currie (1971; open symbols) and Wells (1979; closed symbols).

(1) Al_2SiO_5 stability fields (Holdaway, 1971)

(2) Muscovite breakdown curve (Evans, 1965; Kerrick, 1972)

(3) Melting curve of water-saturated granite (Luth and others, 1964)

conditions for these gneisses to the field above the water-saturated granite-melting curve (Fig. 3), if water pressure was equal to lithostatic pressure during metamorphism. Under these conditions melting in felsic gneisses would be well advanced at temperatures approximately 150°C above the water-saturated granite-melting curve. However, if water pressure was less than lithostatic pressure during metamorphism (i.e. if metamorphism involved a mixed vapour phase or was vapour free) then the stability field of muscovite would be extended as shown on Figure 3 (Kerrick, 1972), and the beginning of melting would occur at higher temperatures than those indicated by the calibration of Wells (1979). The existence of a CO_2-rich vapour phase during granulite facies metamorphism has been suggested by several authors (e.g., Hoefs and Touret, 1975; Collerson and Fryer, 1978).

Sample 44772 plots well into the kyanite stability field using the calibration of Wells (1979), suggesting that either the calibration is incorrect or one of the assumptions regarding the suitability of this sample was incorrect. It is possible that the biotite and sillimanite intergrowths surrounding many cordierites in this sample are the result of the partial breakdown of cordierite to biotite and sillimanite with decreasing temperature after peak metamorphic conditions had been reached or during a period of retrogression. If this is the case, then garnet (which is particularly unreactive under these conditions) would no longer be in equilibrium with the cordierite, rendering meaningless the estimated metamorphic conditions (using either calibration).

The cluster of Proterozoic points on Figure 3 suggests that the pressure and temperature conditions indicated are typical of Proterozoic high-grade regional metamorphism in the mobile belts which surround the Yilgarn Block. The estimated pressure-temperature conditions (using either calibration) fall within the range of pressure-temperature conditions reported for similar Proterozoic terrains by Watson (1978). Also, the geothermal gradients indicated fall within the range of modern regionally maintained crustal geotherms, which range from less than 10°C/km for continental cratons to about 50°C/km in island arcs and other active plate margins (Watson, 1978).

The three Archaean samples studied indicate pressure of 460–510 MPa and temperatures of 760–780°C (using the calibration of Currie, 1971) or 520–550 MPa and 600–660°C (using the calibration of Wells, 1979). The abundance of amphibole and other hydrous minerals in lithologies associated with these samples suggests that the assumption that water pressure was equal to lithostatic pressure during metamorphism is geologically reasonable in this case. Consequently, the presence of muscovite in sample 69504D and the absence of anatectic phenomena in associated felsic gneisses favour the pressure and temperature range indicated by the calibration of Wells (1979). The values obtained are comparable with estimates of 300–500 MPa and 600–680°C obtained by Binns and Groves (1976) for mid to high amphibolite facies metamorphism at Perseverance.

It is considered that the Western Gneiss Terrain represents an older (3350 m.y.) metamorphosed and repeatedly deformed continental sedimentary sequence, which surrounds and underlies the granitoid-greenstone terrain (Gee and others, in press; de Laeter and others, 1981). This basement was partly remobilized during the major tectonothermal event (2 600–2 700

TABLE 2. CALCULATED PRESSURE AND TEMPERATURE ESTIMATES FOR CO-EXISTING GARNET-CORDIERITE ASSEMBLAGES FROM THE WINDMILL ISLANDS PROTEROZOIC METAMORPHIC TERRAIN

[See Blight and Oliver (in press) for details]

Sample	335/19	335/83	335/274	335/402	335/519
Kd*	7·354	7·445	7·453	7·389	8·476
P–T estimates: A. Using method of Currie (1971)					
P(MPa)	610	580	650	610	570
T(°C)	760	762	762	760	794
P–T estimates: B. Using method of Wells (1979)					
P(MPa)	635	600	675	650	600
T(°C)	653	650	650	652	610

* Kd: distribution coefficient

m.y.) which was responsible for the essentially solid-state emplacement of a suite of pre- and syntectonic granitoids and the regional deformation and metamorphism of greenstone sequences. The greenstone sequences were deposited immediately prior to, and during, this episode. Tectonic activity culminated with the widespread emplacement of a suite of magmatic post-tectonic granitoids.

Samples from both the Western Gneiss Terrain and the granitoid-greenstone terrain indicate similar pressure and temperature conditions, suggesting that they are typical of Archaean regional metamorphism at this grade in the Yilgarn Block. The geothermal gradients indicated (from 30°C/km to 45°C/km, depending on calibration used) are higher than equilibrium continental geothermal gradients estimated for the Archaean by Bickle (1978), namely 1·2 to 1·5 heat flow units (equivalent to 25–30°C/km), and within the range of geothermal gradients reported for other granitoid-greenstone and gneiss terrains (Watson, 1978). The widespread occurrence of andalusite in greenstone belts within the Yilgarn Block (Binns and others, 1976) indicates that low-pressure metamorphism (i.e. with geothermal gradients of greater than about 40°C/km) was typical in low- to medium-grade metamorphic terrains. Extrapolation of this trend to the medium- to high-grade terrains reported in this study indicates that the regional metamorphic geotherm observed in the granitoid-greenstone terrain is convex towards the temperature axis of Figure 3, if the calibration of Wells (1979) is used.

The Yilgarn Block is considered to have been relatively stable since Archaean times (Gee and others, in press). Its present crustal thickness ranges from 32 km at Kalgoorlie to about 46 km at the western edge (Gee and others, in press). Our pressure-temperature estimates of those rocks from the Yilgarn Block indicate that they formed at depths around 17 km (Fig. 3). This presumably has since been eroded away, but when added to the present crustal thickness implies that the crust of the Yilgarn Block during Archaean times was in the range of 50–60 km thick. Any evolutionary model for the Yilgarn Block would need to take this considerable thickness into account.

Both calibrations produce two distinct fields of equilibrium conditions. The samples from Archaean terrains indicate similar temperatures, but consistently lower pressures than the samples from Proterozoic terrains. An apparently obvious conclusion that can be drawn from these data is that the Archaean geothermal gradients were greater than those in the Proterozoic terrains. However, this is very much an over-simplification.

Because heat generation from the decay of radioactive nuclides in the earth was much greater in the Archaean, much discussion has revolved around the probability that Archaean geothermal gradients were steeper than those of later times. However, in a comprehensive discussion of Precambrian thermal regimes, Watson (1978) has outlined some of the difficulties encountered in establishing this premise. Evaluation of former thermal regimes depends not only on the estimation of geothermal gradients from individual localities, but also on the correct assessment of the proportion of the crust for which they are representative. Within the framework of modern plate tectonic processes a number of different thermal regimes exist. For example, tectonic environments such as mid ocean ridges and island arcs have higher heat flows and thus higher geothermal gradients than stable continental or oceanic crust. While it is usually possible to distinguish crustal environments for which differing geothermal gradients can be inferred in Phanerozoic and Proterozoic terrains, the recognition of Archaean tectonic environments is much less certain.

Another problem encountered is that metamorphic mineral assemblages do not always reflect equilbrium geothermal conditions. This problem has been reviewed by England and Richardson (1977) who concluded that estimates of geothermal gradients from areas characterized by igneous activity will be biased towards values higher than the equilibrium gradients. Consequently, the mineral assemblages of rocks exposed at the surface in a terrain where crustal thickening and subsequent metamorphism and deformation has been the result of the addition of hot magma, will indicate a metamorphic geotherm convex towards the temperature axis on a pressure-temperature diagram. Estimates of geothermal gradients from terrains which have undergone overthrusting and subsequent burial metamorphism can either be higher or lower than the equilibrium gradient, depending on the depth of burial and rate of uplift. Precambrian amphibolite and granulite facies mineral assemblages presumably equilibrated at sufficient depths such that heating during uplift is unlikely to have elevated the thermal gradient significantly above the equilibrium value.

Nevertheless, despite these uncertainties, some general observations are possible. There is a growing opinion that plate-tectonic processes such as those which have operated from Phanerozoic times onward did not operate during Archaean times (Kroner, 1979; Gorman and others, 1978; and Binns and others, 1976). Furthermore, the Yilgarn Block lacks blue-schist metamorphics (Binns and Marston, 1976), and calc-alkaline volcanism is random in distribution rather than conforming to an island arc pattern (Giles, in press). It is also becoming apparent that the Yilgarn Block greenstones formed on sialic crust (Gee and others, in press), thus precluding a mid-ocean-ridge environment.

As the Archaean metamorphosed greenstone belts formed during a major tectonothermal event they reflect a zone of higher heat flow than normal continental crust of that time. The thermal regime represented by the Western Gneiss Terrain is more difficult to evaluate; however, most likely, it represents an Archaean mobile zone and, as such, would also represent a higher heat flow than stable continental crust of similar times. The Proterozoic samples we have examined all come from mobile belts and thus reflect zones of higher heat flow than stable Proterozoic continental area.

Thus, all the samples we have examined are manifestations of zones of higher heat flow than time-equivalent stable continental areas. More difficult to evaluate is the relative flux strength of these higher heat-flow zones. Because the Archaean greenstone rocks formed under a comparable pressure-temperature regime to these rocks of the Western Gneiss Terrain, which in turn are considered to have formed under similar tectonic conditions to the Proterozoic samples (namely, mobile zones) all the rocks examined by us should have relatively the same pressure-temperature conditions of formation. These data indicate this is not the case, and, thus, we conclude that the apparent difference in heat flow, as reflected in geothermal gradients, from the earth in Archaean times compared with that in Proterozoic times, is real.

CONCLUSIONS

Preliminary estimates of pressure-temperature conditions during metamorphism suggest that Archaean pelitic gneisses from the Yilgarn Block equilibrated at similar temperatures, but at lower pressures than Proterozoic pelitic gneisses in the surrounding mobile belts.

We believe this distinction is real and reflects fundamental differences in the thermal regimes of Archaean and Proterozoic metamorphic terrains. There is clearly a need for further studies of this and other suitable mineral assemblages to establish more precisely the variations in pressure and temperature conditions which occurred during the evolution of Precambrian metamorphic terrains in Western Australia.

APPENDIX

4931 Location: Northampton Block. Lat. 28°26′10″S, long. 114°44′27″E.

Geological setting: Proterozoic mobile belt; dominantly pelitic gneisses with intercalated quartzites and mafic granulites. Age of metamorphism approximately 1 000 m.y. (Compston and Arriens, 1968).

Description: A pelitic gneiss with a granoblastic polygonal to interlobate texture, with grain size ranging from 0·1 mm to 4 mm. The mineral assemblage is quartz, cordierite, microcline (perthitic), plagioclase, garnet, sillimanite and biotite, with minor fine-grained opaques. Myrmekite is locally developed where plagioclase and microcline are in contact. A weak parallelism of sillimanite prisms and biotite plates defines a gneissic foliation.

40148 Location: Northampton Block. Lat. 27°50′04″S, long. 114°44′16″E.

Geological setting: As for sample 4931.

Description: A pelitic gneiss with a seriate, granoblastic elongate texture, with grain size ranging from 0·1 mm to 3 mm and some large porphyroblasts of garnet up to 6 mm in size. The mineral assemblage is quartz, cordierite, microcline (perthitic), plagioclase, garnet, sillimanite and biotite, with minor fine-grained opaques. Large garnet porphyroblasts are commonly poikiloblastic. The granoblastic elongate texture and strong parallelism of sillimanite prisms and biotite plates define a gneissic foliation.

44772 Location: Gascoyne Province. Lat. 25°21′40″S, long. 116°11′20″E.

Geological setting: Proterozoic mobile belt; sequence of pelitic and quartzofeldspathic gneisses. Age of metamorphism early Proterozoic (S. J. Williams, pers. comm.).

Description: A pelitic gneiss with a granoblastic elongate texture, with grain size ranging from 0·1 mm to 2 mm. The mineral assemblage is quartz, cordierite, plagioclase, garnet, sillimanite and biotite, with minor microcline and fine-grained opaques. Cordierite is commonly rimmed by fine intergrowths of biotite and sillimanite. The granoblastic elongate tecture and strong parallalism of sillimanite prisms and biotite plates define a gneissic foliation.

50803 Location: Yilgarn Block. Lat. 31°17′30″S, long. 118°38′30″E.

Geological setting: Archaean granitoid-greenstone terrain; sequence of pelitic gneisses, mafic and ultramafic emphibolites and granulites within a small greenstone belt. Age of metamorphism is 2 600–2 700 m.y. (Chapman and others, in press).

Description: A pelitic gneiss with a seriate granoblastic interlobate texture, with grain size ranging from 0·02 mm to 2 mm and with some large porphyroblasts of garnet up to 5 mm in size. The mineral assemblage is quartz, cordierite, plagioclase, garnet, fibrolitic sillimanite, and biotite, with some minor fine-grained opaques. Sillimanite occurs in clusters with a strong preferred orientation and, with biotite plates, defines a gneissic fabric.

57260 Location: Yilgarn Block. Lat. 26°31′30″S, long. 116°23′00″E.

Geological setting: Archaean gneiss terrain; sequence of pelitic and quartzofeldspathic gneisses. Age of metamorphism approximately 3 350 m.y. (de Laeter and others, 1981).

Description: A pelitic gneiss with a granoblastic polygonal to interlobate texture with grain size ranging from 0·05 mm to 2 mm. The mineral assemblage is quartz, cordierite, plagiclase, garnet, sillimanite and biotite, with minor fine-grained opaques. Parallelism of sillimanite prisms and biotite plates defines a gneissic foliation.

69504D Location: Yilgarn Block. Lat. 30°54′50″S, long. 117°49′10″E.

Geological setting: Archaean granitic-greenstone terrain; sequence of pelitic gneisses and para-amphibolites within a small greenstone belt. Age of metamorphism 2 600–2 700 m.y. (Chapman and others, in press).

Description: A fine-grained pelitic gneiss with a granoblastic elongate texture (average grain size, 0·25 mm). The mineral assemblage is quartz, cordierite, plagioclase, garnet, sillimanite and biotite, with minor muscovite and fine opaques. Larger garnet and cordierite grains are commonly poikiloblastic. The granoblastic elongate texture and strong parallelism of sillimanite prisms and biotite plates define a gneissic foliation.

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REFERENCES

Bickle, M. J., 1978, Heat loss from the earth: a constraint on Archaean tectonics from the relation between geothermal gradients and the rate of plate production: Earth and Planetary Sci Letters, v. 40, p. 301–315.

Binns, R. A., 1964, Zones of progressive metamorphism in the Willyama Complex, Broken Hill District, New South Wales: Geol. Soc. Australia Jour., v. 11, p. 283–330.

Binns, R. A., and Groves, D. I., 1976, Iron-nickel partition in metamorphosed olivine-sulfide assemblages from Perseverance, Western Australia: American Mineralogist, v. 61, p. 782–787.

Binns, R. A., Gunthorpe, R. J., and Groves, D. I., 1976, Metamorphic patterns and development of greenstone belts in the eastern Yilgarn Block, Western Australia: *in* Windley, B. F. (ed.), The early history of the Earth: London, Wiley, p. 303–313.

Binns, R. A., and Marston, R. J., 1976, Archaean geology of the Yilgarn Block, Western Australia: 25th I.G.C. Excursion Guide No. 40A.

Blight, D. F., and Oliver, R. L., in press, Aspects of the geological history of the Windmill Islands, Antarctica: *in* Craddock, C. (ed.), Antarctic Geoscience: University of Wisconsin Press.

Chapman, H. J., de Laeter, J. R., Gorton, M. P., Anderson, L. S., Bettenay, L. F., Bickle, M. J., Binns, R. A., and Groves, D. I., in press, Isotopic study of granitic rocks from the Central Yilgarn Block, Western Australia: Geol. Soc. Australia, Special Pub. 7.

Collerson, K. D., and Fryer, B. J., 1978, The role of fluids in the formation and subsequent development of early continental crust: Contr. Miner. Petrol. v. 67, p. 151–167.

Compston, W., and Arriens, P. A., 1968, Precambrian geochronology of Australia: Canadian Jour. Earth Sci., v. 5, p. 561–583.

Currie, K. L., 1971, The reaction 3 cordierite = 2 garnet + 4 sillimanite + 5 quartz as a geological thermometer in the Opincon Lake Region, Ontario: Contr. Miner. Petrol., v. 33, p. 215–226.

de Laeter, J. R., Williams, I. R., Rosman, K. J. R., and Libby, W. G., 1981, A definitive 3 350 m.y. age from banded gneiss, Mount Narryer area, Western Gneiss Terrain: West. Australia Geol. Survey Ann. Rept 1980, p. 94–98.

England, P. C., and Richardson, S. W., 1977, The influence of erosion upon the mineral facies of rocks from different tectonic environments: Geol. Soc. London Jour., v. 134, p. 201–213.

Evans, B. W., 1965, Application of a reaction rate method to the breakdown equilibria of muscovite and muscovite plus quartz: American Jour. Sci., v. 263, p. 647–667.

Gee, R. D., Williams, I. R., Wilde, S. A., and Baxter, J. L., in press, Crustal evolution of the Yilgarn Block: Geol. Soc. Australia, Special Pub. 7.

Giles, C., in press, Archaean calc-alkaline volcanism in the Eastern Goldfields Province of Western Australia: Geol. Soc. Australia, Special Pub. 7.

Gorman, B. E., Pearce, T. H., and Birkett, T. C., 1978, On the structure of Archaean Greenstone Belts: Precambrian Research, v. 6, p. 23–41.

Green, D. H., 1977, Experimental petrology related to extreme metamorphism: Tectonophysics, v. 43, p. 1–5.

Hensen, B. J., and Green, D. H., 1973, Experimental study of cordierite and garnet in pelitic compositions at high pressures and temperature: III. Synthesis of experimental data and geological applications: Contr. Miner. Petrol. v. 38, p. 151–166.

Hoefs, J., and Touret, J., 1975, Fluid inclusions and carbon isotope study from Bamble granulites (south Norway): Contr. Miner, Petrol., v. 52, p. 165–174.

Holdaway, M. J., 1971, Stability of andulasite and the aluminium silicate phase diagram: American Jour. Sci., v. 271, p. 97–131.

Hutcheon, I., Froese, E., and Gordon, T. M., 1974, The assemblage quartz-sillimanite-garnet-cordierite as an indicator of metamorphic conditions in the Daly Bay Complex, NWT: Contr. Miner. Petrol., v. 44, p. 29–34.

Kerrick, D. M., 1972, Experimental determination of muscovite and quartz stability with $P_{H_2O} < P_{TOTAL}$: American Jour. Sci., v. 272, p. 946–958.

Kroner, A., 1979, Precambrian crustal evolution in the light of plate tectonics and the undation theory: Geologie en Mijnbouw, v. 58, p. 231–240.

Luth, W. C., Jahns, R. H., and Tuttle, O. F., 1964, The granite system at pressures of 4 to 7 kilobars: Jour. Geophysical Research, v. 69, p. 759–773.

Norton, I., and Molnar, P., 1977, Implications of a revised fit between Australia and Antarctica for the evolution of the eastern Indian Ocean: Nature, v. 267, p. 338–340.

Oliver, R. L., 1971, Some aspects of Antarctic-Australian geological relationships, *in* Adie, R. J. (ed.), Antarctic Geology and Geophysics: Oslo, Universitetsforlaget, p. 859–864.

Playford, P. E., Horwitz, R. C., Peers, R., and Baxter, J. L., 1970, Geraldton, Western Australia: West. Australia Geol. Survey 1:250 000 Series Explan. Notes.

Watson, J. V., 1978, Precambrian thermal regimes: Royal Soc. London Phil. Trans. A, v. 288, p. 431–440.

Weisbrod, A., 1973, Cordierite-garnet equilibrium in the system Fe-Mn-Al-Si-O-H: Carnegie Institute of Washington Year book, v. 72, p. 515–518.

Wells, P. R. A., 1979, Chemical and thermal evolution of Archaean sialic crust, Southern West Greenland: Jour. Petrol., v. 20, p. 187–226.

Winkler, H. G. F., 1975, Petrogenesis of metamorphic rocks (4th ed.): Berlin, Springer-Verlag, 334 pp.

THE LOGUE BROOK GRANITE: AGE AND SIGNIFICANCE OF DEFORMATION ZONES ALONG THE DARLING SCARP

by D. F. Blight, W. Compston* and S. A. Wilde

ABSTRACT

A number of porphyritic granite bodies along the Darling Scarp show fabrics indicative of progressively increasing deformation westward toward the present Darling Fault. We describe petrographic changes, within the Logue Brook Granite near Harvey, that show how the progressive sequence from granite through augen and layered gneiss to mylonite developed by flattening and mineral ductility contrasts. New isotopic data are interpreted to show that the Logue Brook Granite formed around 2 575 m.y. ago and was deformed during or soon after emplacement. The name "proto-Darling Fault" is proposed for this Precambrian shear zone that was to act as the locus for the later Darling Fault.

INTRODUCTION

The southwestern Yilgarn Block consists of a number of Archaean metamorphic belts invaded by granitic rocks (Wilde, 1980). Zircons from gneisses in the Jimperding Metamorphic Belt at Toodyay give maximum ages of around 3 340 m.y.† (Nieuwland and Compston, in press) whereas the granites have an age of about 2 660 m.y. (Arriens, 1971). The granitic rocks vary in texture, but are chiefly adamellite in composition.

There are, however, a number of distinct porphyritic granite (*sensu stricto*) intrusions close to the Darling Fault, between Mogumber in the north and Wellington Dam in the south (Fig. 1). They exhibit a characteristic style of deformation, being overprinted by gneissic and mylonitic fabrics that become more intense to the west. Mylonitization is not confined to these granites (Fig. 1), but its progressive development is best observed within them.

The porphyritic granite extending south from Mogumber almost to the Swan-Avon River reveals increasing cataclastic deformation west toward the Chittering Metamorphic Belt (Wilde and Low, 1978a). Fold axes can be traced from the metamorphic belt into the granite, and layers of augen gneiss—probably representing deformed granite—are infolded with the metasedimentary rocks.

East of Pinjarra, a body of porphyritic granite is progressively converted to augen gneiss containing mylonite zones (Wilde and Low, 1976). The exact relationship with layered gneisses occurring further west on the Darling Scarp is unclear: some of the rocks are undoubted paragneisses, but many appear to be orthogneiss derived from the granite.

This style of increasing deformation is best exposed along the western margin of the Logue Brook Granite in the vicinity of Harvey (Figs. 1 and 2). The Logue Brook Granite occupies approximately 900 km² of the Darling Range from east of Waroona to Wellington Dam in the south and takes its name from Logue Brook Dam (lat. 33°00′S, long. 115°59′E). The type area of the granite is the disused quarry near Samson Brook Dam (lat. 32°52′55″S, long. 116°00′20″E). Here, grey porphyritic granite contains abundant microcline megacrysts, up to 3 cm long, set in a medium-grained groundmass of quartz, microcline, plagioclase, biotite, minor opaques, apatite and zircon. There is some evidence of recrystallization, but this is considerably less than in most other areas.

The most westerly exposures of mylonite are less than 1 km from the inferred position of the Darling Fault, a major feature on the earth's surface; it is nearly 1 000 km long and downthrown to the west as much as 15 km. On the Collie 1:250 000 Sheet (Wilde and Walker, 1979), the deformed western portions (orthogneiss) are infolded with a supracrustal sequence consisting of quartzite, banded iron-formation, mica schist and paragneiss. The supracrustal sequence and orthogneiss together constitute the Balingup Metamorphic Belt (Wilde, 1980), which, near Bridgetown, yielded a Rb/Sr age of 2 838 ± 200 m.y. (D. A. Nieuwland, written communication, 1977).

One aim of this study was to attempt to date the granite and the derived gneiss at Logue Brook, as it seemed possible that the granite was older than any other granitic rock so far dated in the Yilgarn Block. This postulate is not substantiated but the petrographic and isotopic data provide some evidence on the nature and origin of these high-strain zones in Archaean rocks close to the Darling Fault.

DEVELOPMENT OF LAYERED GNEISS AND MYLONITE

A detailed petrofabric analysis of a mylonite sample from Cookernup, 11 km north of Harvey, has recently been reported (Price, 1978; Lister and Price, 1978). The mylonite was developed from pre-existing granitic gneisses, and, as previously mentioned, some of these layered gneisses were developed from the porphyritic Logue Brook Granite by deformation and recrystallization. These features are well exposed near Honeymoon Road, approximately 4 km northeast of Harvey, where, over a distance of about 100 metres, various stages of gneiss development can be seen, commencing with weakly deformed porphyritic granite (Fig. 3A) and passing through augen gneiss to well-layered and folded equigranular granitic gneiss (Fig. 3H).

The development of a layered rock by flattening from a parent body was first described by Sclar (1950) and since then many authors have described similar features (Sclar, 1958 and 1965; Prinz and Poldervaart, 1964; Vernon, 1974; Shelley, 1974; Sinha Roy, 1977a and b; Wakefield, 1977; and Myers, 1978). Myers (1978) describes, with many examples, the formation of layered gneiss from a variety of rock types, ranging from granitic varieties to basic volcanics. The layering he describes is generated by extreme flattening of pre-existing structures, such as pillow lavas, xenoliths or vein networks, in the rock being deformed. However, at the Harvey location, the Logue Brook Granite contains no such structures.

The microstructural development of a mylonite has been well documented (Bell and Etheridge, 1973; White, 1973) and most of the processes are the same as those involved in the development of layered gneiss. Sinha Roy (1977a) describes this gneiss development as follows: "An initial shearing stage was followed by a flattening one when the characteristic mylonitic microstructures and banding developed. These stages were punctuated and overlapped by phases of recovery and recrystallization". White (1973) had also recognized that deformation, recovery and recrystallization were continuing and overlapping phases: "This sequence is one of continual recovery, of which dynamic recrystallization is a part, during a basically steady stage flow. Recovery features can and do co-exist with one another, for example, lamellae with subgrains". The recognition of these phases of recovery and recrystallization enables a similar tectonic development to that described by Sinha Roy (1977a), to be observed in the above-mentioned samples of deformed Logue Brook Granite. They preserve various stages of this history, depending upon how much recovery and recrystallization have taken place.

The samples taken from near Honeymoon Road exhibit the following features commensurate with progressive deformation. Sample 50394 still retains its gross porphyritic igneous texture (Fig. 3A); however, it has suffered shear strain, the evtdence

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†Literature ages quoted throughout this paper have been recalculated using a ^{87}Rb decay constant of $1{\cdot}42 \times 10^{-11}$/year.

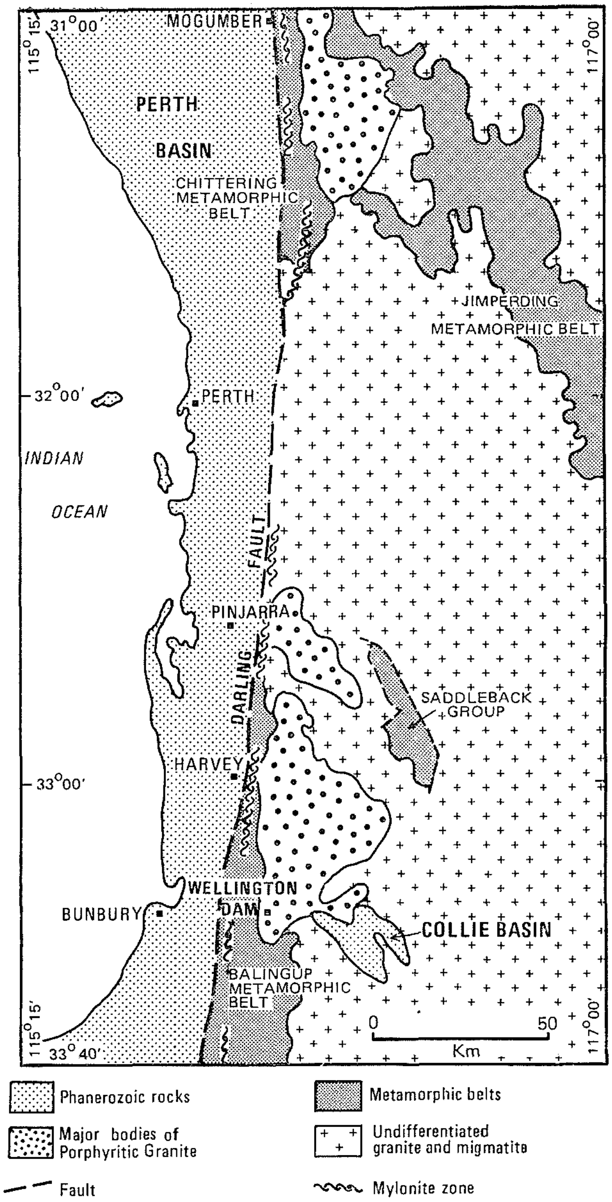


Figure 1 Geological sketch map of part of the Darling Fault zone.

of which is manifest by a set of conjugate zones that are rich in biotite, and along which recrystallization has occurred (Fig. 3B). The elongate relict microcline phenocrysts become rounded, and biotite-rich aggregates of extremely fine-grained, strained quartz and feldspar occur around the margins. These biotite-rich aggregates presumably represent the beginning of layer development. Between relict phenocrysts (now strictly porphyroclasts), quartz has recrystallized into a fine-grained interlobate to polygonal mosaic. This rock would correspond to stage 2 of Sinha Roy's (1977a) sequence of events.

A strong planar fabric has developed in sample 50393 (Fig. 3C and D) by further flattening of the conjugate shear zones. Mineral segregation has produced a layering such that there are biotite-rich layers alternating with layers of platy quartz. The layers of platy quartz (Q in Fig. 3D) are discontinuous and have possibly been formed by the recrystallization and sub-grain growth of the earlier flattened quartz mosaics. There is also a grain-size layering. Some porphyroclasts (probably those initially oriented at a high angle to the flattening plane) have been broken up and have produced discontinuous layers rich in coarse-grained microcline. Other porphyroclasts, elongated in the fabric direction, have very rounded ends with pressure shadows of fine-grained quartz mosaics (P in Fig. 3C). This corresponds to stage 4 of Sinha Roy's sequence.

In sample 50392, the feldsper grains have been further broken up, and with continued flattening, the compositional layering becomes more pronounced (Fig. 3E and F). All mineral grains in the biotite-rich layers are extremely small, and the platy quartz grains, which formed more continuous layers, have begun to recrystallize into polygonal mosaics.

Samples 50389 and 50391 show how the planar mylonitic fabric, described for samples 50394 and 50392, is destroyed as recrystallization proceeds and produces coarser more equidimensional grains. The mineral layering, which was produced early in the deformation, is still evident and may be accentuated. The eventual product is a poorly equigranular, interlobate textured, medium-grained, layered gneiss with rare microcline porphyroclasts (Fig. 3G and H).

Grocott (1977) has shown that, in a deformation zone, shear strain changes from brittle at shallow levels to more ductile in the deeper crustal levels. Wakefield (1977) considers, from an examination of the Lethakane shear zone in Botswana, that deformation processes of this type were "controlled by a mineralogical heterogeneity: essentially the ductility contrast between quartz and feldspar". The textures in the rocks from Harvey, especially those of quartz, are indicative of syntectonic recrystallization with slow strain rates at elevated temperatures (cf. White, 1975). The regional metamorphic grade is middle to upper amphibolite facies (Blight, 1978; and Wilde and Walker, 1979), and thus it is apparent that this mylonitic deformation operated under amphibolite facies conditions. Sinha Roy (1977a) concludes that the large initial grain size of minerals resistant to deformation and pressure solution (e.g. microcline phenocrysts in a granitic rock) seems to favour the development of layering in mylonites. Within the Logue Brook Granite large microcline phenocrysts appear to be more resistant to ductile deformation and, through a more brittle mode, break up and tend to form layers. In other words, the ductility contrast between the quartz and microcline appears to have considerable control on the deformational style and the production of layering.

Sinha Roy (1977a and b) contends that mylonitic layering is the combined effect of deformation and chemical mobility, and he describes changes in chemistry associated with development of layered mylonites from granitoids. Table 1 displays major and selected trace element analyses of some of the rocks examined in this study. There are no systematic chemical changes associated with progressive deformation of this suite, suggesting that the production of layered gneiss by deformation of homogeneous porphyritic Logue Brook Granite is essentially isochemical.

GEOCHRONOLOGY

MATERIAL ANALYSED

Two main suites of rocks were selected for isotopic analyses for the purposes of determining both the age of granite emplacement and the age of deformation that produced the orthogneiss and mylonite. Samples representing the least deformed Logue Brook Granite available were taken from Site 52478, at a quarry near Samson Brook Dam (lat. 32°52'50", long. 116°00'20"). A group of rocks representative of the orthogneiss were collected from site 52483, at the Harvey Weir spillway (lat. 33°04'25", long. 115°55'50"). In addition, selected samples ranging from porphyritic granite to mylonite were taken fron site 52475 on on the northeastern side of Logue Brook Dam (lat. 32°59'40", long.115°59'00") and from site 52476, at the Harvey Weir Quarry (lat. 33°04'24", long. 115°55'50") (Fig. 2). Individual samples from each site are indicated by upper case letters, and brief petrographic descriptions of the analysed samples are given in Table 2. Samples of unweathered material of at least 5 kg were collected. These were passed through a jaw crusher; then a smaller representative sample of between 100 and 200 gm was taken by means of a sample splitter. This representative sample was pulverized in a ring grinder to less than 200 mesh.

Procedures standard for the ANU laboratory were employed for the determination of Rb and Sr by mass spectrometric isotope dilution. The mixed ^{85}Rb –^{84}Sr tracer used gives an age of 1 415 $\pm$ 2 (σ_m) m.y. for the K-feldspar reference sample SRM 607. The co-efficient of variation for a single ^{87}Rb/^{86}Sr measurement is 0·5%, and the precision for ^{87}Sr/^{86}Sr is given separately in Table 3 for each analysis. For the Logue Brook samples, experimental error is negligible in comparison with the scatter about the original isochron produced by later geological processes. Ages have been calculated using 1·42 x 10^{-11} per year for the ^{87}Rb decay constant.

THE ORIGINAL AGE OF THE GRANITE

The analytical data obtained are presented in Table 3 and, except for 52478A, displayed in Figure 4. The undeformed biotite-rich sample, 52478A, differs markedly from all others in its much younger model age (Table 3). It has either gained Rb or lost Sr at a time equal to or younger than $\sim$1 020 m.y. Apparently this difference is related to its comparatively high

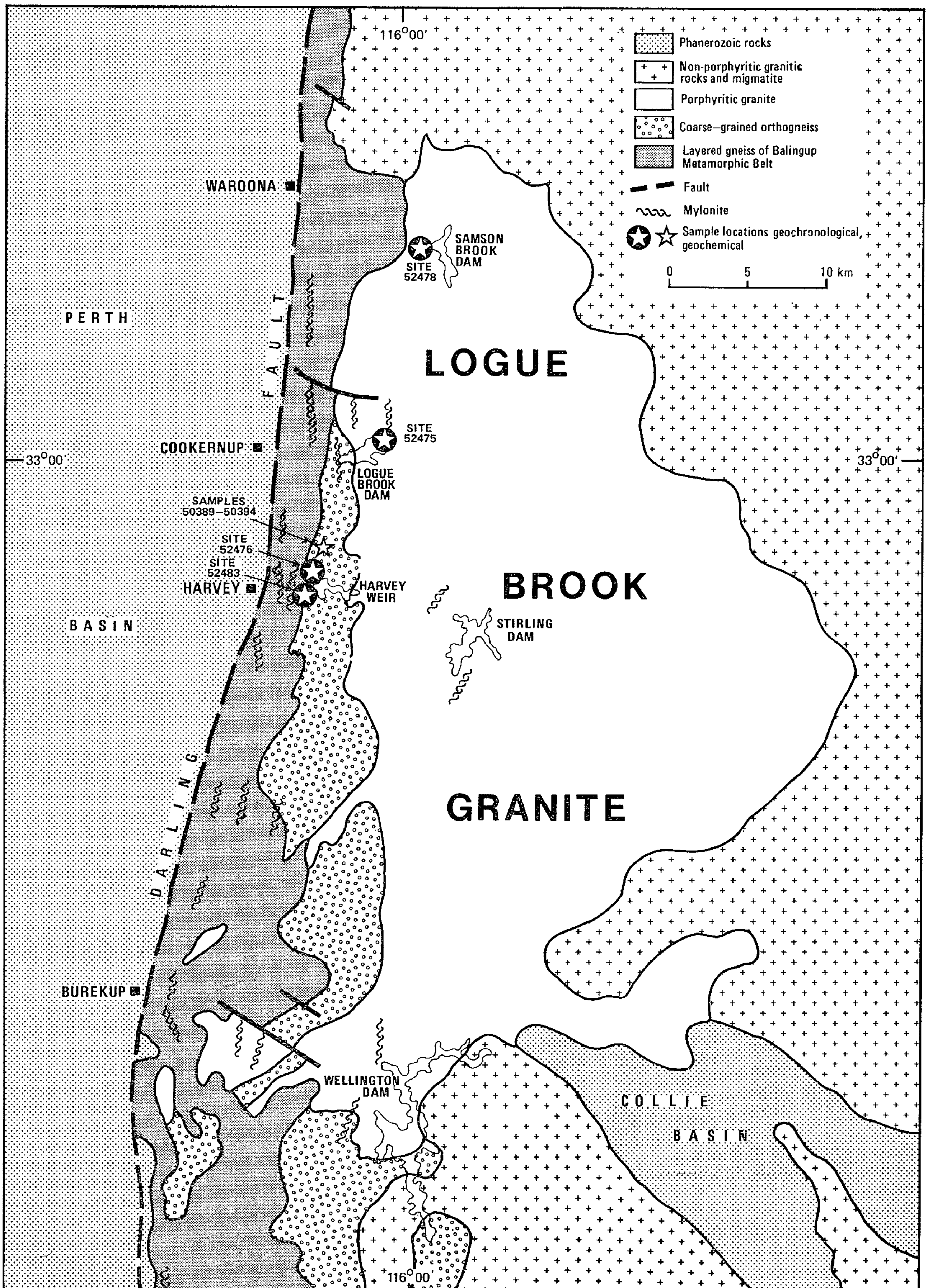


Figure 2 Geology of the Logue Brook Granite.

TABLE 1. WHOLE ROCK AND SELECTED TRACE ELEMENT ANALYSES OF SAMPLES SHOWING THE DEVELOPMENT OF A LAYERED GNEISS FROM A PORPHYRITIC GRANITE BY PROGRESSIVE DEFORMATION

Element	Slightly deformed granite	(Deformation increases to right)				Layered gneiss
	50394	50393	50392	50391	50390	50389
(%)						
SiO_2	74·2	71·4	71·4	71·4	71·7	72·3
Al_2O_3	13·2	14·3	13·6	14·2	13·3	13·3
Fe_2O_3	0·8	1·1	1·8	1·0	1·0	0·8
FeO	1·09	1·29	2·44	1·61	1·61	1·38
MgO	0·38	0·43	0·71	0·58	0·49	0·42
CaO	1·24	1·43	2·19	1·79	1·46	1·27
Na_2O	2·83	2·99	3·26	3·15	2·64	2·87
K_2O	4·70	5·40	3·00	4·60	5·60	5·40
TiO_2	0·28	0·29	0·49	0·31	0·35	0·27
MnO	0·01	0·01	0·03	0·03	0·02	0·01
P_2O_5	0·09	0·11	0·19	0·14	0·17	0·10
H_2O^+	0·60	0·55	0·86	0·54	0·45	0·46
H_2O^-	0·10	0·06	0·10	0·08	0·07	0·06
Total	99·52	99·36	100·07	99·39	98·86	98·64
(ppm)						
As	<1	<1	<1	<1	<1	<1
Ba	670	810	450	680	960	720
Pb	50	65	25	30	35	50
Li	5	5	15	<5	<5	<5
Rb	210	220	190	220	250	230
Sr	90	105	100	115	120	105
Th	60	60	40	45	20	50
U	2	4	<1	<1	<1	2
Zr	210	190	250	220	160	190
Rb/Sr	2·33	2·09	1·90	1·91	2·08	2·19

Figure 2 gives sample locations
Analysts: N. L. Marsh and A. G. Thomas, Western Australian Government Chemical Laboratories.

content of biotite ~15%, Table 2) and to the known propensity of biotite to lose radiogenic ^{87}Sr during later metamorphism. Biotites and feldspars from farther north at Wellington Dam (Riley, 1961) and Canning Dam (Pidgeon and Compston, 1978) give Rb-Sr ages in the range 600 to 700 m.y. while biotite-rich total rock samples from Canning Dam also register young model ages. Libby and de Laeter (1979) showed a progressive westward decrease in biotite ages from 2 500 m.y. at Meckering to about 500 m.y. at the Darling Scarp, thus confirming the young ages close to the western margin of the Yilgarn Block. These young ages presumably reflect a more complete response to the same event that altered sample 52478A.

Other Logue Brook Granite samples would also have been altered, and inspection of Figure 4 shows that such undeformed samples as 52478C and M were indeed open systems subsequent to their original crystallization. Thus our attempted measurements of the age of emplacement of the Logue Brook Granite and of its subsequent deformation must also allow for the unwanted effects of a superposed younger thermal event (taken as 635 m.y.).

The above situation can be modelled by a two-stage Sr-evolution method described by Compston and Collerson (1979) and Cameron and others (in press) in which "geological scatter" about an originally well-fitted isochron is assigned to local Sr-isotope exchange during a single later metamorphism. During the later metamorphism, differences in $^{87}Sr/^{86}Sr$ between adjacent samples which grew with time because of differences in their $^{87}Rb/^{86}Sr$, are smoothed out by diffusive exchange of ^{87}Sr. Subsequently, the same differences in $^{87}Rb/^{86}Sr$ produce correlated y, x residuals, with respect to the undisturbed primary isochron, along a slope corresponding to the age of metamorphism. Cameron and others (in press) give the correct regression method for estimating the original age and initial $^{87}Sr/^{86}Sr$ for this situation, including the recommendation that each point should be weighted as the inverse square of the mean $^{87}Rb/^{86}Sr$ of its local exchange system. In addition, as Compston and Collerson (1979) also discuss, it may be preferable to model the initial $^{87}Sr/^{86}Sr$ rather than attempt to estimate it. For this purpose, the original granite is assumed to be produced from the so-called "unfractionated Sr reservoir" (De Paolo and Wasserburg, 1976) which has a $^{87}Rb/^{86}Sr$ of approximately 0·085 6 and a present-day $^{87}Sr/^{86}Sr$ of approximately 0·704 7 and constitutes a "fixed-point".

Table 4 lists regression analyses of various combinations of the samples by the methods of Cameron and others (in press). Sample 52478A has been excluded from all regressions as its response to the later metamorphism so greatly exceeds

TABLE 2. LOCATION AND BRIEF DESCRIPTION OF ISOTOPICALLY ANALYSED SAMPLES

Site	Locality	Latitude	Longitude	Sample	Notes
52475	Northeast side of Logue Brook Dam	32°59′40″	115°59′00″	C	Pegmatite with 60% microcline phenocrysts. Weakly recrystallized
				F	Porphyritic granite. Partly recrystallized. Granoblastic, seriate interlobate texture.
				H	Granitic blastomylonite. Fine-grained flaser texture wi.h rare porphyroclasts.
52476	Quarry 200 m north of Harvey Weir	33°4′24″	115°55′50″	B, C	Granitic augen gneiss. Granoblastic, seriate polygonal texture over-printing flaser texture.
				I	Granitic gneiss. As B and C except for smaller and rarer porphyroclasts.
52478	Quarry near Samson Brook Dam	32°52′50″	116°00′20″	A	Dark tonalitic pod with up to 15% biotite.
				C	Porphyritic granite, partly recrystallized quartz. Feldspar and biotite marginal to phenocrysts.
				D	Porphyritic granite. Coarser than C and less biotite.
				D (K-Feld)	Large microline crystal separated from D.
				G	Porphyritic granite. Similar to C, but less biotite.
				K	Medium-grained granite/adamellite. Microcline perthitic and slightly coarser than plagioclase. Granoblastic recrystallization.
				L	Porphyritic granite. Megacryst-rich, weakly recrystallized.
				M	Biotite tonalitic gneiss. Origin obscure, but seems to be a vein through granite
				N	Porphyritic granite. Similar to C and G. Fairly typical of Logue Brook Granite.
52483	Harvey Weir Spillway	33°04′25″	115°55′50″	A	Layered granitic gneiss. Granoblastic to mylonitic with rare porphyroclasts. Perthitic microcline.
				B	Granitic augen gneiss. Granoblastic to mylonitic with large microcline augen. Strong biotite fabric. Polygonal recrystallization of quartz.
				C	Layered granitic augen gneiss. Larger augen than B.
				D	Granitic augen gneiss. Similar to B. but smaller augen.
				E	Layered grani.ic augen gneiss. Similar to C.

TABLE 3. ANALYTICAL DATA OF SPECIMENS OF LOGUE BROOK GRANITE AND ASSOCIATED ORTHOGNEISSES FROM VARIOUS LOCATIONS (see Figure 2).

	ppm Rb	ppm Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	Age based on R_i $_\sigma$ of 0·701
Site 52475 (*Logue Brook Dam*):					
C	343·5	98·0	10·118	1·081 28 ± 11	2 592 m.y.
F	245·3	76·6	9·237	1·052 75 ± 4	2 633 m.y.
H	233·8	66·1	10·200	1·068 58 ± 4	2 491 m.y.
Site 52476 (*North of Harvey Weir Spillway*):					
B	159·8	80·5	5·725	0·923 87 ± 7	2 687 m.y.
C	159·4	82·1	5·602	0·925 76 ± 5	2 769 m.y.
I (i)	97·3	105·8	2·653	0·827 51 ± 5	3 281 m.y.
(ii)	100·9	112·5	2·588	0·828 27 ± 6	3 381 m.y.
Site 52478 (*Samson Brook Dam*):					
A	580·1	32·6	51·25	1·451 3 ± 1	1 023 m.y.
C	354·4	73·5	13·92	1·185 16 ± 5	2 407 m.y.
D	345·9	85·3	11·70	1·129 4 ± 3	2 532 m.y.
D (K-feld)	408·2	98·8	11·92	1·152 8 ± 2	2 620 m.y.
G	247·4	72·1	9·90	1·074 23 ± 5	2 606 m.y.
K	185·2	57·0	9·36	1·061 93 ± 6	2 665 m.y.
L	332·4	76·5	12·53	1·152 35 ± 4	2 492 m.y.
M	231·8	62·0	10·79	1·058 57 ± 8	2 296 m.y.
N	258·1	74·2	10·035	1·083 64 ± 4	2 635 m.y.
Site 52483 (*Harvey Weir Spillway*)·					
A	164·6	98·8	4·806	0·888 33 ± 6	2 692 m.y.
B	178·2	91·7	5·604	0·916 52 ± 9	2 658 m.y.
C	188·4	91·0	5·977	0·924 31 ± 5	2 583 m.y.
D	199·6	137·5	4·186	0·840 18 ± 5	2 303 m.y.
E	193·2	93·5	5·961	0·918 5 ± 1	2 524 m.y.

The ages are calculated using a ^{87}Rb decay constant of 1·42 x 10^{-11}/year.

the comparatively uniform response of the others. However inspection of the residuals suggest that samples 52476I, 52483D and 52478M also have a greater geological scatter than the remainder, so that our preferred estimate of the original age is 2 577 ± 50 m.y. (regression 4, Table 4). The uncertainties of the free-line estimates of initial $^{87}Sr/^{86}Sr$ are so high as to make the estimates almost worthless.

Although we favour exclusion of sample 52476I from the regression analysis, its position well above the 2 577 m.y. isochron (and hence its very high model age) is nevertheless consistent with the mechanism proposed for metamorphic redistribution. This particular sample absorbed an unusually large amount of radiogenic ^{87}Sr, and may be viewed as an analogue of the mafic pod 52478A, which lost an unusually large fraction of its radiogenic ^{87}Sr. Plagioclases from the Canning Dam area have absorbed even greater fractions of ^{87}Sr and give absurdly old model ages (Pidgeon and Compston, 1978). The presence of sample 52476I is important because it demonstrates that the process of metamorphic disturbance, in the case of the Logue Brook Granite, involves local ^{87}Sr redistribution. Otherwise we could not exclude the possible alternative process discussed by Nieuwland and Compston (in press), of regional loss of radiogenic Sr, in which the oldest model age is a minimum estimate for the original age.

AGE OF DEFORMATION

Inspection of Figure 4 shows that no difference in age can be detected between the deformed and undeformed samples. It follows that either (a) the difference in age between emplacement and deformation of the Logue Brook Granite was small or (b) the deformation process itself did not alter the Rb-Sr total-rock ages and may have occurred at any later date.

TABLE 4. REGRESSION ANALYSES OF TWO GROUPINGS OF LOGUE BROOK GRANITE SAMPLES, USING THE METHODS OF CAMERON AND OTHERS (IN PRESS).

Regression	Number of samples	R_i	Age m.y.
Free-line method			
1. All except 52478A	20	0·721 +16 −19	2 410 −185 +230
		*0·718 +17 −21	*2 440 −185 +250
2. All except 52478A, 52476I (i), (ii), 52483D, and 52478M	16	0·717 +13 −15	2 465 −120 +135
		*0·716 +13 −15	*2 465 −120 +140
Fixed-point method			
3. As in 1.	20	0·701 54 +10 −11	2 574 −78 +85
		*0·701 54 +10 −11	2 575 −77 +85
4. As in 2.	16	0·701 53 ± 6	2 577 −49 +51
		*0·701 53 ± 6	*2 577 −48 +52

The "free-line" method estimates both the age and initial $^{87}Sr/^{86}Sr$, whereas the "fixed-point" method constrains the initial $^{87}Sr/^{86}Sr$ to bulk earth values and estimates the age only. The age of metamorphism is taken as 635 m.y. Results are also shown, marked with an asterisk, for a maximum age of metamorphism of ∽ 1 020 m.y.

Figure 3 Sequence of photographs illustrating various stages in the production of layered gneiss (50389) from porphyritic Logue Brook Granite (50394). All samples taken from a 100 m-wide section 4 km northeast of Harvey near Honeymoon Road (Fig. 2).

(A) Relatively undeformed Logue Brook Granite, showing the abundant and aligned nature of microcline phenocrysts; slight rounding at the ends of certain phenocrysts is evident . (50394).

(B) Photomicrograph showing how the rounding at the ends of microcline phenocrysts as the result of conjugate shear sets, along with recrystallization has occurred; quartz and feldspar form a fine-grained mosaic that is rich in recrystallized biotite (crossed polars, 50394).

(C) Further flattening of the conjugate shear sets results in a strong planar fabric; mineral segregation and variations in grain-size define a conspicuous layering; microcline porphyroclasts have distinctly tapered ends, with pressure shadows (P) of fine-grained quartz mosaics (plane-polarized light, 50393).

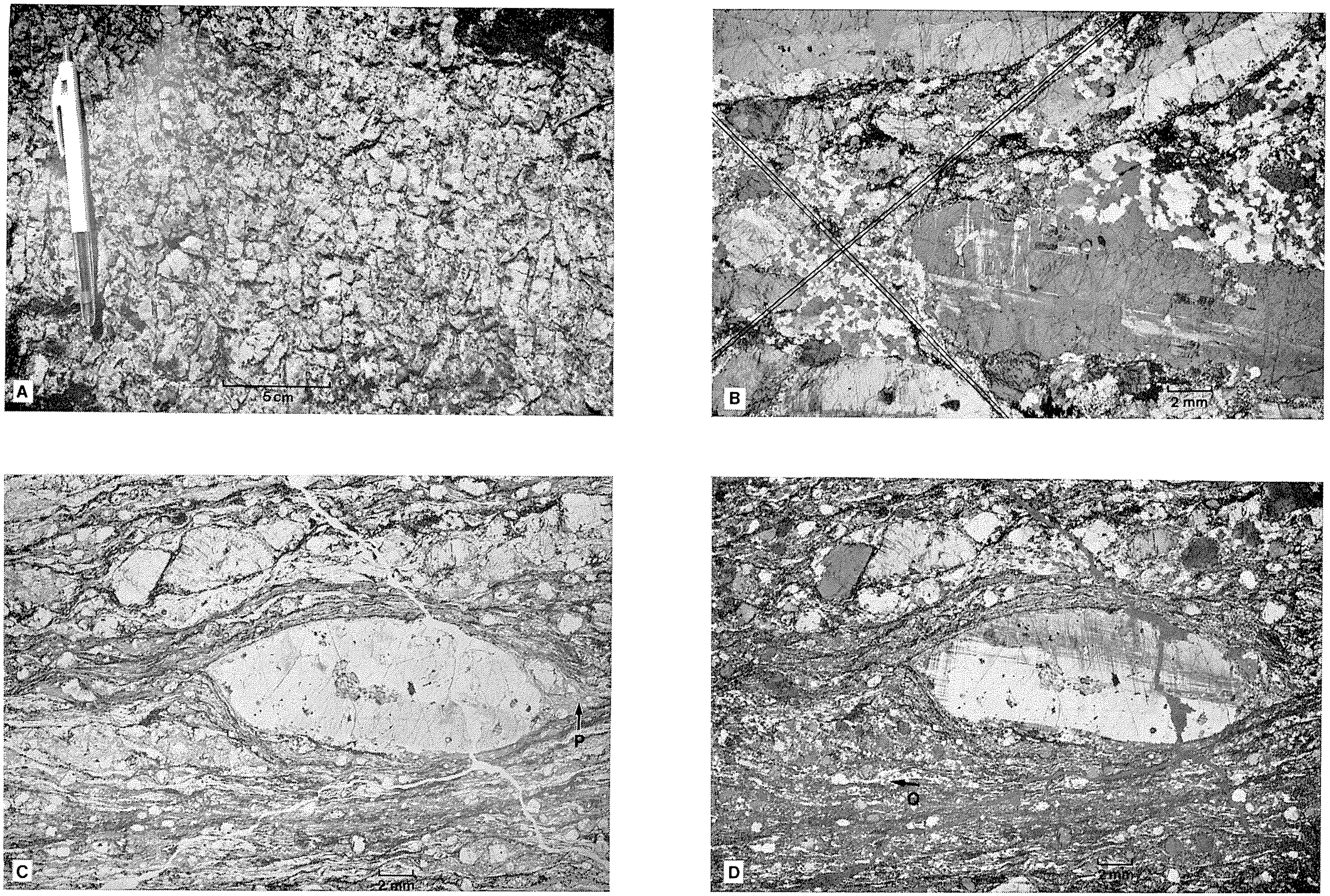
(D) As (c), but illustrating discontinuous layers of platy quartz (Q) possibly formed by recrystallization of previously flattened quartz mosaics (crossed polars, 50393).

(E) Continued flattening and reduction in grain-size of feldspar results in a more pronounced compositional layering, all mineral grains are extremely small in the biotite-rich layers. (plane-polarized light, 50392).

(F) As (e), but emphasizing how the platy quartz grains have begun to recrystallize into polygonal mosaics (crossed polars, 50392).

(G) Further recrystallization results in destruction of the mylonitic fabric, with the formation of coarser, more equidimensional grains; the early mineral layering is not destroyed and may be further emphasized by recrystallization of biotite (crossed polars, 50389).

(H) Folded, layered gneiss, approximately 100 m west across strike from 50394 (50389).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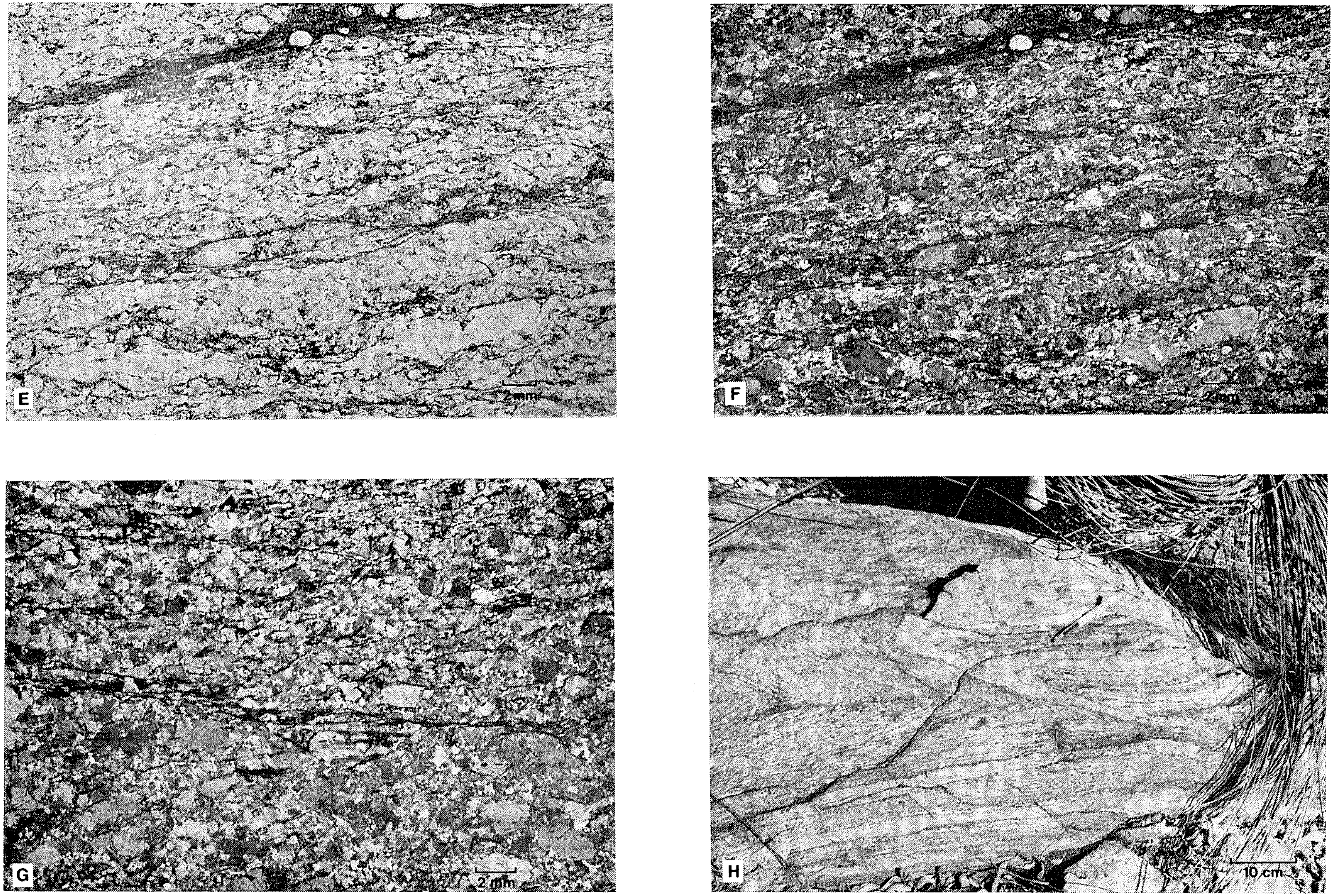
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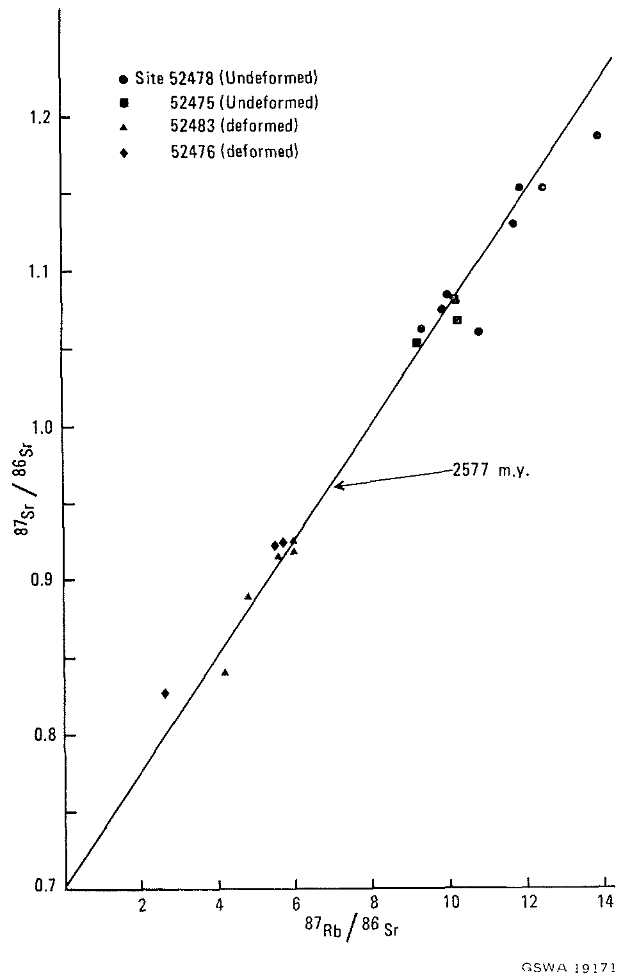

Figure 4 Logue Brook Granite isotopic data and reference isochron.

All the deformed samples which were analyzed isotopically have lower Rb/Sr than the undeformed samples (Figure 5). The 50389–94 series samples, which were not analysed isotopically, also have lower Rb/Sr but there is no difference within this series between the slightly deformed sample 50394 (Table 1) and the progressively more deformed samples. Figure 2 shows that all samples having low Rb/Sr, including the 50389–94 series, belong to the coarse-grained orthogneiss unit. It remains possible therefore, that the transformation of porphyritic granite into orthogneiss was accompanied by a decrease in Rb/Sr, (through gain of Sr) during the recrystallization of original minerals and growth of new minerals. Such a change in Rb/Sr need not be accompanied by a significant change in major element composition. This evidence could be used to support alternative (a). On the other hand, we cannot exclude the possibility that the distribution of Rb and Sr shown in Figure 5 is a primary igneous distribution, and that the apparent difference in Rb/Sr between the deformed and undeformed samples could be due to their having been collected from different parts of the original pluton.

Despite the lack of conclusive evidence for change of Rb/Sr due to deformation, we consider it very likely that local Sr isotopic equilibration would have occurred during the process. As shown in a previous section, the deformation was accompanied by recrystallization and by the growth of new minerals, which would promote rapid isotopic exchange via interstitial fluid and result in isotopic homogenization. Black and others (1979) have shown that different deformational events can be measured by using closely spaced total-rock samples from localities at which a particular deformation is strongly developed. The mineralogical changes believed to accompany the later thermal event (saussuritization, growth of minor epidote and carbonate) are trivial compared with those associated with the development of layered gneiss, yet this apparently minor thermal event was accompanied by substantial ^{87}Sr transfer between total-rock samples. Assuming that local Sr isotopic equilibration did occur during deformation, the Rb-Sr alignment of deformed samples per single locality will approximate to the age of deformation. Figure 4 shows that the mean alignment for deformed samples from the two localities examined is close to the original 2 577 m.y. isochron. Specifically, the apparent ages, using the Cameron and others (in press) free-line method are 3 355 + 1 220 or —945 m.y. for locality 52483, but with an inadmissably-low initial $^{87}Sr/^{86}Sr$, and 2 210 + 400 or —265 m.y. for locality 52476. The age for the combined localities is 2 415 + 1 545 or —560 m.y.

CONCLUSIONS

Isotopic data indicate that the emplacement of the Logue Brook Granite, near Harvey, took place around 2 575 m.y. ago. It has been demonstrated on field and petrographic evidence that augen gneiss, layered gneiss and mylonite have developed from this porphyritic granite by intense shear deformation and that this process was essentially isochemical. Our interpretation of all available data is that deformation occurred during or soon after granite emplacement.

Other bodies of porhpyritic granite cropping out between Mogumber and Harvey (Figure 1) are deformed in a similar fashion to the Logue Brook Granite and have been changed to mylonites. Similar mylonites are also present in adjacent gneissic rocks. These extensive mylonite zones are restricted to within 10 km of the present Darling Fault and extend as far south as Northcliffe, a total distance of 420 km. The mylonites are subparallel to the Darling Fault even where the fault swings south eastward near Northcliffe (Wilde and Walker, in prep.). The intensity of deformation increases westward towards the Darling Fault and it is suggested that the mylonite zones are deep-level manifestations of a major Archaean shear zone.

Various workers (Prider, 1952; Wilson, 1958; Wilson and others, 1960; Wilde and Low, 1978a, b; and Wilde, 1980) have postulated the existence of an Archaean deformation zone subparallel to the present Darling Fault. Prider (1952) referred to this as the "Darling Archaean Fault" and gave evidence of sinistral transcurrent movement. It is also evident that this zone was active during the sedimentation and subsequent deformation of the Proterozoic Cardup, Moora, and Yandanooka Groups. Similarly, dolerite dykes of believed Proterozoic age increase in abundance toward the fault and lie subparallel to that feature. Many have also undergone later shearing, especially along their margins (Klenowski, 1975). Wilson (1958) proposed that there was periodic re-activation along this zone, and this was later substantiated by isotopic data on pegmatites (ca. 1 100 m.y. at Mullalyup; Wilson and others, 1960); on the granitized margins of dolerite dykes (560 to 590 m.y.; Compston and Arriens, 1968) and on biotite from both granite and pegmatite (634 to 740 m.y.; Wilson and others, 1960).

It would thus appear that this zone acted as the locus for the Darling Fault, a major Phanerozoic feature which was initiated during the Silurian as a normal fault (Playford and others, 1976). It underwent its greatest amount of movement between Middle Triassic and Early Cretaceous times resulting in a downthrow to the west of 15 km near Perth. To distinguish clearly between the Darling Fault and this earlier shear zone with possible transcurrent movement, we propose that the name "proto-Darling Fault" be used for the Precambrian deformation zone.

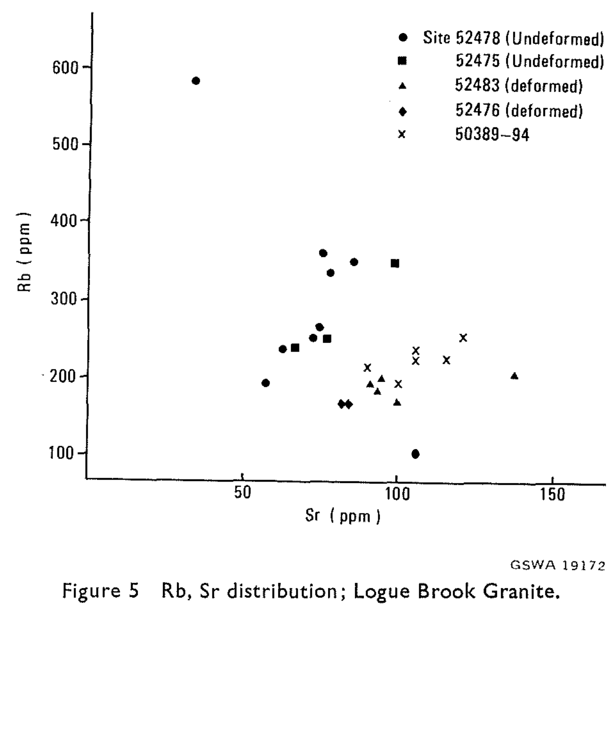

Figure 5 Rb, Sr distribution; Logue Brook Granite.

REFERENCES

Arriens, P. A., 1970, The Archaean geochronology of Australia: Geol. Soc. Australia Spec. Publ. No. 3, p. 11–23.

Bell, T. H., and Etheridge, M. A., 1973, Microstructures of mylonites and their descriptive terminology: Lithos, No. 6, p. 337–349.

Black, L. P., Bell, T. H., Rubenach, N. J., and Withnall, I. W., 1979, Geochronology of discrete structural-metamorphic events in a multiply deformed Precambrian terrain: Tectonophysics, v. 54, p. 103–137.

Blight, D. F., 1978, High-grade retrogressive metamorphism and mineral corona development in basic rocks of the Collie area, Western Australia: West. Australia Geol. Survey Ann. Rept 1977, p. 66–68.

Cameron, M., Collerson, K. D., Compston, W., and Morton, R., in press, Statistical analysis and interpretation of imperfectly fitted Rb-Sr isochrons from polymetamorphic terrains: Geochim. Cosmochim. Acta.

Compston, W., and Arriens, P. A., 1968, The Precambrian geochronology of Australia: Canadian Jour. of Earth Sciences v. 5, p. 561–583.

Compston, W., and Collerson, K. D., 1979, Interpretation of scattered Rb-Sr isotopic data for early Archaean gneisses from Labrador and Greenland: Workshop on Ancient Crusts of the Terrestrial Planets, Lunar and Planetary Science Institute, Contrib. 371, p. 22–24.

De Paolo, D. J. and Wasserberg, G. J., 1976, Inferences about magma sources and mantle structure from variations of $^{143}Nd/^{144}Nd$: Geophys. Res. Lett., 3, p. 743–746.

Grocott, J., 1977, The relationship between Precambrian shear belts and modern fault systems: Geol. Soc. London, Jour., v. 133, p. 257–262.

Klenowski, G., Shear zones in Precambrian rocks of the Darling Range: nature, origin and engineering significance: West. Australia Geol. Survey Ann. Rept, 1974, p. 29–33.

Libby, W. G. and de Laeter, J. R., 1979, Biotite dates and cooling history of the western margin of the Yilgarn Block: West. Australia Geol. Survey Ann. Rept 1978, p. 79–87.

Lister, G. S., and Price, G. P., 1978, Fabric development in quartz-feldspar mylonite: Tectonophysics, v. 49, p. 37–78.

Myers, J. S., 1978, Formation of banded gneisses by deformation of igneous rocks: Precambrian Research, v. 6, p. 43–64.

Nieuwland, D. A., and Compston, W., in press, Crustal evolution in the Yilgarn Block near Perth, W.A.: International Archaean Symposium, 2nd Perth, 1980, Geol. Soc. Aust. Spec. Publ. No. 7.

Playford, P. E., Cockbain, A. E., and Low, G. H., 1976, Geology of the Perth Basin, Western Australia: West. Australia Geol. Survey Bull. 124.

Pidgeon, R. T. and Compston, W., 1978, Geochronology of the western margin of the Yilgarn Block: Australian National University, Research School of Earth Sciences, Annual Report, p. 160–161.

Prinz, M., and Poldervaart, A., 1964, Layered mylonite from Beartooth Mountains, Montana: Geol. Soc. America Bull. v. 75, p. 741–744.

Price, G. P., 1978, Study of heterogeneous fabric and texture within a quartz-feldspar mylonite using the photometric method: Geol. Soc. America Bull. v. 89, p. 1359–1372.

Prider, R. T., 1952, South-west Yilgarnia, *in* Glaessner, M. F. and Rudd, E. A. (eds) Sir Douglas Mawson Anniversary Volume: The University of Adelaide, p. 143–152.

Riley, G. H., 1961, The techniques and application of Rb-Sr geochronology: Univ. Western Australia, Perth, PhD Thesis (unpublished).

Sclar, C. B., 1950, Origin of a layered ultramylonite from southeastern Connecticut (Abstract): Geol. Soc. America Bull. v. 61, p. 501.

———— 1958, The Preston Gabbro and associated metamorphic gneisses, New London County, Connecticut: Connecticut Geol. Nat. History Survey Bull. v. 88, p. 131.

———— 1965, Layered mylonites and the process of metamorphic differentiation: Geol. Soc. America Bull. v. 76, p. 611–612.

Shelley, D., 1974, Mechanical production of metamorphic banding—a critical appraisal: Geol. Mag. v. 111, p. 287–292.

Sinha Roy, S., 1977a, Mylonitic microstructures and their bearing on the development of mylonites—an example from deformed trondhjemites of the Bergen Arc region, S.W. Norway: Geol. Mag. v. 114, p. 445–458.

———— 1977b, Deformation and chemical processes in mylonite genesis: Geologiska Foreningens i Stockholm. Fordandlingar, v. 99, p. 3–9.

Vernon, R. H., 1974, Controls of mylonitic compositional layering during non-cataclastic ductile deformation: Geol. Mag. v. 111, p. 167–277.

Wakefield, J., 1977, Mylonitization in the Lethakane shear zone, eastern Botswana: Geol. Soc. London Jour. v. 133, p. 263–275.

White, S., 1973, Syntectonic recrystallization and texture development in quartz: Nature, v. 244, p. 276–278.

———— 1975, Estimation of strain rates from microstructures: Geol. Soc. London, Jour. v. 131, p. 577–583.

Wilde, S. A., 1980, The Jimperding Metamorphic Belt in the Toodyay area and the Balingup Metamorphic Belt and associated granitic rocks of the Southwestern Yilgarn Block: International Archaean Symposium, 2nd, Perth, 1980, Geol. Soc. Australia, Excursion Guide.

Wilde, S. A. and Low, G. H., 1978a, Perth, Western Australia: West. Australia Geol. Survey 1:250 000 Geological Series Explanatory Notes.

———— 1978b, Explanatory notes on the Pinjarra Western Australia 1:250 000 Geological Sheet: West. Australia Geol. Survey Rec. 1978/5.

Wilde, S. A. and Walker, I. W., 1979, Explanatory notes on the Collie 1:250 000 geological sheet, Western Australia: West. Australia Geol. Survey Rec. 1979/11.

———— in prep., Explanatory notes on the Pemberton-Irwin Inlet 1:250 000 geological sheet, Western Australia: West. Australia Geol. Survey Rec.

Wilson, A. F., 1958, Advances in the knowledge of the structure and petrology of the Precambrian rocks of southwestern Australia: Royal Soc. West. Australia Jour. v. 41, p. 57–83.

Wilson, A. F., Compston, W., Jeffery, P. M. and Riley, G. H., 1960, Radioactive ages from the Precambrian rocks in Australia: Geol. Soc. Australia Jour. v. 6, p. 179–196.

THE RELATIONSHIP OF NEW Rb-Sr ISOTOPIC DATES FROM THE RUDALL METAMORPHIC COMPLEX TO THE GEOLOGY OF THE PATERSON PROVINCE

by R. J. Chin and J. R. de Laeter*

ABSTRACT

The Paterson Province consists principally of a basement of multiply deformed and metamorphosed granite, gneiss and metasediments known as the Rudall Metamorphic Complex, unconformably overlain by sedimentary rocks of the Yeneena Group. This latter sequence has been subject to one major period of folding.

A Rb-Sr geochronology programme to attempt to date the events in the Rudall Metamorphic Complex commenced with a series of nine samples selected from previous reconnaissance collections. A poorly fitted isochron at 1 533 ± 29 m.y. was obtained. Subsequent collecting provided a series of six samples of retrogressed gneiss which gave a well-fitted isochron at 1 333 ± 44 m.y. This date is considered to be the age of the pervasive metamorphism and deformation in the Rudall Metamorphic Complex, and the oldest possible depositional age of the Yeneena Group. Other samples showed a scatter of data indicating that the isotopic system has been disturbed by later metamorphism and alteration. An age of 595 ± 27 m.y. was found from six of these samples and compares favourably with the relatively young age of the granite which intrudes the Yeneena Group near Mount Crofton in the northern part of the province. Pegmatite veins in the metamorphic basement produced an isochron at 1 132 ± 21 m.y., an age which may relate to the deformation of the Yeneena Group.

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Two samples of undeformed adamellite from the southeast part of the Rudall Metamorphic Complex gave an age of about 1 080 m.y., the first indication of granite intrusion of this age in the Paterson Province. This age compares closely with that of younger granite intrusions into the Proterozoic mobile belts of the Musgrave Block and the Albany-Fraser Province. Metamorphic ages from the Rudall Metamorphic Complex are similar to the age of granulite metamorphism in these provinces.

INTRODUCTION

The Paterson Province is located in the remote western part of the Gibson and Great Sandy Deserts. The mining town of Telfer lies in the northern part of the province. It is normally thought of as an exposed part of a Proterozoic orogenic belt, abutting the Pilbara Block and Hamersley Basin to the west, and unconformably overlain by the Proterozoic Bangemall Group and the Phanerozoic Officer and Canning Basins to the south, east and north.

It consists of two principal rock groups, a metamorphic complex and a folded sedimentary cover, the ages of which have been subject to speculation since the first geological reconnaissance was made by H. W. B. Talbot in 1908–09. He recognized the distinction between "granite and crystalline schist" (now known as the Rudall Metamorphic Complex) and the younger sedimentary rocks which are now considered to form part of the Yeneena Group (Talbot, 1910). He initially considered the sedimentary rocks to have a Devonian age, but later (Talbot, 1920) assigned these rocks to the Nullagine Series (Maitland, 1919). No further geological work was carried out in the Paterson Province until 1954 when Traves and others (1956) surveyed the Canning Basin and published the Paterson Range and Tabletop Sheets of the 4-mile Geological Series (Wells, 1959, 1960). They arbitrarily assigned an early Proterozoic age to the rocks of the province. In 1966 and 1969 L. E. de la Hunty and J. G. Blockley of the Western Australian Geological Survey (G.S.W.A.) made reconnaissance trips to assist in the preparation of the 1966 and 1973 editions of the State Geological Map. They thought that the main sedimentary sequence (Yeneena Group) was equivalent to part of the Proterozoic Bangemall Group (Blockley and de la Hunty, 1975). More recent geological mapping (Williams and others, 1976) has demonstrated that the Bangemall Group unconformably overlies the Yeneena Group. Adamellite, which intrudes the Yeneena Group near Mount Crofton in the northern part of the province, was dated by Trendall (1974) using the Rb-Sr technique. The ages determined were 598 $\pm$ 24 m.y. for six granite samples and 581 $\pm$ 1 m.y. for the same samples plus a pegmatite from a cross-cutting vein. These were surprisingly young ages considering the inferred age of the rocks they intrude. Biotite from four of the granite samples gave ages between 556 and 579 m.y. (de Laeter and others, 1977). All ages quoted in this paper from other references have been recalculated using a value of $1 \cdot 42 \times 10^{-11}$ yr^{-1} for the decay constant, of ^{87}Rb.

A geochronology project to clarify the age of rocks in the Paterson Province (including the Gregory Granitic Complex which at that stage was regarded as the most westerly part of the province) was commenced in 1970 using samples in the G.S.W.A. rock collection, which were rather randomly collected by Talbot from several traverses made between 1908 and 1914, and by J. G. Blockley and L. E. de la Hunty in 1966 and 1969. Geochronological results from the Gregory Granitic Complex have been published by de Laeter and others (1977). Initial results from the Paterson Province were broadly referred to by Blockley and de la Hunty (1975), and quoted as "about 1 500 m.y." by Blockley (1974). Systematic mapping of the Paterson Range Sheet (Chin and Hickman, 1977), Ruddall Sheet (Chin and others, 1979), Runton Sheet (Crowe and Chin, 1978), Gunanya Sheet (Williams and Williams, 1977) and Tabletop Sheet (Yeates and Chin, 1979) revealed complex deformation and metamorphism throughout the Paterson Province, and showed the necessity for further collection and analysis of selected samples to arrive at a better understanding of the geological history.

The objectives of the Rudall project were to determine the ages of the important metamorphic events in the Rudall Metamorphic Complex and to define more precisely the age limits of the deposition of the Yeneena Group. It was also hoped that an indication of the age of the parent rocks that gave rise to the Rudall Metamorphic Complex might be found.

REGIONAL GEOLOGY

The regional geology of the Paterson Province (Fig. 1) is characterized by two major rock groups, the Rudall Metamorphic Complex and the unconformably overlying Yeneena Group. Both pass unconformably below Phanerozoic rocks of the Canning and Officer Basins at the northeastern and eastern boundaries. The Yeneena Group passes unconformably beneath the gently dipping Proterozoic Bangemall Group (about 1 050 m.y.) in the south and southwest. The Yeneena Group rests unconformably on the Archaean Gregory Granitic Complex (about 2 590 m.y.) and the Proterozoic Hamersley and Fortescue Groups (about 2 600–2 500 m.y.) on the western side of the province. However, the relationship between the Rudall Metamorphic Complex and the older sequences on this western side is obscured by the Yeneena Group.

Both the basement and the cover rocks in the Paterson Province have been deformed by north-northwesterly folds. A third, restricted, group of Proterozoic rocks in the Paterson Province is the Karara Formation which unconformably overlies the Yeneena Group. Granite and adamellite which lack metamorphic fabric have intruded the Yeneena Group in the northern part of the province and have intruded the Rudall Metamorphic Complex in the extreme southeast.

During the Permian the region was subjected to glaciation. Large U-shaped valleys and striated, polished pavements are still preserved on the exhumed pre-Permian unconformity, and outliers of the Permian glacigene Paterson Formation are present.

RUDALL METAMORPHIC COMPLEX

The Rudall Metamorphic Complex consists of two metamorphic suites. The older suite is of gneissic and granitic rocks, and contains structures produced by an early metamorphic and deformation event (F_1) which predates the formation of the predominantly metasedimentary younger suite. The dominant fabric in both rock suites is produced by a pervasive metamorphic and deformation event (F_2) which has extensively broken down the older metamorphic textures and transposed primary layering in both metamorphic suites. However, sufficient textures and structures are preserved to identify the parent rocks.

The dominant gneissic rock is banded gneiss derived during F_1 from a variety of granitoid types. Although these gneisses exhibit a compositional range between granite and tonalite, adamellite composition is most common. The banding is principally derived by metamorphic differentiation but some is possibly of sedimentary origin. In the Mount Connaughton area, this banded gneiss encloses belts of quartzite, paragneiss and orthogneiss derived from a layered sequence of mafic, ultramafic and sedimentary rocks. Although this gneiss also has undergone retrogression, it still retains relict metamorphic assemblages attained during F_1. In particular, relict staurolite, sillimanite and kyanite in the paragneiss indicate middle to upper amphibolite facies metamorphism. North of Karara Well, migmatite was formed by the veining and partial assimilation of a complex of banded gneiss with enclaves of mafic and ultramafic gneiss and paragneiss, by stockworks of granitic and aplitic dykes. In this same area and in the Rudall River area, large bodies and dykes of medium- and coarse-grained porphyritic and even-grained adamellite intrude the gneiss.

All the rocks described above have a dominant F_2 fabric derived from the breakdown and recrystallization of primary minerals. Associated retrograde minerals, including chlorite, tremolite, epidote and muscovite, characterize all gneisses.

Gneisses in this older metamorphic suite closely resemble those in Archaean cratons. In particular, juxtaposed quartzite, paragneiss, mafic gneiss and banded granitic gneiss which grades into migmatite are characteristic rock types and associations of the West Yilgarn Gneiss Domain (Gee, 1979).

The younger metamorphic suite of the Rudall Metamorphic Complex is dominated by thick, monotonous quartzite horizons with abundant quartz-muscovite schist. The quartzite is derived from a supermature quartz sandstone. Pebble conglomerate beds are present but rare. Less abundant rock types at apparently higher stratigraphic levels are banded iron-formation, quartz-feldspar-mica schist, graphitic schist and interbanded marble and chlorite-carbonate schist. An extensive outcrop of metabasalt with thin intercalated chert bands is thought to be part of the younger suite. Lithologically, this obvious sedimentary sequence contrasts with other sedimentary sequences adjoining the Pilbara Block but resembles the basal units in the Proterozoic Glengarry Subgroup of the Nabberu Basin described by Bunting and others (1977).

The younger metamorphic suite lacks the high-grade gneissic foliation of the older suite, and is strongly folded by the F_2 deformation. The accompanying metamorphism is prograde in nature, with growth of muscovite, biotite and, to a lesser extent, chlorite, along the axial-planar foliation. Porphyroblastic andalusite and garnet is indicative of upper greenschist to low amphibolite facies metamorphism.

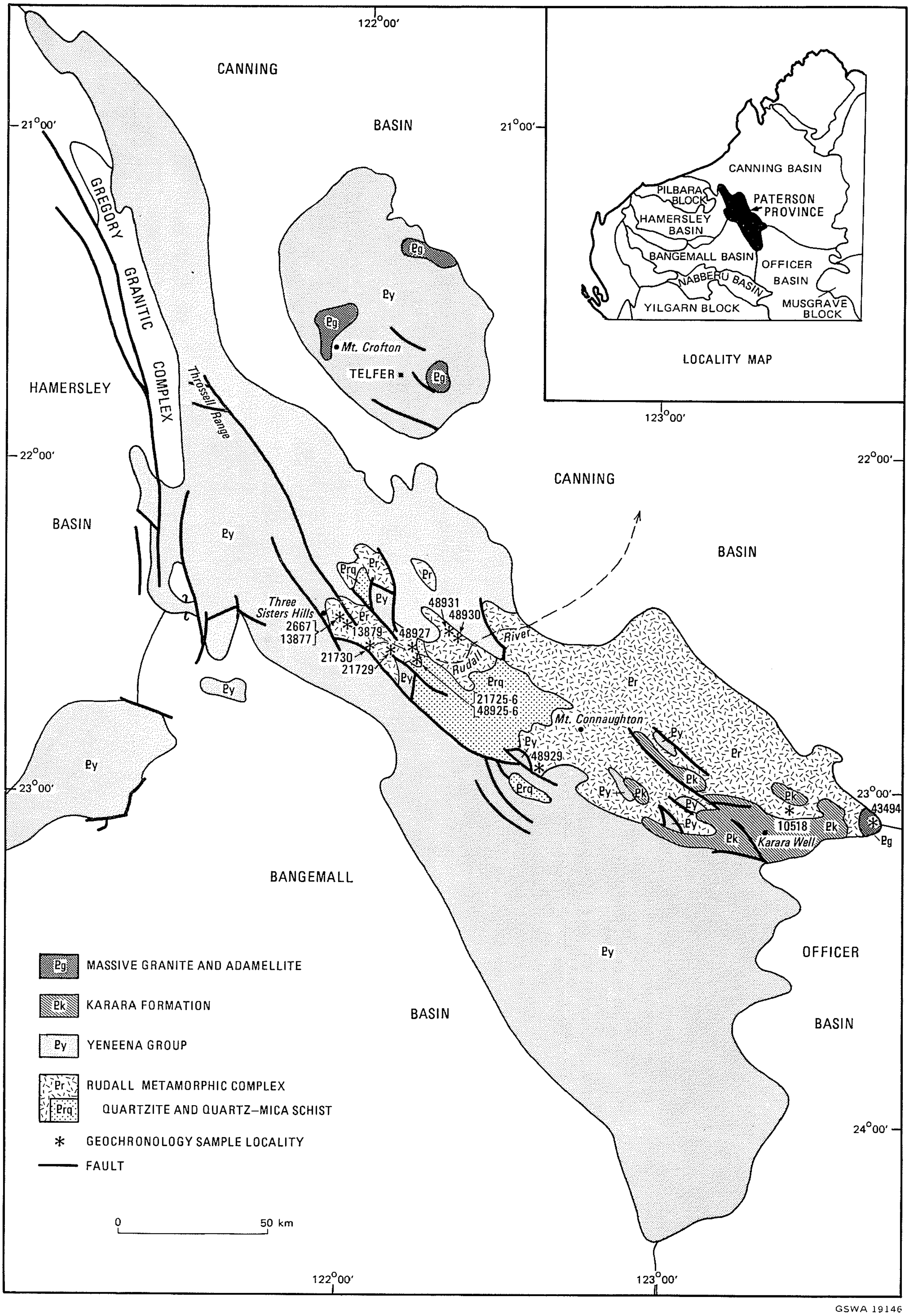


Figure 1 Geological map of the Paterson Province showing geochronology sample locations.

Towards the end of the F_2 event, bodies of serpentinized peridotite and small plugs of altered pyroxenite were emplaced into the metamorphic complex. The largest bodies are up to 1 km in diameter and have sheared margins, suggesting solid-state emplacement. These bodies resemble Alpine-type ultramafics and may, therefore, represent tectonic slices of the mantle emplaced during the deformation.

Pegmatite, dominantly rich in plagioclase, quartz and muscovite, forms dykes and veins which cut the F_2 foliation. Some veins are continuous up to the unconformity with the Yeneena Group have not been found in the Yeneena Group. However, it has not been indisputably proven that the pegmatite predates the unconformity. The mineralogy shows evidence of deformation and recrystallization during the F_3 deformation, which took place after deposition of the Yeneena Group. The pegmatite does not appear to be related to granite activity and was most probably a mobile phase, either generated during the intense F_2 metamorphism and subsequently emplaced into its present position, or generated during the early part of the F_3 event and emplaced before the end of the deformation period.

The last widespread deformation (F_3) produced crenulation and folding in the F_2 foliation of the metamorphic rocks. The resulting foliation trends north-northwesterly and is marked by slight mineral flattening and minor crystallization of sericite and chlorite along the crenulation surfaces.

SEDIMENTARY GROUPS

The Yeneena Group presumably occupied a basin, to the east of the Pilbara Block and Hamersley Basin, which extended throughout the full extent of the Paterson Province. The group consists mainly of an eastern facies of marine sandstone, shale and carbonate, and a western facies of dominantly fluviatile and deltaic conglomerate, sandstone and siltstone. The demarcation between the facies corresponds to an axial zone which controlled sedimentary patterns in the basin. This zone coincides with the western side of the Anketell Gravity Ridge (Fraser, 1974) that runs from the Throssell Range southeast to Karara Well where it swings easterly. It is thought to mark the boundary of a stable shelf to the southwest and a subsiding marine basin to the northeast. This axial zone also marks the zone of most intense thrust faulting, and strongest development of F_3 cleavage within the Yeneena Group. Southwest of this zone, the F_3 folding has an open style with little cleavage development.

The Karara Formation unconformably overlies the Yeneena Group. The uplift of the area of the Paterson Province along the zone of thrust faulting possibly initiated and confined the deposition in the Karara Formation which consists of an 1 800 m thick sequence of conglomerate, sandstone and shale. Its stratigraphic relationship to the Bangemall Group is uncertain.

GRANITE AND ADAMELLITE INTRUSIONS

Several bodies of granite and adamellite intrude the Yeneena Group. In the northern part of the province, they post-date the major folding (F_3) and accompany extensive static metamorphism in this region. The age of 598 ± 24 m.y. (581 ± 1 m.y. if a pegmatite sample is included) for one body near Mount Crofton was determined by Trendall (1974) using Rb-Sr isotopic methods.

An even-grained adamellite (informally referred to as the Runton adamellite), which forms part of the present investigation, outcrops in the extreme east of the central part of the province. Although its precise relationship to the Rudall Metamorphic Complex is not evident, the lack of metamorphic foliation suggests it is younger than the F_3 deformation.

MATERIAL ANALYSED

All the samples for Rb-Sr isotopic analyses are from the Rudall Metamorphic Complex, taken from localities shown in Figure 1. The location of sample 2669 collected by Talbot in 1908–1909 is not accurately known.

Samples comprising the randomly selected series in the initial investigation, were from the old field collections of Talbot (1910, 1920) and Blockley and de la Hunty (1975). All are retrograded biotite gneiss from the older gneiss suite. Three samples from this series have subsequently been discarded on the strong suspicion they are exotic glacial erratics, eroded from the Paterson Formation. The Archaean age which they generated was alluded to by Blockley and de la Hunty (1975, p. 116), and led to the presently unsubstantiated suggestion that ". . . remnants of Archaean rocks may have locally retained their isotopic age through a Proterozoic metamorphism". Nine samples in the first investigation were considered acceptable for the more recent dating project, for which further sampling was undertaken.

Seven different rock types were sampled; they included retrograded banded gneiss (48929, 48930), retrograded fine-grained and porphyritic granitic rocks (48925 and 48927, respectively) which intrude the gneiss, serpentinized peridotite (48926) from an ultramafic plug, intrusive pegmatite (48931) from the retrograded gneiss, and two samples (43494) from the undeformed Runton adamellite which intrudes the Rudall Metamorphic Complex. Six samples of each rock type, except 43494, were collected and these are referred to as "series" in this paper. Of these, the serpentinized peridotite (48926) proved to contain too little phlogopite for separation as a source for Rb and Sr, and preliminary XRF analysis showed that the porphyritic adamellite (48927) had insufficient spread of Rb/Sr ratios to warrant isotopic analysis.

The fine-grained adamellite samples (48925 series) were selected from a pile of abandoned drill core obtained by Northwest Oil & Minerals Co., who drilled two serpentinized peridotite plugs and the country rock in the Rudall area. The rock type selected fits most closely with the main surface exposures around the plug south of the Rudall River. The micas are predominantly metamorphic biotite which defines the F_2 foliation. Some later muscovite and chlorite, together with sericitized and epidotized feldspar, are indicative of later metamorphism or alteration.

Banded gneiss of granitic composition (48929 series) was selected from an area measuring 50 m by 100 m situated 18 km southwest of Mount Connaughton. This area is some distance from major faults and unconformities and shows little effects of later (F_3 and F_4) deformation or metamorphism. The F_2 foliation is poorly developed and the texture appears to be entirely granoblastic with no relict igneous texture. As in most samples, chloritization of biotite and saussuritization of plagioclase is widespread throughout this series of samples.

The 48930 series, from a locality 54 km northwest of Mount Connaughton, is gneiss with well-developed compositional banding and obvious retrogressive effects. Metamorphic biotite forms the directional fabric (F_2) but most of this group has extensive alteration products of epidote, muscovite, chlorite and carbonate. Quartz-epidote veining is common. Recrystallization is indicated by well-developed elongate granoblastic texture. One type of banding is represented by sharply bounded veins which formed before the F_2 deformation and metamorphism. These veins are composed of coarse-grained quartz and pink feldspar, and possibly are early pegmatitic segregations. The other type of banding is more diffuse and is expressed by compositional variations from microcline-plagioclase-quartz-biotite granofels to leucocratic granofels which is rich in microcline and devoid of biotite.

The pegmatite (48931 series) was sampled from two northwesterly trending parallel dykes about 120 m apart, located 1 km northwest of sample locality 48930. They crosscut both the gneissic banding and the F_2 metamorphic foliation of the retrograded gneiss, but have a strong F_3 cleavage. One dyke (48931A, B, C) is pegmatite composed of quartz, muscovite and abundant albite. The proportion of microcline varies from almost zero in 48931A to about equal with albite in 48931B. Samples 48931D, E and F from the other dyke are similar except that muscovite is less abundant. Minerals in both dykes are extensively crushed and crenulated by F_3. Fine sericite pervades most of the feldspar.

Two samples (43494A, B) are from the younger adamellite which intrudes the Rudall Metamorphic Complex. Sample 43494A is even-grained adamellite which intrudes weakly foliated adamellite as irregular dykes up to 1 m wide. Sample 43494B is from the weakly foliated phase. Because of similarity in composition and overall texture, these are thought to be phases of the same intrusion. The weak foliation in the early phase possibly results from the forceful injection of the younger phase.

EXPERIMENTAL PROCEDURES

The experimental procedures used in this study were essentially the same as those described by de Laeter and others (1981). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0·710 2 ± 0·000 1, normalized to a $^{88}Sr/^{86}Sr$ value of 8·375 2. The value of $1{\cdot}42 \times 10^{-11}\ yr^{-1}$ was used for the decay constant of ^{87}Rb (Steiger and Jäger, 1977).

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 1,. Errors accompanying the data are at the 95% confidence level. The Rb and Sr concentrations for all samples except those from the first group are also listed. However, these concentrations are only accurate to ± 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 1 are plotted in Figure 2. Regression of the data has been carried out using the least-squares programme of McIntyre and others (1966) and the results are

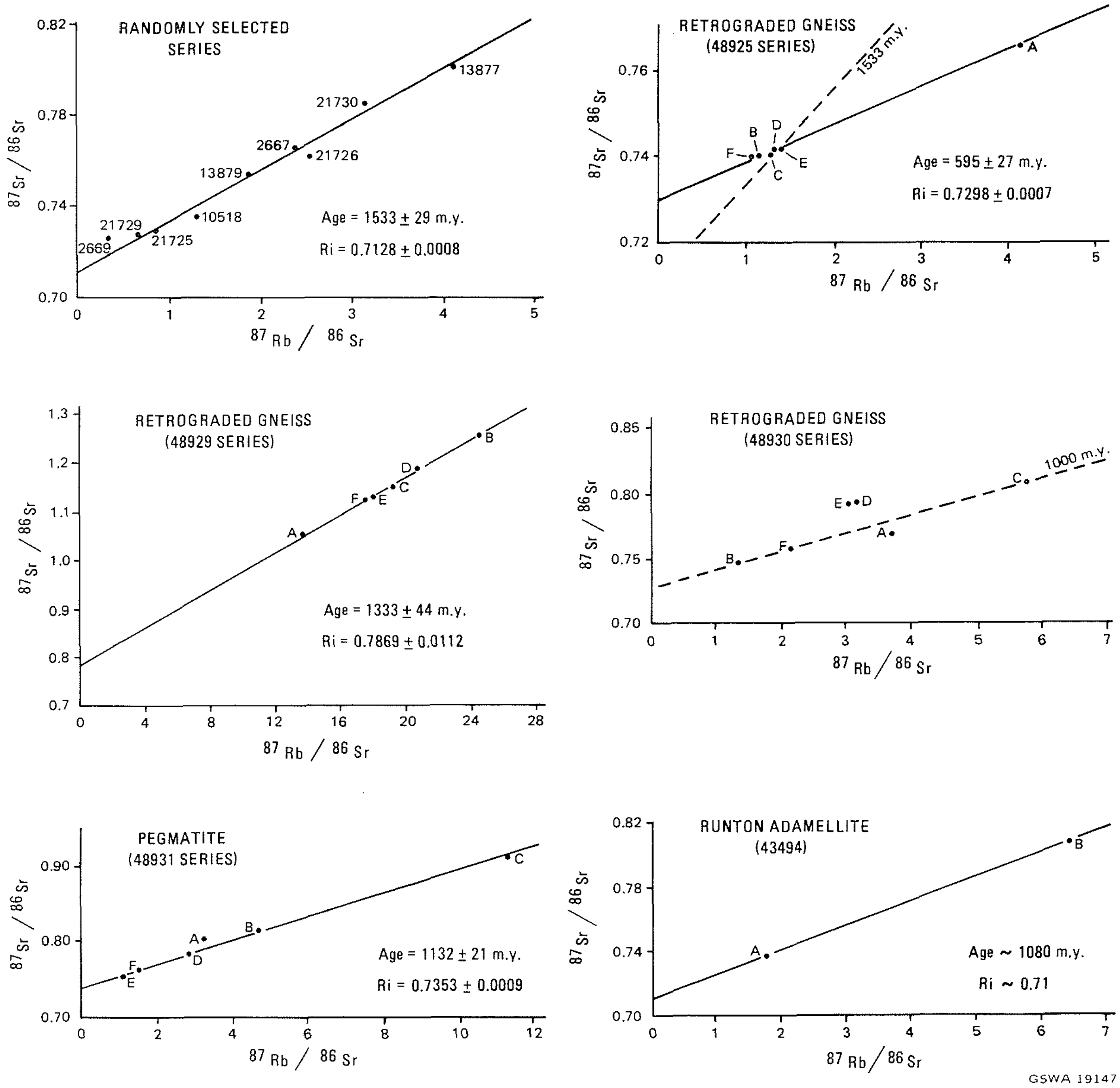


Figure 2 Rb-Sr isochron plots of sample series from the Rudall Metamorphic Complex.

summarized in Table 2. The regressed (Model 1) age (1 533 ± 29 m.y.) and initial ratio (0·712 8 ± 0·000 8) for the randomly selected series does not include samples 2669, 10518, 21726 as values for these points obviously do not form part of a well-defined isochron. The mean square of weighted deviates (MSWD) for this set of samples is 13·9. This indicates a scatter in the data which is probably due to a real variation in age.

The age of the 48925 series is 595 ± 27 m.y. with an initial ratio of 0·729 8 ± 0·000 7. The low MSWD suggests that this result can be classified as Model 1 (experimental error only). However, the reliability of this result is reduced by the fact that samples 48925B-F are concentrated over a small range and the age is consequently largely controlled by the sample 48925A. The age and initial ratio of the 48929 series is 1 333 ± 44 m.y. and 0·786 9 ± 0·011 2 and the data give a good fit. The 48930 series shows such a wide scatter of data that no computer regression was undertaken. The 48931 series give a poorly fitted isochron of 1 132 ± 21 m.y. and an initial ratio of 0·735 3 ± 0·000 9 (MSWD = 18·7). The Runton adamellite samples (43494A, B) generate a two-point isochron at about 1 080 m.y. and an initial ratio of about 0·71.

DISCUSSION

It is anticipated that the pervasive F_2 metamorphism, which has produced the metamorphic mica in the main foliation, would have the greatest control over the redistributon and homogenization of Sr isotopes. If homogenization was complete, the data will record a well-marked metamorphic date which lies between the age of the Bangemall Group and the age of the oldest known sedimentary basins which surround the Pilbara Block and from which the younger metasedimentary rocks of the Rudall Metamorphic Complex are likely to be derived. This indicates expected age limits between about 1 100 m.y. and 2 500 m.y. (Gee, 1980). High initial ratios in all series confirm prior crustal histories for the gneiss and granite prior to F_2 metamorphism but a definitive primary age for the gneiss could not be established from the results. However, the results are consistent with the older Archaean age for the gneiss that is suggested by geological considerations.

The rocks which show the least effects of alteration and metamorphism during later (F_3 and F_4) deformational events are the 48929 series which produce a good isochron at 1 333 ± 44 m.y. The high initial ratio of 0·786 9 ± 0·011 2 results from thorough metamorphic reworking of existing granitic rocks considerably enriched in Rb and ^{87}Sr relative to other samples analysed from the province. The data define a well-fitted isochron which indicates that there is sufficient homogenization of Sr isotopes over the area from which this series was selected. In view of the predominance of a single generation of metamorphic mica and corresponding metamorphic textures, the good isochron also suggests that the recorded age is that of the pervasive F_2 metamorphism at this locality.

The randomly selected series shows a high degree of scatter of data about the 1 533 m.y. isochron. Their petrology shows the predominance of the same style of F_2 metamorphic fabric as that of the 48929 series and also suggests that Sr isotope redistribution took place during this same event. The moderately high initial ratio (0·712 8 ± 0·000 8) indicates a crustal history prior to metamorphism. All samples used in the regression analysis were located in the headwaters of the

TABLE 1. ANALYTICAL DATA FOR WHOLE-ROCK SAMPLES FROM RUDALL METAMORPHIC COMPLEX

Sample	Rb (ppm)*	Sr (ppm)*	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Randomly selected series:					
2669	....	....	0·120 5 ± 0·001	0·349 ± 0·003	0·726 9 ± 0·000 2
21729	....	....	0·237 ± 0·002	0·686 ± 0·007	0·728 1 ± 0·000 2
21725	....	....	0·306 ± 0·003	0·886 ± 0·009	0·731 8 ± 0·000 2
10518	....	....	0·461 ± 0·004	1·335 ± 0·01	0·735 5 ± 0·000 2
13879	....	....	0·650 ± 0·004	1·885 ± 0·01	0·754 2 ± 0·000 2
2667	....	....	0·825 ± 0·008	2·390 ± 0·02	0·765 2 ± 0·000 2
21726	....	....	0·875 ± 0·009	2·540 ± 0·03	0·762 9 ± 0·000 2
21730	....	....	1·080 ± 0·010	3·140 ± 0·03	0·784 6 ± 0·000 4
13877	....	....	1·416 ± 0·014	4·130 ± 0·03	0·801 2 ± 0·000 2
48925 series:					
48925F	90	244	0·370 ± 0·003	1·07 ± 0·01	0·739 34 ± 0·000 27
48925B	110	275	0·400 ± 0·004	1·16 ± 0·01	0·739 79 ± 0·000 26
48925C	128	288	0·445 ± 0·004	1·29 ± 0·01	0·740 34 ± 0·000 14
48925D	130	290	0·449 ± 0·004	1·30 ± 0·01	0·740 73 ± 0·000 28
48925E	134	285	0·468 ± 0·005	1·36 ± 0·01	0·741 20 ± 0·000 12
48925A	152	107	1·42 ± 0·01	4·12 ± 0·04	0·764 84 ± 0·000 20
48929 series:					
48929A	320	70	4·57 ± 0·10	13·63 ± 0·2	1·047 21 ± 0·000 23
48929F	355	61	5·83 ± 0·11	17·52 ± 0·2	1·124 17 ± 0·000 27
48929E	355	60	5·96 ± 0·12	17·91 ± 0·2	1·127 27 ± 0·000 19
48929C	380	60	6·37 ± 0·13	19·19 ± 0·3	1·152 60 ± 0·000 31
48929D	365	53	6·87 ± 0·14	20·75 ± 0·3	1·185 35 ± 0·000 25
48929B	400	50	8·03 ± 0·16	24·43 ± 0·3	1·252 76 ± 0·000 28
48930 series:					
48930B	125	280	0·45 ± 0·01	1·30 ± 0·02	0·748 46 ± 0·000 18
48930F	130	175	0·74 ± 0·02	2·15 ± 0·03	0·757 00 ± 0·000 21
48930E	135	130	1·05 ± 0·02	3·06 ± 0·04	0·790 52 ± 0·000 23
48930D	170	160	1·07 ± 0·02	3·11 ± 0·04	0·790 55 ± 0·000 20
48930A	200	160	1·26 ± 0·03	3·66 ± 0·05	0·768 03 ± 0·000 28
48930C	220	110	1·98 ± 0·04	5·77 ± 0·1	0·808 95 ± 0·000 24
48931 series:					
48931E	40	100	0·41 ± 0·01	1·19 ± 0·02	0·753 41 ± 0·000 18
48931F	45	80	0·54 ± 0·01	1·57 ± 0·03	0·760 56 ± 0·000 15
48931D	110	110	0·99 ± 0·02	2·88 ± 0·04	0·783 57 ± 0·000 31
48931A	110	100	1·12 ± 0·02	3·31 ± 0·08	0·799 28 ± 0·000 21
48931B	160	100	1·60 ± 0·03	4·67 ± 0·1	0·812 61 ± 0·000 25
48931C	300	85	3·50 ± 0·07	11·21 ± 0·2	0·913 08 ± 0·000 28
Runton adamellite:					
43494A	200	335	0·60 ± 0·01	1·74 ± 0·02	0·737 70 ± 0·000 18
43494B	290	130	2·19 ± 0·04	6·39 ± 0·02	0·809 37 ± 0·000 24

* Rb and Sr concentrations for randomly selected series were not determined.

Rudall River. Amongst the samples excluded were 10518 (10 km northeast of Karara Well) and 2669 whose location is not known. The scatter of points about the isochron possibly reflects lack of complete Sr isotope homogenization across the wider area of sampling in contrast to the apparent homogenization in the smaller area of collection of the 48929 series. Furthermore, slight disturbance of the isotopic system may be due to other events which are shown by the results of the other series discussed below.

From the uniform intensity and penetrative style of the F_2 metamorphism and deformation throughout the Rudall Metamorphic Complex, it can be inferred that the age of 1 333 m.y. from the controlled 48929 series is a single event. It is then likely that the isochron of the randomly selected series is a composite of an older age largely modified by the younger F_2 metamorphism. However, it cannot be altogether discounted that the closure of the Rb-Sr isotopic system occurred earlier (at 1 533 m.y.) in the northwestern part, and later (at 1 333 m.y.) in the central part, of the Rudall Metamorphic Complex.

Because the deposition of the Yeneena Group clearly postdates the F_2 metamorphic foliation, the 1 333 m.y. age is considered to be the oldest possible age so far identified for the Yeneena Group.

The 48925 series which produces a well-defined isochron at 595 ± 27 m.y. possesses F_2 metamorphic micas, but these rocks are affected by various degrees of sericitization and saussuritization of feldspar and chloritization of biotite. Most of the samples (B-F) form a cluster with an elongate distribution along the isochron. These points also cluster close to the isochron produced by the randomly selected series (see Fig. 2), and probably relate to that series.

There is no geological evidence for the event at about 600 m.y. recorded by the 48925 series in the Rudall River area. Alteration, which may be the result of an event of this age, cannot be easily distinguished from other post-F_2 metamorphic alteration. The 600 m.y. age is known from granite intrusion metamorphism in the Mount Crofton area in the northern part of the Paterson Province. Although granite intrusions which postdate the F_3 fabric are not known in the Rudall Metamorphic Complex, alteration of 600 m.y. age can reasonably be expected in the Rudall River area. Local crenulation and alteration by a later event (F_4), although not observed in retrograded gneiss, were observed in the general area and possibly provide another explanation for the scatter effects of the Rb–Sr isotopic equilibrium.

The 48930 series is located close to the Yeneena Group unconformity and consequently has been subject to significant deformation (F_3) which folds the Yeneena Group. The series has also possibly been subject to the 600 m.y. event recorded by the 48925 series. From the wide spread of the data, it is concluded that these later events resulted in some irregular distribution of the Sr isotopes. In particular, the F_3 metamorphism has initiated the growth of sericite and chlorite along the foliation but, due to the low grade of metamorphism, complete Sr homogenization was not accomplished.

Petrological observations of the 48930 series do not reveal any relationship between the degree of alteration of a sample and its position in the isotopic plot. In one instance, the most altered sample (48930E), which contains abundant carbonate sericite and epidote, plotted in almost the same position as the least altered sample (48930D) whose metamorphic biotite (generated during F_2 metamorphism) is free of alteration.

TABLE 2. WHOLE-ROCK AGES FROM RUDALL METAMORPHIC COMPLEX

Samples	No. of samples	MSWD*	Age (m.y.)	Initial ratio (R_i)	Model
Randomly selected series	6	13·9	1 533 ± 29	0·712 8 ± 0·000 8	1
			1 535 ± 91	0·712 7 ± 0·001 7	2
48925	6	1·06	595 ± 27	0·729 8 ± 0·000 7	1
48929	6	1·14	1 333 ± 44	0·786 9 ± 0·011 2	1
48930	6	N.D.	N.D.	N.D.	....
48931	6	18·7	1 132 ± 21	0·735 3 ± 0·009	1
43494	2	....	1 080	0·71	....

* Mean square of weighted deviates.
N.D. Not determined.

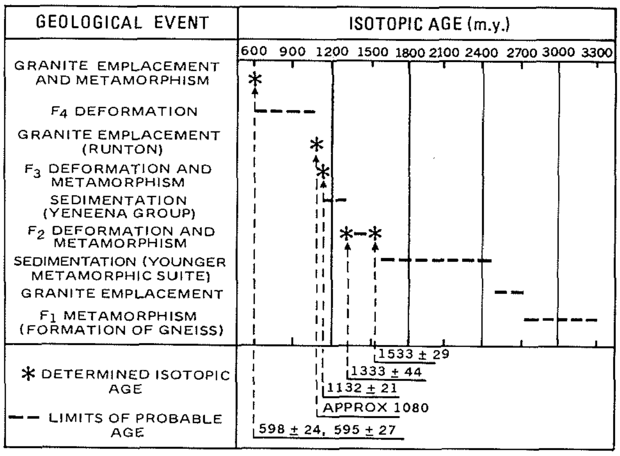
The pegmatite (48931 series) clearly was emplaced after the F_2 metamorphism had waned and if generated during that event would be expected to have an age around 1 300 m.y. It was probably subject to the same metamorphic and alteration conditions as the 48930 series, and recrystallization during the F_3 deformation may be responsible for redistribution of Sr and some scattering of points off the isochron (MSWD = 18·7). Thus the isochron may record the approximate date of the F_3 deformation in the Yeneena Group.

However, a second interpretation is that the pegmatite was generated within the Rudall Metamorphic Complex during the early part of the F_3 event but was not emplaced into the Yeneena Group. In this case 1 132 m.y. is possibly the primary age of the pegmatite. This interpretation leads to the same conclusion that this is also the approximate age for the F_3 deformation of the Yeneena Group.

The two-point isochron for the Runton adamellite samples (43494) is the first evidence obtained from the Paterson Province for granite activity along the zone of the Anketell Gravity Ridge. The age (about 1 080 m.y.) is consistent with the lack of foliation in the adamellite. The moderately high initial ratio (0·71) suggests that there is considerable crustal reworking prior to the adamellite emplacement.

CHRONOLOGICAL SUMMARY OF EVOLUTION OF THE PATERSON PROVINCE

From the geochronological results reported in this paper and the geological knowledge of the Paterson Province, the chronological sequence of events has now been established and is summarized in Figure 3.



GSWA 19148

Figure 3 Age of important geological events in the Paterson Province.

AGES OF POSSIBLY RELATED PROTEROZOIC PROVINCES

The Musgrave Block lies at the eastern end of the Anketell Gravity Ridge and, consequently, possibly comprises part of the same tectonic structure manifested by the gravity ridge. Even though the style and grade of metamorphism and deformation is different from that of the Rudall Metamorphic Complex, similar ages from gneisses and granites have been recorded.

A study of the ages of granulite metamorphism by Gray (1979) revealed an age of about 1 550 m.y. in the region north of a prominent fault (the Hinckley Fault) and 1 330 m.y. in the southern region. In the Rudall Metamorphic Complex the ages from the randomly selected series and the 48929 series correspond fairly closely to both ages in the Musgrave Block.

The ages of granitic intrusions within granulite of the Musgrave Block were determined by Arriens and Lambert (1969). Model 3 ages of 1 099 ± 27 m.y. are recommended for the isochron defined by all the granite samples and 1 098 ± 96 m.y. for the Ernabella Adamellite alone. The age is comparable to the Runton adamellite (43494) and possibly corresponds to the same tectonic activity along the Anketell Gravity Ridge. Initial ratios of about 0·71 are also comparable and may reflect a similar crustal history for both granites.

The Albany-Fraser Province, like the Paterson Province, borders an Archaean craton. In the northeastern part it contains a number of tectonic zones ranging in age between about 1 690 m.y. and 1 250 m.y. (Bunting and others, 1976). From the granulite zone in the Fraser Range, an age of 1 300 m.y. has been determined (Arriens and Lambert, 1969). Intrusions in other parts of the province have been dated at 1 077 ± 50 m.y. (initial ratio 0·712 ± 0·006) for the Albany Adamellite (Turek and Stephenson, 1966) and 1 057 ± 50 m.y. (initial ratio 0·715 ± 0·0006) from porphyritic granite at Balladonia Rock (Arriens, pers. comm., quoted by Doepel, 1975).

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REFERENCES

Arriens, P. A., and Lambert, I. B., 1969, On the age and strontium isotopic geochemistry of granulite-facies rocks from the Fraser Range, Western Australia and the Musgrave Ranges, Central Australia: Geol. Soc. Aust. Spec. Pub. No. 2, p. 377–388.

Blockley, J. G., 1974, Notes on the Paterson Range gold prospects: West. Australia Geol. Survey Ann. Rept 1973, p. 71–73.

Blockley, J. G., and de la Hunty, L. E., 1975, Paterson Province, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 114–119.

Bunting, J. A., Commander, D. P., and Gee, R. D., 1977, Preliminary synthesis of Lower Proterozoic stratigraphy and structure adjacent to the northern margin of the Yilgarn Block: West. Australia Geol. Survey Ann. Rept 1976, p. 43–48.

Bunting, J. A., de Laeter, J. R., and Libby, W. G., 1976, Tectonic subdivisions and geochronology of the northeastern part of the Albany-Fraser Province, Western Australia: West. Australia Geol. Survey Ann. Rept 1975, p. 117–126.

Chin, R. J., and Hickman, A. H., 1977, Proterozoic geology of the Paterson Range, W.A., 1:250 000 Sheet: West. Australia Geol. Survey Rec. 1977/11 (unpublished).

Chin, R. J., Williams, I. R., Williams, S. J., and Crowe, R. W. A., 1979, Explanatory notes on the Rudall 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1978/17.

Crowe, R. W. A., and Chin, R. J., 1978, Explanatory notes on the Runton, W.A., 1:250 000 Geological Sheet: West. Australia Geol. Survey Rec. 1977/17 (unpublished).

de Laeter, J. R., Hickman, A. H., Trendall, A. F., and Lewis, J. D., 1977, Geochronological data concerning the eastern extent of the Pilbara Block: West. Australia Geol. Survey Ann. Rept 1976, p. 56–62.

de Laeter, J. R., Williams, I. R., Rosman, K. J. R., and Libby, W. G., 1981, A definitive 3 350 m.y. age from banded gneiss, Mount Narryer area, Western Gneiss Terrain: West. Australia Geol. Survey Ann. Rept 1980, p. 94–98.

Doepel, J. J. G., 1975, Albany-Fraser Province, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 94–102.

Fraser, A. R., 1974, Reconnaissance helicopter gravity survey of the Northwest of Western Australia, 1969: Australia Bur. Mineral Resources Rec. 1974/27.

Gee, R. D., 1979, Structure and tectonic style of the Western Australia Shield: Tectonophysics, v. 58, p. 327–369.

———— 1980, Summary of the Precambrian stratigraphy of Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 85–90.

Gray, C. M., 1979, Geochronology of granulite-facies gneisses in the western Musgrave Block, Central Australia: Geol. Soc. Australia, Jour., v. 25, p. 403–414.

Maitland, A. G., 1919, A summary of the geology of Western Australia, *in* The Mining Handbook of Western Australia: West. Australia Geol. Survey Mem. 1, Ch. 1.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb–Sr isochrons: Jour. Geophys. Research, v. 71, p. 5459–5468.

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on use of decay constants in Geo- and Cosmochronology: Earth and Planetary Sci. Letters. v. 36, p. 359–362.

Talbot, H. W. B., 1910, Geological observations in the country between Wiluna, Hall's Creek, and Tanami: West. Australia Geol. Survey Bull. 39.

———— 1920, The geology and mineral resources of the Northwest, Central and Eastern Divisions between Long. 119° and 122°E and Lat. 22° and 28°S: West Australia Geol. Survey Bull. 83.

Traves, D. M., Casey, J. N., and Wells, A. T., 1956, The geology of the southwestern Canning Basin, Western Australia: Australian Bur. Mineral Resources Rept No. 29.

Trendall, A. F., 1974, The age of a granite near Mount Crofton, Paterson Range Sheet: West. Australia Geol. Survey Ann. Rept 1973, p. 92–96.

Turek, A., and Stephenson, N. C. N., 1966, The radiometric age of the Albany Granite and the Stirling Range Beds, southwest Australia: Geol. Soc. Australia Jour., v. 13, p. 449–456.

Wells, A. T., 1959, Paterson Range—4-mile geological series sheet: Australia Bur. Mineral Resources Explanatory Notes No. 17.

———— 1960, Tabletop—4-mile geological series sheet: Australia Bur. Mineral Resources Explanatory Notes No. 18.

Williams, I. R., Brakel, A. T., Chin, R. J., and Williams, S. J., 1976, The stratigraphy of the Eastern Bangemall Basin and Paterson Province: West. Australia Geol. Survey Ann. Rept 1975, p. 79–83.

Williams, I. R.. and Williams S. J., 1977, Explanatory notes on the Gunanya 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1977/7 (unpublished).

Yeates, A., and Chin, R. J., 1979, Explanatory Notes Tabletop, W.A., 1:250 000 Geological Sheet: Australia Bur. Mineral Resources.

MERCURY IN SOME WESTERN AUSTRALIAN MINERALIZED ROCKS

by R. Davy, R. J. Marston and C. J. Dodd*

ABSTRACT

The mercury contents of some Western Australian mineralized rocks, together with concentrates prepared from these samples, have been determined, and show a wide range of variation. Mercury is preferentially concentrated in sphalerite where that phase is present. The stratabound copper-zinc deposits of volcanigenic origin commonly contain in excess of 1 ppm mercury. Vein deposits show a wide range of mercury (25 ppb–4·4 ppm), but magmatic nickel-copper deposits lack appreciable mercury (<200 ppb). Further research into mercury-halo prospecting in Western Australia should be directed towards the stratabound copper-zinc deposits.

INTRODUCTION

The use of Hg as a pathfinder element for base and precious metal deposits is now well documented (for example, Williston, 1964; Ozerova and others, 1975), and has been used for this purpose by various exploration organizations in Western Australia. Reference is made to its use by Cordwell (1965, at Kalgoorlie South) and by Smith (1980, at Mons Cupri), but no data pertinent to either its use in practice, or even to the presence or absence of Hg in different types of mineralization, have been published. This study is intended to provide some preliminary data on the Hg content of some mineralized rocks in Western Australia in the hope that it will stimulate more detailed studies.

An earlier study which showed that there were wide variations in the Hg content of 20 mineralized samples (Davy and Dodd, 1979) has been extended to include samples of copper mineralization collected as part of a statewide appraisal of copper occurrences (Marston, 1979). Additional samples were collected at Golden Grove and Teutonic Bore, by courtesy of Esso Exploration and Production Australia Inc. and Seltrust Mining Corporation Pty Ltd respectively.

The study has been based on that of Sears (1971). An attempt is made to classify qualitatively those types of mineralization which contain enough Hg for measurable dispersion away from the deposit. Considering the generally low content of Hg (<100 ppb†) in unmineralized rocks and soils (USGS, 1970; Jonasson, 1970; Jonasson and Boyle, 1972) and the extremely low detection limit of present-day analytical methods (about 5 ppb), deposits containing about 1 ppm Hg may be detectable at the surface by their Hg halo.

Jonasson and Sangster (1975) showed that Hg is preferentially collected in sphalerite rather than in chalcopyrite in those rocks where the two minerals occur together. In this study, therefore, the opportunity was taken to compare sphalerite and chalcopyrite concentrates and bulk ("head") sample analyses. In the case of non-cupriferous rocks, a single concentrate was obtained. In some instances this was monomineralic, but in others there was a mixture of various sulphides and heavy oxides. No attempt was made to separate pyrite and pyrrhotite concentrates from any sample. The Hg content of pyrite and pyrrhotite is generally thought to be of the same order as that of chalcopyrite (Jonasson and Boyle, 1972; Jonasson and Sangster, 1975).

*Western Australian Government Chemical Laboratories

†1 ppb = 1 x 10^{-9} g/g = 1 ng/g

PROCEDURES

SAMPLE PREPARATION

Each sample was crushed and lightly ground in a Rocklabs ring mill. A portion of the crushed material was retained for reference, and a further portion was analysed as a bulk sample. Fine-grained material less than 300 mesh BSS (53 μm aperture) was discarded.

An attempt was made to avoid contamination of the concentrates by minimizing their contact with laboratory reagents. Where possible, concentrates were obtained by separation from the less than 120 mesh and greater than 300 mesh fraction using a Frantz isodynamic magnetic separator. However, separation of concentrates from very fine-grained material or from interlocked compound-mineral grains was not possible in this way. Accordingly, separation had to be achieved using conventional tetrabromoethane and Clerici Solution heavy-liquid methods, in conjunction with the Frantz.

Clean separations of sphalerite were sometimes made but in many cases chalcopyrite concentrates contained up to 10% of other minerals, mainly pyrite or pyrrhotite. Care was taken to eliminate sphalerite from chalcopyrite concentrates. Tests on pyrite and pyrrhotite showed low values of Hg (<200 ppb) and further separation was not considered warranted because the diluent effects are contained within the limits of analytical error. The purity of the concentrates was checked at each stage by the preparation of polished sections.

All powdered samples and concentrates were refrigerated between preparation and analysis to minimize redistribution of the contained mercury.

ANALYTICAL METHOD

The method consisted of the dissolution of the sample by a concentrated nitric-hydrochloric acid mixture followed by concentrated sulphuric acid (Jonasson and others, 1973). Excess potassium permanganate ensured complete oxidation (Agemian and others, 1975), and ammonium metavanadate was used as catalyst (Dietz and others, 1973). The only residues were silica, and ferrites in nickel-bearing samples.

The contained Hg was reduced to the elemental state by stannous chloride and carried by air through a closed system to a quartz absorption cell in the optical path of a spectrometer (modified from Hatch and Ott, 1968). The absorbance of the Hg 253·7 nm line was measured and compared with several USGS standard rocks and with other prepared standards analysed by the same technique. The detection limit was 5 ppb. Statistical tests on 3 samples before commencement of routine analyses (Table 1) established the overall precision at approximately 20% (co-efficient of variation). Reliability was improved by routinely analysing samples and concentrates in duplicate.

RESULTS

The main results are given in Table 2. This provides not only the range of Hg values found but also a classification of the types of deposit, the inferred approximate temperature of formation of the mineralization, and the grade of metamorphic events affecting the deposit.

TABLE 1. STATISTICAL STUDY OF ANALYTICAL PRECISION
(Values in ppb)

GSWA No.	Deposit	Sample Type	Number of Determ-inations	Range	Mean $\bar{x}$	Standard Deviation σ	Coefficient of variation $100\sigma/\bar{x}$
59422	Golden Grove	Bulk	14	587–936	762	116	15·2
		Chalcopyrite	15	605–1 313	913	158	17·3
59425	Elverdton	Bulk	13	230–515	351	95	27·0
		Chalcopyrite	6	700–840	769	49	6·4
62929	Teutonic Bore	Bulk	8	3 265–4 022	3 561	263	7·4
		Sphalerite	6	4 495–5 915	5 047	495	9·8

HIDDEN SECRET MINE, KALGOORLIE

The apparent absence of any Hg in an Au-Te mineralized sample from the Hidden Secret Gold Mine, Kalgoorlie is notable. Conventional analysis suggested that no Hg was present, but attempts to recover Hg from a sample spiked with 100 nanograms of Hg were unsuccessful, the Hg being totally absorbed by the sample. This is probably due to the amalgamating effects of Au and particularly Te, and it is probable that the fresh rock contains several parts per million of Hg.

DISCUSSION

The Hg-halo prospecting technique is of most use in the search for blind metalliferous ore bodies. Where ore bodies, or their related caprocks, are exposed, it is considered that direct analysis for a wide range of metals of economic interest will be as cheap as, and more informative than, analysis for Hg. Though many of the deposits sampled in this study do crop out, subsequent discussion is directed towards blind ore bodies.

The results do not attempt to describe the overall Hg content of any particular mineralized body. Analyses for the deposits at Golden Grove and at Teutonic Bore, and results published for Woodlawn, NSW, and Broken Hill, NSW (Ryall, 1979a, 1979b) give some indication of the range of values expected. However, it is still possible to recognize in general terms those deposits where substantial Hg can be predicted. There is consistency between samples from deposits of the same type which suggests that the general conclusions are valid. It is recognized that a low value for a single sample from a deposit does not preclude high Hg values elsewhere in the deposit.

TYPE OF DEPOSIT AND TEMPERATURE OF FORMATION

Three main types of mineral deposit have been studied:

(a) Ni-Cu sulphide deposits associated with gabbroic and ultramafic rocks,

(b) stratabound Cu-Zn deposits, and

(c) vein deposits of various kinds.

A few deposits, such as those of the Ravensthorpe area, overlap the boundaries between vein and stratabound deposits. One sample has been taken from a metamorphosed greisen (Mount Mulgine) in mafic and ultramafic rocks, and another from a syngenetic disseminated Cu-pyrite deposit (Arrino).

The results (Table 2) indicate that the potential for using Hg to locate Ni-Cu deposits is minimal. No analysed sample contains more than 200 ppb Hg and there is little preferential concentration in the various concentrates.

The stratabound deposits are consistently high in Hg except for the Bunnawarra Cu-Zn deposit in the Murchison Province. However, the sample analysed came from the Cu-rich part of the deposit and contained no sphalerite. A Zn-rich zone (Marston, 1979, p. 129) was not tested.

The greatest variations in Hg values occur in the vein deposits. Bulk samples containing as much as 4·8 ppm (Moonlight mine, Wiluna) and as little as 25 ppb (Ridge Bros. mine, Evanston) were recorded.

The relationship between the Hg content and the type of mineralization is dependent, among other things, on:

(a) the absolute amount of Hg available,

(b) the availability of suitable minerals to retain Hg, and

(c) the temperature of formation of the deposit.

The data support the findings of Jonasson and Sangster (1975) in that sphalerite is shown to carry large amounts of Hg. Table 3 lists samples from which separate sphalerite and chalcopyrite concentrates could be obtained. In these samples, sphalerite contains up to 10 times the Hg content of the chalcopyrite. Where sphalerite and chalcopyrite co-exist the actual concentrations of Hg in the two phases is a function of the relative proportions of the minerals and a function of a partition law regulating the distribution of Hg.

Where chalcopyrite occurs separate from sphalerite there is a wide variation in Hg content, though the absolute amount is normally low. Chalcopyrite from Turtle Creek (Halls Creek Province) and from Whim Creek (Pilbara Block), which contains high Hg, also contains small inclusions of unidentified sulphides/sulphosalts, probably tetrahedrite or bournonite (Marston, 1979). These minerals are known as excellent collectors of Hg (Jonasson and Boyle, 1972) and probably contain most of the Hg.

Of the other sulphides studied, stibnite from the Moonlight mine, Wiluna, and a combined cobaltite and chalcopyrite concentrate from the Alice Mary mine, Kundip, contain 4·4 ppm and 3·2 ppm Hg, respectively. Arsenopyrite, pyrite, galena and molybdenite all contain low amounts of Hg (<700 ppb).

Many of the differences in the Hg content of the various deposits may be explicable in terms of the temperatures of formation. Suggested temperatures of formation for the mineralized deposits are given in Table 2, though in no case has geothermometry work been carried out. The estimates given are based on theoretical or actual examples from the literature; or, where deposits are considered to be of metamorphic origin, the temperature relates to the metamorphic grade given. The deposits containing most Hg are those formed between 100 and 400°C. It is unlikely that Hg, even if present in the original magma, would be retained in the high-temperature deposits. Experimental work by Reed and others (1972) and Watling and others (1973) suggests that Hg is released thermally from all sulphides at temperatures in excess of 625°C. It is unlikely that Hg would be retained in the lattice of sulphides formed above this temperature.

In the case of the low temperature sandstone hosted deposit like that of Arrino, the Cu is derived from ambient-temperature solutions which probably contained no Hg ions.

EFFECTS OF METAMORPHISM

The effects of metamorphism on Hg in mineral deposits is not fully understood. The works of Watling and others (1973), Reed and others (1972), and Ozerova and others (1975) indicate that Hg is likely to be lost during high-temperature metamorphism. However, Sears (1971), Jonasson and Sangster (1975) and Ryall (1979b) have all found high Hg levels in highly metamorphosed sulphide deposits.

The metamorphic grade of the samples studied is given in Table 2. Most deposits which contain appreciable Hg lie in greenschist facies rocks. Only in the Ravensthorpe area, at the Copper King, Last Venture and Alice Mary mines, is Hg present above 1 ppm when the metamorphic grade is amphibolite facies.

It may be significant that the Hg content of 3 veins (Ridge Bros mine, Evanston; Mistletoe mine, Day's Find; and Copper Queen mine, Mulline) from amphibolite facies terrains is quite low. Clearly more study is needed on the effects of metamorphism.

Veins which, subsequent to formation, have never been metamorphosed above greenschist facies conditions, and which contain little Hg, probably never contained any greater amount of Hg. Veins in rocks of the Ravensthorpe area are not of simple hydrothermal origin. Marston (1979, p. 135) argued that many of the Cu deposits, now in veins, are the product of metamorphic mobilisation of stratabound volcanigenic deposits. If the vein sulphides are identical in composition to the original stratabound sulphides, the original Hg content of deposits from the Ravensthorpe, Mount McMahon and Mount Desmond Groups of mines (represented here by samples from Elverdton, Ravensthorpe, Mount Benson and Mount Cattlin mines) was unusually low. However, these veins were subject to amphibolite facies metamorphism, the sulphide compositions may not be equivalent to those of the original sulphides, and Hg may have been lost from the system.

TABLE 2. MERCURY CONTENT OF ANALYSED SAMPLES CLASSIFIED BY DEPOSIT

Deposit (locality)	Mineralization	Temperature of formation (approx. °C)	No. of samples	Range of Hg Content				Metamorphic grade
				Bulk	Chalcopyrite	Sphalerite	Other (named)	
				parts per billion				
Nickel-Copper Deposits:								
Sally Malay (HC)	....	>1 000	3	60–150	140–300	....	....	G
Mount Sholl (P)	....	>1 000	1	110	....	....	....	LG
Carr Boyd (Y)	....	>1 000	2	40–80	30–55	....	....	LA
Mount Edwards (Y)	....	>1 000	2	60–80	110–170	....	....	MA
Mount Windarra (Y)	....	>1 000	1	110	110	....	....	MA
Nepean (Y)	....	>1 000	1	55	....	....	....	UA
Spargoville (Y)	....	>1 000	1	55	20	....	....	MA
Widgiemooltha (Y)	....	>1 000	1	100	210	....	....	MA
Stratabound Copper-Zinc Deposits				parts per million				
Yarraloola (G)	Cu-Pb-Zn	250–300	1	15	1·6	17	....	LG
Turtle Creek (HC)	Cu-Pb-Zn	250–300	2	28–38††	....	....	....	LG
			1	300††	400††	....	....	LG
Big Stubby (P)	Zn-Pb-Cu-Ba	250–300	1	16	2·7	....	....	?LG
Whim Creek (P)	Cu-Zn	250–300	1	0·54	....	....	....	?LG
			3	1·2–23	2·3–52	....	....	
			1	160	....	340	....	
Bunnawarra (M)	Cu-Zn	250–300	1	0·07	0·1	....	....	UG
Golden Grove (M)	Cu-Zn	250–300	1	0·90	1·5	16	....	G
			4	5·1–6·4	....	5·7–8·1	....	
			6	0·12–0·35	0·17–1·8	....	....	
Nangaroo (Y)	Zn-Cu	250–300	1	3·7	....	....	....	LG
			3	0·27–1·4	0·45–0·61	....	....	
			1	2·0	....	2·4	....	
Teutonic Bore (Y)	Zn-Cu	250–300	6	0·25–3·3	0·20–4·0	....	....	G
			6	2·7–7·1	....	3·3–11	....	
			2	0·65–1·0	0·85–0·86	3·1–3·5	....	
Copper King (R)	Cu(-Zn)	?	1	0·42	1·2	4·5	....	A
Last Venture (R)	Cu-Zn	?	2	0·13–6·6	0·28–5·2	....	....	A
Vein Deposits:								
Ridge Bros, Evanston (Y)	Au	550	1	0·03	....	....	0·22 (Arsenopyrite)	HA
Mistletoe, Day's Find (Y)	Au	450–500	1	0·10	....	....	0·25 (Arsenopyrite*)	LA
Copper Queen, Mulline (Y)	Au-Cu	450–500	1	0·50	0·40	....	....	....
Gladiator, Laverton (Y)	Au	400	1	0·12	....	....	0·10 (Pyrite/Magnetite)	G
Great Boulder (Y)	Au	400	1	0·21	....	....	0·70 (Pyrite†)	G
Hidden Secret, Kalgoorlie (Y)	Au-Te	400	1	‡	....	....	‡	G
Lilly Blanche, Roebourne (P)	Cu	400	1	2·4	2·5	....	....	?G
Q.E., Carlow Castle (P)	Cu-Au	400	1	3·7	1·3	4·5	....	?G
Moonlight, Wiluna (Y)	Au-Sb	300	1	4·8	....	....	4·4 (Stibnite)	LG
Nooka (N)	Pb-Zn	100–150	1	0·57	....	0·60	....	U
Wanernooka (N)	Cu-Pb	100–150	1	1·2	0·97	....	....	U
Mundijong (SW)	Pb	?	1	0·07	....	....	0·09 (Galena)	?
Alice Mary (R)	Au-Co	?	1	3·6	....	....	3·2 (Cobaltite + chalcopyrite)	A
Elverdton (R)	Cu-Au	?	2	0·12–0·22	0·16–0·22	....	....	A
Ravensthorpe (R)	Cu	?	1	0·14	0·08	....	....	A
Mount Benson (R)	Cu-Au	?	1	0·15	0·10**	....	....	A
Mount Cattlin (R)	Cu-Au	?	2	0·06–0·08	0·04–0·09	....	....	A

OTHER DEPOSITS				Bulk	Concentrates	
Greisen:						
Mount Mulgine (M)	Mo-W	500–700	1	0·13	0·31 (molybdenite) 0·18 (magnetite)	G
Sandstone-hosted:						
Arrino (PB)....	Cu	>50	1	0·10	0·13 (Chalcopyrite)	U

KEY:
- * contains minor pyrite
- † contains minor arsenopyrite
- ‡ see discussion in text
- ** contains 10% pyrrhotite
- †† contains bournonite and tetrahedrite

LOCALITY (TECTONIC PROVINCE):
- HC Halls Creek Province
- P Pilbara Block
- Y Eastern Goldfields Province, Yilgarn Block
- G Gascoyne Province
- M Murchison Province, Yilgarn Block
- R Ravensthorpe area, S. Yilgarn Block
- SW Southwestern Yilgarn Block
- PB Perth Basin
- N Northampton Block

METAMORPHIC GRADE:
- G Greenschist Facies
- LG Lower Greenschist Facies
- UG Upper Greenschist Facies
- A Amphibolite Facies
- LA Lower Amphibolite Facies
- MA Middle Amphibolite Facies
- UA Upper Amphibolite Facies
- U Unmetamorphosed

COMPARISON OF FRESH CORE WITH PREVIOUSLY CRUSHED SAMPLES

It has been widely postulated that Hg is so mobile that only fresh samples should be analysed, and that Hg can be lost or gained through inadequate storage (e.g. Ryall, 1979c). This effect was tested on samples from Teutonic Bore. Results from samples of core were compared against equivalent samples taken by Seltrust Mining Corporation Pty Ltd, and crushed and analysed for base metals three years previously. The crushed remnants had been stored in calico bags in the open air at Boulder, Western Australia. Results are presented in Table 4. The Hg content of most of the crushed bulk samples is lower, and that of the chalcopyrite obtained from the crushed samples is much higher, than those of equivalent samples of the drill core. There is very little difference in the Hg content of the sphalerite, and it is considered that most of the variation in content between core and crushed samples is due to different proportions of sulphides in the bulk samples. However, the chalcopyrite concentrates taken from the crushed samples are consistently higher than those from fresh drill core and it is possible that there has been some migration of Hg into the chalcopyrite.

FUTURE DIRECTIONS IN Hg-HALO STUDIES IN WESTERN AUSTRALIA

This pilot study provides data which indicate that Hg is of potential use as a pathfinder element in prospecting. The study has shown that Hg in excess of 1 ppm can be expected in stratabound base-metal deposits of volcanigenic origin and also in hydrothermal veins containing Au, Sb, Zn, and possibly Co. Further research into Hg as a pathfinder element should be focused on these deposits.

Suggestions for additional work are as follows:

(i) investigation of other Western Australian base-metal and Au deposits, including other styles of mineralization;

(ii) systematic study of the distribution of Hg in individual deposits;

TABLE 3. MERCURY CONTENT OF CO-EXISTING CHALCOPYRITE AND SPHALERITE

(Values in ppb)

G.S.W.A. No.	Locality	Bulk	Chalcopyrite	Sphalerite
49048....	Copper King (Ravensthorpe)	420	1 165	4 500
59413....	Golden Grove	900	1 500	16 000
62921....	Teutonic Bore	650	860	3 500
62927....	Teutonic Bore	1 000	890	3 100
49145....	Yarraloola	15 000	1 600	16 800

TABLE 4. COMPARISON OF MERCURY IN DRILL CORE COMPARED WITH EQUIVALENT PULVERISED AND STORED MATERIAL

— Samples from Teutonic Bore

(Values in ppb)

G.S.W.A. No.	Drill Core			Pulverised samples		
	Bulk	Chalcopyrite	Sphalerite	Bulk	Chalcopyrite	Sphalerite
62921	650	860	3 500	370	2 580	3 200
62922	3 500	....	3 800	1 100	....	4 400
62923	220	200	....	150	810	....
62924	5 800	....	7 600	2 900	....	8 000
62925	1 700	1 500	....	2 900	2 750	....
62926	370	440	....	240	900	....
62927	1 000	890	3 100	910	5 100	3 300

(iii) investigation of the Hg content of surface rocks, including those in various stages of alteration and weathering, and investigation of the possible modes of transport between buried Hg-bearing mineralization and the surface;

(iv) investigation of the effects of metamorphism on the Hg content of mineralization, and of the relationships of Hg in association with mineralization by geographic province and by geologic time.

REFERENCES

Agemian, H., Aspila, K. I., and Chou, A. S. Y., 1975, A comparison of the extraction of mercury from sediments by using hydrochloric-nitric acid; sulphuric-nitric acid and hydrofluoric acid—aqua regia mixtures: Analyst, v. 100, p. 253–258.

Cordwell, K. S., 1965, Theoretical and technical aspects of rapid appraisal, *in* Lawrence, L. J., (ed.) Exploration and mining geology: Commonwealth Mining Metall. Australia and New Zealand Congress 8th Pub., v. 2, Aust. I.M.M. Melbourne, p. 61–71.

Davy, R., and Dodd, C. J., 1979, The mercury content of some Western Australian sulphide-bearing rocks: West. Australia Geol. Survey, Geochem. Rept. 16 (unpublished).

Dietz, F. D., Sell, J. L., and Bristol, D., 1973, Rapid sensitive method for the determination of mercury in a variety of biological samples: Assoc. Official Analytical Chemists Jour., v. 56, p. 378–382.

Hatch, W. R., and Ott, W. L., 1968, Determination of sub-microgram quantities of mercury by atomic absorption spectroscopy: Analyt. Chem., v. 40, p. 2 085–2 087.

Jonasson, I. R., 1970, Mercury in the natural environment: a review of recent work: Canada Geol. Survey, Pap. 70–57.

Jonasson, I. R., and Boyle, R. W., 1972, Geochemistry of mercury and origins of natural contamination of the environment: CIM Bull., p. 32–39.

Jonasson, R. I., Lynch, J. J., and Trip, W., 1973, Field and laboratory methods used in the Geological Survey of Canada in geochemical surveys. No. 12. Mercury in ores, rocks, soils, sediments and water: Canada Geol. Survey, Pap. 73–21, 22p.

Jonasson, R. I., and Sangster, D. F., 1975, Variations in the mercury content of sphalerite from some Canadian sulphide deposits, *in* Elliott, I. L., and Fletcher, W. K. (eds), Geochemical exploration 1974: Amsterdam, Elsevier, p. 313–332.

Marston, R. J., 1979, Copper mineralization in Western Australia: West. Australia Geol. Survey Mineral Resources Bull. 13.

Ozerova, N. A., Rusinov, V. L., and Ozerova, Y. K., 1975, The mercury in sulphide deposits emplaced in volcanic suites: Mineralium Deposita, v. 10, p. 228–233.

Reed, G. W., Jovanovic, S., and Tennissen, A. C., 1972, Concentrations and thermal release of Hg from iron and zinc sulphides: Earth Plan. Sci. Letters, v. 14, p. 28–30.

Ryall, W. R., 1979a, Mercury distribution in the Woodlawn massive sulphide deposit, New South Wales: Econ. Geol., v. 74, p. 1 471–1 484.

Ryall, W. R., 1979b, Mercury in the Broken Hill (NSW, Australia) lead-zinc-silver lodes: Jour. Geochem. Explor., v. 11, p. 175–194.

———— 1979c, Guidelines for the collection, preparation and storage of geochemical samples for mercury analysis: Australia C.S.I.R.O., Inst. Earth Resour., Tech. Comm. 67.

Sears, W. P., 1971, Mercury in base metal and gold ores of the Province of Quebec: CIM Special Volume 11, p. 384–390.

Smith, M. E., 1980, Mons Cupri Cu–Pb–Zn–Ag deposit, Pilbara Block, W.A.: Jour. Geochem. Explor., v. 12, p. 168–171.

United States Geological Survey, 1970, Mercury in the environment: U.S. Geol. Survey, Prof. Pap. 713.

Watling, R. J., Davis, G. R., and Meyer, W. T., 1973, Trace identification of mercury compounds as a guide to sulphide mineralization at Keel, Eire: *in* Jones, M. J. (ed.), Geochemical exploration 1972: London, Inst. Min. Metall., p. 59–70.

Williston, W. H., 1964, The mercury halo method of exploration: Engineering and Mining Jour., v. 165, p. 98–101.

SMALL CONICAL STROMATOLITES FROM THE ARCHAEAN NEAR KANOWNA, WESTERN AUSTRALIA

by K. Grey

ABSTRACT

Chert in an Archaean felsic volcanic sequence near Kanowna in the Yilgarn Block, Western Australia, contains well-preserved stromatolites, which consist of tabular sheets of small, laterally linked subcylindrical columns with conical tops. Poorly preserved filaments are present in some columns. The gross morphology of the columns invites comparison with similar forms occurring in a modern hot-spring environment in Yellowstone National Park, U.S.A. The chert is poorly exposed, but most probably occurs in an olistostrome at the base of a basinal slope. The stromatolites may have been constructed during hydrothermal activity in the surrounding volcaniclastic sequence from which the chert blocks were derived.

INTRODUCTION

Samples of chert collected in late 1979 from a complex Archaean mafic-felsic volcaniclastic sequence near Kanowna by R. D. Gee, A. H. Hickman and myself provided some well preserved columnar stromatolites.

The discovery is of significance because few stromatolite horizons have been recorded in the Archaean (Walter, 1978), and this is the first documentation of stromatolites in the Archaean of the Yilgarn Block. Furthermore, only a few of the known occurrences of Archaean stromatolites are of conical shape. The oldest well-established occurrence of stromatolites is a domal form in the 3·4 to 3·5 b.y. old Warrawoona Group of the eastern Pilbara Block (Walter and others, 1980). The oldest known conical stromatolites have also been reported from the Warrawoona Group, from a recrystallized evaporite, by Lowe (1980). Other conical forms of Archaean age occur in the Insuzi Group (Pongola Supergroup) South Africa; they are approximately 2·9 to 3·0 b.y. old, and probably formed in a tidally influenced environment associated with extensive volcanic activity (Mason and Von Brunn, 1977); yet others occur in the 2·5 to 3·0 b.y. old Belingwe Greenstone belt, Rhodesia, in a shallow-water sedimentary sequence associated with volcanic activity (Bickle and others, 1975; Martin and others, 1980). All known examples of Archaean conical stromatolites consist of small cones (usually with a relief of less than 10 cm); lack a well-defined, thickened crestal zone; are composed of fine laminae, which are laterally linked to form extensive sheets; and are found in sequences in which there is evidence of extensive volcanic activity. In all these features they resemble the conical stromatolites from Kanowna.

Although these previously described conical forms have usually been compared with *Conophyton* Maslov, a large conical stromatolite occurring in the Proterozoic, there are significant differences; the Archaean cones show a closer resemblance to stromatolites forming in hot springs in Yellowstone National Park, U.S.A. (Walter and others, 1976) and to forms of the Family Thyssagetaceae Vlasov from the Satka Formation (Lower Riphean) of the U.S.S.R. (Vlasov, 1977).

Conophyton is usually regarded as indicative of quiet water and subtidal conditions (probably below wave base). The previously described Archaean conical stromatolites have all been interpreted as occurring in shallow-water, intertidal to subtidal environments; these interpretations are based to some extent on comparisons with *Conophyton*. However, Archaean conical stromatolites need not necessarily be restricted to such environments, and a possible hot-spring origin within a shallow water sequence, either marine or non-marine, should not be ruled out.

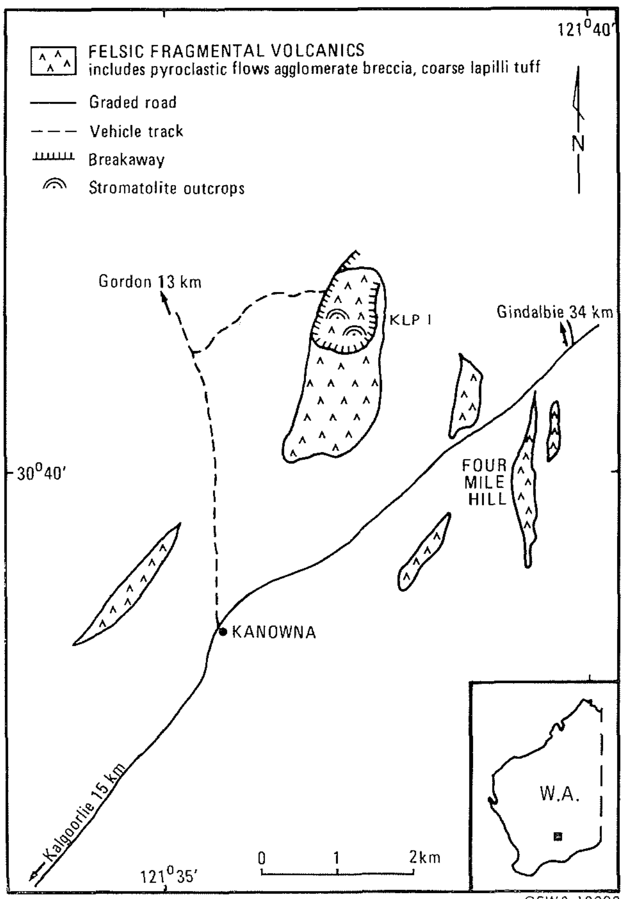


Figure 1 Sketch map showing stromatolite locality near Kanowna.

LOCALITY DETAILS

The stromatolites occur in two small chert outcrops at the base of a breakaway (locality KLP1) approximately 5 km north-northeast of Kanowna townsite (Fig. 1) on the western part of the Kurnalpi 1:250 000 geological sheet (121°37′E, 30°34′S). The locality is marked on the Kurnalpi geological map as an alunite deposit. It has been briefly described by Simpson (1948) and Groves and Gee (1980) who refer to it as the "alunite locality".

The Gindalbie Formation, in which the stromatolites occur, is the result of the widespread extrusion and intrusion of ultramafic and felsic igneous rocks, accompanied by the deposition of associated sediments on a platform shelf or a shallow basin-like surface (Williams, 1975). The locality at the alunite deposit has a deeply weathered, complex association of komatiitic rocks, pillowed basalts, and felsic volcaniclastics.

At both stromatolite outcrops, chert boulders protrude through a thin covering of colluvium and scree which has slipped down from the face of the breakaway. The relationship of the chert to the stratigraphically underlying and overlying units of the felsic complex is obscured by these later deposits. At one outcrop, approximately 1 m long, the chert boulders show an alignment parallel to the strike of bedding lamination, and recognizable bedding dips 70°. There is little doubt that, at this locality, the chert was largely undisturbed during the recent weathering cycle. At the second outcrop, the boulders are randomly orientated on a scree slope near the foot of the breakaway, and appear to have been disturbed by solifluction.

The cherts at both localities range from black to pale grey. In hand specimen, much of the black chert has a mottled texture and consists of finely laminated, stratiform stromatolites with

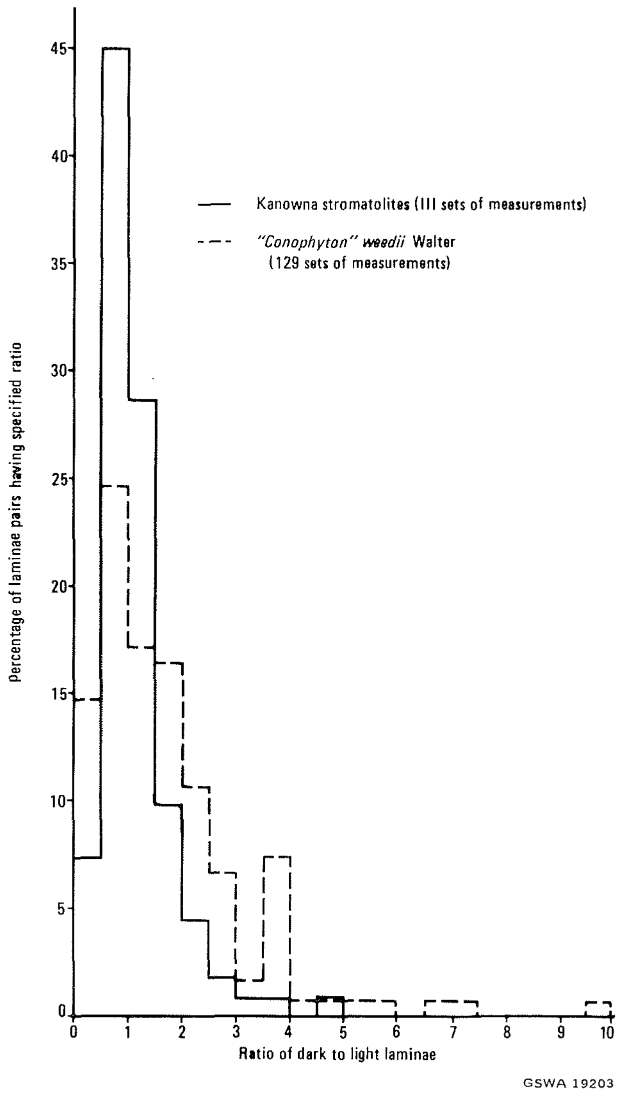


Figure 2 Frequency distribution of the ratios of dark to light laminae in the Kanowna stromatolites. A plot for the modern form "*Conophyton*" *weedii* is shown for comparison (after Walter and others, 1976 Fig. 32).

some small laterally linked columns up to 1 cm high and less than 5 mm wide. Fragments of this type of chert are less common than the dark-grey to almost white chert boulders in which the conical stromatolites occur. In hand specimen, the chert with conical stromatolites has a stripy texture with wavy laminations about 2 cm in both amplitude and wavelength. Stylolites emphasize the wavy markings, and the shape of the cones may be commonly observed on weathered surfaces.

Although the facing at one of the chert outcrops is consistent with facings in the felsic volcanics, the chert is probably not in its position of formation. Groves and Gee (1980 p. 57) quote a personal communication from T. Taylor, who interprets the complex association of rocks at the alunite deposit as having been deposited at the base of a slope in a moderately deep basin, with debris flows and olistostromes resulting from subaqueous slumping in a volcanic environment. The stromatolitic cherts are probably large olistoliths, which slipped down the basinal slope as large tabular blocks.

The Gindalbie Formation is older than 2·6 b.y. (Williams, 1975), the general age of granite intrusion; and Gee (1980) concluded that the greenstones of the Yilgarn Block are probably about 2·8 to 2·7 b.y. old.

DESCRIPTION OF STROMATOLITES

MODE OF OCCURRENCE

The stromatolites occur in sheets averaging 2 cm but ranging from a few millimetres to 3 cm or more thick. The upper and lower boundaries of a sheet are marked by a discontinuity of the columns (Fig. 3C) and by stylolites. The extent of the sheets cannot be determined because of the fragmented nature of the samples, but they may grade laterally into black cherts with small pillar-like columns and finely laminated stratiform stromatolites.

COLUMN SHAPE

Columns are subcylindrical and erect, and normally have conical tops (Figs 3A, B, C), although some have flattened tops. Transverse sections are subcircular to oval. Oval columns usually show a parallel elongation. Columns range from 0·6 to 3 cm in diameter, but the majority are about 1·5 cm wide. The columns can be 8 cm or more in height, but the height of an individual lamina above the substrate (the synoptic relief) is approximately 2·5 cm. The distance between the apices of the columns is variable, but is usually between 1 and 2 cm. Columns are usually contiguous.

Ridges and small spinose projections are commonly present; and on weathered surfaces or in vertical sections are marked by lines of darker chert approximately 1 mm wide which are formed by small superimposed peaks in successive laminae. The ridges have a radial orientation (Fig. 3B).

LAMINA SHAPE

Laminae are irregularly conical (Figs 3C, D) with sharp to blunt apices. The apical line is difficult to detect but is gently wavy. Laminae are mostly smooth, but some are wrinkled and wavy.

CRESTAL ZONE

The nature of the crestal zone is difficult to determine, because it is poorly defined and narrow, being rarely wider than 2 mm. The laminae appear to be at least twice as thick in the crestal zone as they are on the flanks.

MICROSTRUCTURE

The stromatolites have a streaky microstructure (one in which the laminae are moderately continuous, and the darker laminae are usually the more distinct). The laminae range between 3 and 176 μm thick. The thinnest laminae were probably formed by single filaments. Some of the thicker laminae have a linear fabric arranged perpendicular to the laminae (Fig. 3D) which may indicate the distribution of former microbial filaments. This radial fabric is best preserved in the black cherts associated with the conical stromatolites (Fig. 3E).

Dark laminae range in thickness from 4 to 176 μm (with a mean of 15 μm for 111 measurements) and light laminae from 3 to 107 μm (with a mean of 14 μm for 111 measurements). Both types of laminae have a texture in which the mineral grains are bounded by crystal faces (idiotopic), and are formed by quartz with average grain size of 10 μm. The dark laminae owe their colour to finely disseminated pigment, probably organic carbon. The pigment is often clustered as a diffuse sphere at the centre of each quartz grain (Fig. 3F) and may also be concentrated around grain boundaries.

SECONDARY ALTERATION

The stromatolites consist of coarse-grained chert, which has undergone some recrystallization (indicated by the redistribution of pigment along the grain boundaries), but which does not appear to be a replacement of carbonate. There has been little disturbance of the fabric of the conical stromatolites and the laminated black cherts; poorly preserved microbial filaments (Figs 3G, H) can be recognized and the redistribution of the pigment along the grain boundaries is only partial. No relict carbonate rhombs were recognized other than small siderite crystals.

DISCUSSION

The Kanowna stromatolites can be distinguished from conical forms of the group *Conophyton* Maslov by the presence of lateral linkage. They are also very small compared with most forms of *Conophyton* and do not have a well-developed thickened crestal zone. They resemble more closely some of the groups of the Family Thyssagetaceae recently erected by Vlasov (1977), and their closest resemblance is with the modern, linked, conical stromatolites described by Walter and others (1976, particularly figures 8, 11, 12) from the hot springs of Yellowstone National Park and named *Conophyton weedii* by Walter. Hofmann (1980) emphasised the fact that the original diagnosis of *Conophyton* includes only columnar, unlinked structures. The form *weedii* should not be classified in *Conophyton* but should be placed in Thyssagetaceae. Both "*Conophyton*" *weedii* and the Kanowna form have characteristics typical of the group *Thyssagetes*, but more detailed comparison is necessary before formally naming them.

The resemblance between "*Conophyton*" *weedii* and the Kanowna stromatolites extends to the presence of small spines and ridges (Figs 3B, C) the shape of the cones in cross-section (Fig. 3C) and the similarity of laminae thicknesses (Fig. 2). The main difference is in the nature of the crestal zone, which is wider and better developed in "*Conophyton*" *weedii*.

The poor preservation of microbial filaments in the Kanowna stromatolites prevents a detailed assessment of the nature of the stromatolite-building organisms. The filaments are best preserved in the laminated black cherts (Figs 3G, H). They were probably several tens of micrometres long and are approximately 5 μm thick. The vertical tube-like structures cross-cutting the laminae suggest that the organisms coped with burial by either growing (a phototropic response) or gliding (a photoactic response) towards a light source. Studies of Yellowstone conical stromatolites (Walter and others, 1976) indicate that their morphology is a result of the response of the constructing organisms to light in a quiet-water environment, and of cohesion of the filaments. Walter (1980) suggests that the Insuzi conical stromatolites may have been constructed by finely filamentous, phototactic micro-organisms. These may have been similar to the cyanobacterium *Phormidium*, which is the principal organism involved in the construction of the Yellowstone stromatolites. The Kanowna stromatolites were probably also constructed by finely filamentous, light-seeking organisms.

A shallow-water, subtidal to intertidal environment has been suggested for stromatolites from Warrawoona (Lowe, 1980), Insuzi (Mason and Von Brunn, 1977) and Belingwe (Bickle and others 1975; Martin and others, 1980). To some extent in each of these examples the evidence for a marine environment is based on an analogy between the conical

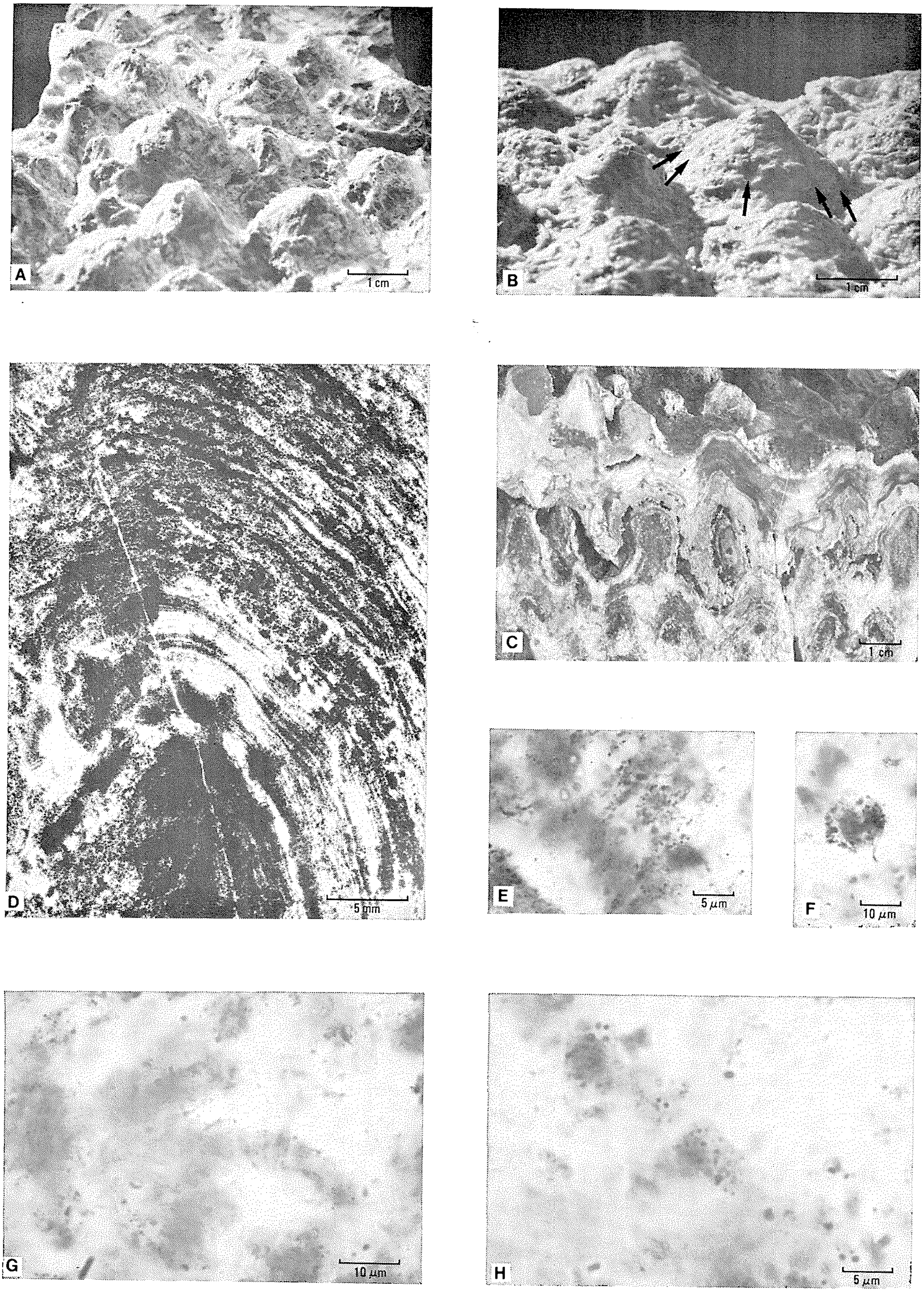
Figure 3 Conical stromatolites and black laminated cherts from Kanowna.

(A) and (B) (GSWA F11668) (A) Conical stromatolites on weathered surface. (B) Detail of cones showing ridges of darker chert (arrowed) radiating from tip of cone.

(C) (GSWA F11670)—Cut surface showing super-position of sheets of contiguous cones. Note the irregular lamina profile where small crests indicate the position of radiating ridges.

(D) (GSWA F11658)—Thin section of cone showing finely-banded laminae. Note the fine radiating structure cross-cutting dark laminae.

(E), (F), (G), and (H) (GSWA F11659) Microstructures from a black chert associated with the conical stromatolites. Co-ordinates are for Leitz Orthoplan microscope 834965. (E) Detail of radiating fabric showing possible filament tubes cross-cutting dark lamina. Coordinates 304, 1311. (F) Sphere of probable organic material at the centre of a quartz grain. Coordinates 294, 1266. (G) Poorly preserved filament cross-cutting a crystal boundary. Coordinates 554, 1107. (H) Poorly preserved filament. Coordinates 289, 1286.


A
1 cm
B
1 cm
D
5 mm
C
1 cm
E
5 μm
F
10 μm
G
10 μm
H
5 μm

stromatolites and the group *Conophyton*, for which Donaldson (1976) proposed a subtidal, quiet-water growth environment. In fact the small conical stromatolites are not *Conophyton*, and therefore cannot be regarded as unequivocally indicating a marine environment. In addition, *Conophyton* is rarely associated with the type of shallow-water and evaporitic structures described from sequences containing the small Archaean conical stromatolites. These small cones most probably occurred subaqueously, and most probably in quiet-water conditions, but not necessarily in a shallow-marine environment; lacustrine or hot-spring environments should also be considered.

The very close morphological similarity between the Kanowna and Yellowstone conical stromatolites suggests that sequences containing small conical stromatolites should be examined carefully for evidence of hydrothermal activity. If the stromatolites were constructed by an organism similar to the modern *Phormidium*, it is quite possible that they occupied a niche in the Archaean similar to that which they occupy at the present day. In this respect, it is interesting to note that the stromatolites from the Warrawoona and Isuzi Groups and from the Belingwe greenstone belt, as well as those from Kanowna, all occur within volcanic sequences.

Walter (1976) suggests that former alkaline hot springs can be recognised by the presence of volcanic rocks, the extensive hydrothermal alteration of host rocks, the presence of geyserite and other siliceous-sediment types, particularly siliceous stromatolites and diatomites, and by a limited areal extent. It is difficult to apply these criteria to the Kanowna stromatolites, which are present at a locality where deep weathering has obscured any trace of hydrothermal activity. The sequence in which the stromatolites now occur is considered by T. Taylor in a personal communication to Groves and Gee (1980, p. 57) ". . . to be the base of a slope in a moderately deep basin in which komatiitic volcanism was proceeding. Intermittent slumping on the subaqueous flanks of the basin produced conglomeratic debris flows and olistostromes", which probably included the stromatolitic cherts. Taylor mentions that the ". . . ultimate provenance of the felsic tuffwackes was presumably subaerial felsic volcanism", so that it is quite probable that the stromatolites grew in hot springs associated with this volcanism, rather than in a marine tidal to subtidal environment.

CONCLUSIONS

Stromatolites are often considered to be indicators of shallow-water, marine environments; but modern stromatolites occur in a wide variety of environments, including hot springs. The remarkable similarity between conical stromatolites from Kanowna and those from Yellowstone suggests that the possibility of a hot-spring environment should not be overlooked in interpreting these Archaean forms.

REFERENCES

Bickle, M. J., Martin, A., and Nisbet, E. G., 1975, Basaltic and peridotitic komatiites and stromatolites above a basal unconformity in the Belingwe greenstone belt, Rhodesia: Earth Planet, Sci. Lett. v. 27(2), p. 155–162.

Donaldson, J. A., 1976, Palaeoecology of Conophyton and associated stromatolites in the Precambrian Dismal Lakes and Rae Groups, Canada; *in* M. R. Walter (editor), Stromatolites: Elsevier, Amsterdam, p. 523–534.

Gee, R. D., 1980, Summary of the Precambrian stratigraphy of Western Australia: Geol. Survey West. Australia Ann. Rept 1979, p. 85–90.

Groves, D. I., and Gee, R. D., 1980, Regional Geology and mineral deposits of the Kalgoorlie-Norseman region: International Archaean Symposium, 2nd, Perth, 1980. Geol. Soc. Australia, Excursion Guide.

Hofmann, H. J., 1978, New stromatolites from the Aphebian Mistassini Group, Quebec: Canadian Journal Earth Sciences v. 16(4), p. 571–585.

Lowe, D. R., 1980, Stromatolites 3 400-Myr old from the Archaean of Western Australia: Nature v. 284, p. 441–443.

Martin, A., Nisbet, E. G., and Bickle, M. J., 1980, Archaean stromatolites of the Belingwe Greenstone Belt (Zimbabwe): Precambrian Research, v. 13, p. 337–362.

Mason, T. R., and Von Brunn, V., 1977, 3-Gyr-old stromatolites from South Africa: Nature v. 266, p. 47–49.

Simpson, E. S., 1948, Minerals of Western Australia, v. 1: Perth, Govt Printer.

Vlasov, F.Ya., 1977, Dokembriiskie stromatolity iz Satkinskoi svity Yuzhnogo Urala. [Precambrian stromatolites from the Satka Formation in the Southern Urals] Materialy po palaeontologii srednego paleozoya Urala i Sibiri. Sverdlovsk: Tr. Inst. Geol. Geokhim, 126 p. 101–128.

Walter, M. R., 1978, Recognition and significance of Archaean stromatolites, *in* Glover, J. E., and Groves, D. I., Archaean cherty metasediments, their sedimentology, micropalaeontology, biogeochemistry and significance to mineralization: University of Western Australia, Geology Department and Extension Service, Publication No. 2.

——— 1980, Palaeobiology of Archaean stromatolites: International Archaean Symposium, 2nd, Perth, 1980, Geol. Soc. Australia Extended Abstracts, p. 22–23.

Walter, M. R., Bauld, J., and Brock, T. D., 1976, Microbiology and morphogenesis of columnar stromatolites (*Conophyton, Vacerrilla*) from hot springs in Yellowstone National Park, *in* M. R. Walter (editor), Stromatolites: Amsterdam Elsevier, p. 273–310.

Walter, M. R., Buick, R., and Dunlop, J. S. R., 1980, Stromatolites 3 400–3 500-Myr old from the North Pole area, Western Australia: Nature v. 284, p. 433–445.

Williams, I. R., 1975, Eastern Goldfields Province, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 33–54.

A DEFINITIVE 3 350 M.Y. AGE FROM BANDED GNEISS, MOUNT NARRYER AREA, WESTERN GNEISS TERRAIN

by J. R. de Laeter,* I. R. Williams, K. J. R. Rosman* and W. G. Libby

ABSTRACT

Thirteen whole-rock samples of banded gneiss from the east side of the Mount Narryer Metamorphic Belt at lat. 26°27′S, long. 116°24′30″E give a Rb-Sr age of 3 348 ± 43 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0·703 7 ± 0·000 5.

This date is substantially older than the 2 500 m.y. to 2 700 m.y. dates commonly reported from most of the Yilgarn Block, and confirms earlier suggestions that older Archaean rocks are involved in the Western Gneiss Terrain along the western margin of the Block.

INTRODUCTION

Regional mapping, undertaken between 1974 and 1978, on the Robinson Range (Elias and Williams, 1977), Glenburgh (Williams, Williams, and others, 1978) and Byro (Williams, Walker, and others, 1980) 1:250 000 sheets clearly delineated a high grade gneiss and migmatite belt that wrapped around the northwestern margin of the Archaean Yilgarn Block. This gneiss belt can be linked southwards to previously described gneiss terrains lying along the western margin of the Yilgarn Block (Baxter, 1974; Muhling and Low, 1977; Baxter and Lipple, 1979; Wilde and Low, 1978). It can also be traced northwards into the Gascoyne Province where reworked gneissic rocks are basement to the Proterozoic rocks of this Province (Williams, Williams, and others, 1978; and Williams, Williams and Hocking, 1980) (Fig. 1).

The extent and significance of these gneiss belts and the possible relationships with the greenstone belts of the Yilgarn Block were discussed by Gee (1979) where he referred to the West Yilgarn Gneiss Domain. In a later, expanded review, Gee and others (in press) placed the same rocks in the Western Gneiss Terrain of the Yilgarn Block.

Early Rb-Sr geochronological work by Arriens (1971) showed that dates older than 2 700 m.y. could be obtained from gneisses lying close to the western margin of the Yilgarn Block. Later, Williams, Elias and de Laeter (1978) interpreted similar gneisses along the northern margin of the Yilgarn Block on the Robinson Range 1:250 000 sheet to be older than 2 600 m.y. Similarly, to the south in the vicinity of Perth, Libby and de Laeter (1979) supported Arriens' work with isochron and model whole-rock ages older than 2 700 m.y.; more recently, Nieuwland and Compston (1980) have reported a zircon uranium-lead date from quartzite of 3 340 m.y., and from orthogneiss of 3 250 m.y.

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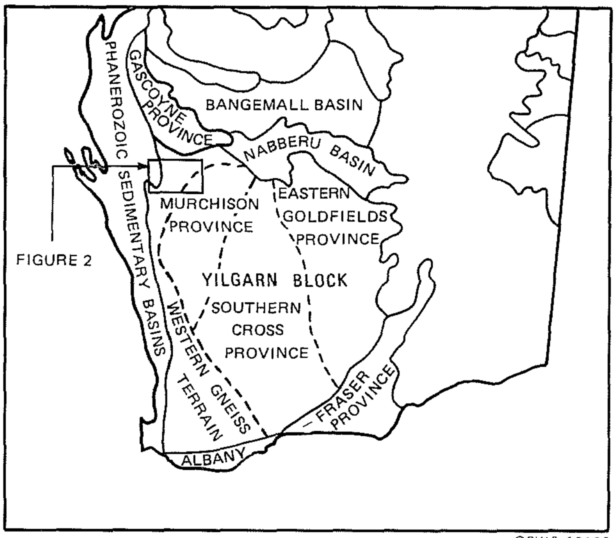

Figure 1 Regional distribution of tectonic units in the southwest of Western Australia, showing location of Mount Narryer area.

The need to obtain definitive geochronological data to back up the preliminary isotopic work and growing geological evidence that the gneiss belts were probably older than the granite-greenstone terrain of the Yilgarn Block (and perhaps therefore part of a pre-greenstone sialic basement) initiated the Older Gneiss Project in 1978.

Four localities, Goanna Bore (Glenburgh Sheet), Milly Milly, Ration Bore and Mount Narryer (all on the Byro Sheet) have, so far, been sampled. All these localities lie in the gneiss-migmatite belt between the northern limit of the Yilgarn intrusive granitoids, which have been dated at about 2 600 m.y. (see de Laeter and others, in press), and the Proterozoic Gascoyne Province.

This paper reports the first definitive early Archaean date from the Older Gneiss Project, which was obtained from the Mount Narryer area. The results and implications are briefly discussed.

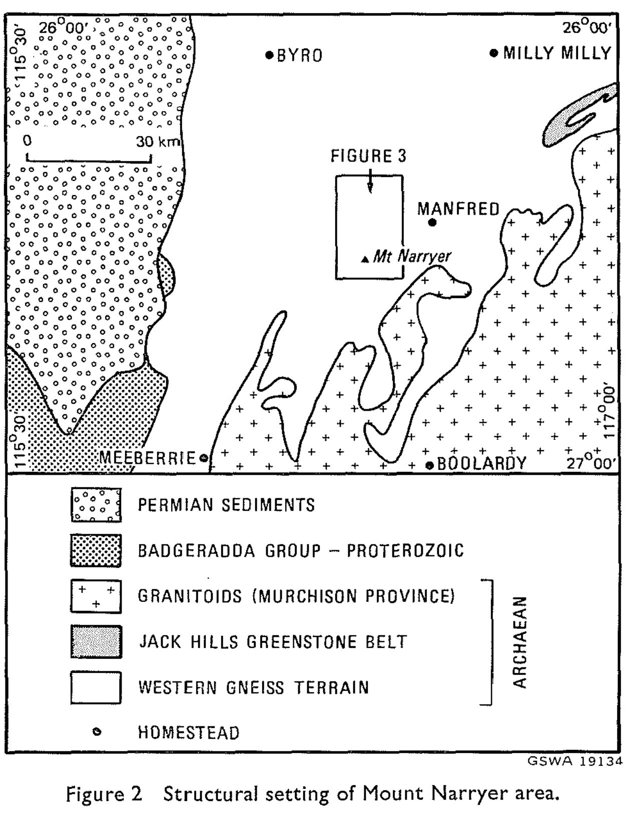

Figure 2 Structural setting of Mount Narryer area.

REGIONAL SETTING

The Mount Narryer area lies in the centre of the Byro 1:250 000 sheet, 240 km north-northeast of Mullewa. The geochronology sample sites lie 13·5 km due west of Manfred homestead and 8·5 km north-northeast of Mount Narryer trig point. Access to the sample localities can be gained along station tracks via Mindle Well from Manfred homestead, or via Warra Well from Mount Narryer homestead (Fig. 3).

Mount Narryer is the highest point in a range of rounded quartzite hills which rises 250 m above the Murchison River flood plain to the east, and the broad Murrum Creek drainage to the west. The range extends for 21 km north-northeast before being dissected by a major east-flowing drainage near Mount Dugel Well.

The Mount Narryer sequence lies near the eastern edge of the region designated the Mount Narryer Metamorphic Belt of the Western Gneiss Terrain (Gee and others, in press). Non-gneissic granitoids of the Yilgarn Block (about 2 600 m.y., belonging to the Murchison Province) crop out 10 km east of Mount Narryer. However, the Manfred Lineament, believed to be a major dislocation, lies between the granite and gneiss exposures (Williams, Walker, and others, 1980). Eroded fault scarps in colluvium, both east and west of Mount Narryer point to recent activity in this area of the Meeberrie Seismic Zone (Williams, 1979).

The Mount Narryer rocks are a high-grade (amphibolite-granulite transition facies) meta-sedimentary sequence. The large hills consist of garnet-sillimanite quartzite (some with fuchsite) interlayered with meta-conglomerate, cordierite-garnet-biotite-sillimanite gneiss and minor quartz-magnetite rock. These rocks are flanked, on both sides, by banded quartz-feldspar-biotite gneiss, with incipient migmatization, interlayered with minor quartz-magnetite rock and amphibolite. Minor ultramafic talc-serpentine-chlorite-amphibole bodies intrude the banded gneiss on the eastern side of the Mount Narryer quartzites. A small body of two-pyroxene mafic granulite (metamorphosed gabbro) lies 10 km north-northwest of Mount Narryer in the banded gneiss. Apart from a small orthogneiss component (non-banded adamellite or granodiorite gneiss) the Mount Narryer sequence appears to have been derived from sediments deposited in a shallow-water shelf environment.

The pressure and temperature of metamorphism of sillimanite-garnet-cordierite-biotite gneiss have been calculated at 510 MPa and 785°C (Blight and Barley, 1981) from co-existing cordierite-garnet pairs in association with sillimanite. The paragneiss providing the pressure and temperature information is interlayered in the quartzite unit at Mount Narryer, which is adjacent to the biotite gneiss unit which was dated.

Both the compositional banding in the gneiss and gneissic foliation have near vertical dips with a general northerly trend. However, the quartzites at Mount Narryer outline a vertical to steep south-plunging synformal structure which is gently bowed at the east (Fig. 3).

The geochronology samples were taken from banded gneiss lying on the eastern side of the quartzite ridge at Mount Narryer.

MATERIAL ANALYSED

Twenty-seven samples of banded gneiss were collected near Mount Narryer for the Older Gneiss Project. Twenty-five samples (numbers 60735 to 60738 and 69625 to 69645) came from fresh exposures lying northeast and southwest of the Manfred-Meeberrie Station boundary fence (lat. 26°27′S; long. 116°24′30″E). The samples were collected from an area of about 14·8 ha with distances between samples ranging from 1·5 m to 450 m. A map compiled with compass and tape, of the localities sampled (marked by steel pegs in the field) is given in Figure 4. All pegged samples within the mapped area are located on the map, though several have not been analyzed.

All samples are banded to nebulitically-banded quartz-feldspar-biotite gneiss, compositionally hovering between adamellite and granodiorite. Microcline is present in all samples, and plagioclase, where determined, is always oligoclase. Samples rich in quartz and microcline contain metamict allanite. All specimens show secondary deformation and recrystallization beyond the primary gneissiose structure. Alteration products include saussuritized plagioclase, powdery aggregates of epidote, and chlorite derived from recrystallization of biotite.

One group (samples 60738, 69627, and 69636 to 69645) lying southwest of the boundary fence have protomylonitic textures. The rock types are summarized in Table 1.

A single sample, 60734, came from an outcrop 2·1 km northeast of the main locality (lat. 26°26′00″S, long. 116°25′30″E). This rock is a banded biotite-amphibole-cummingtonite granodiorite gneiss.

A second sample, 60739, a plagioclase-quartz-epidote gneiss, comes from 350 m on a bearing of 295° from the main locality.

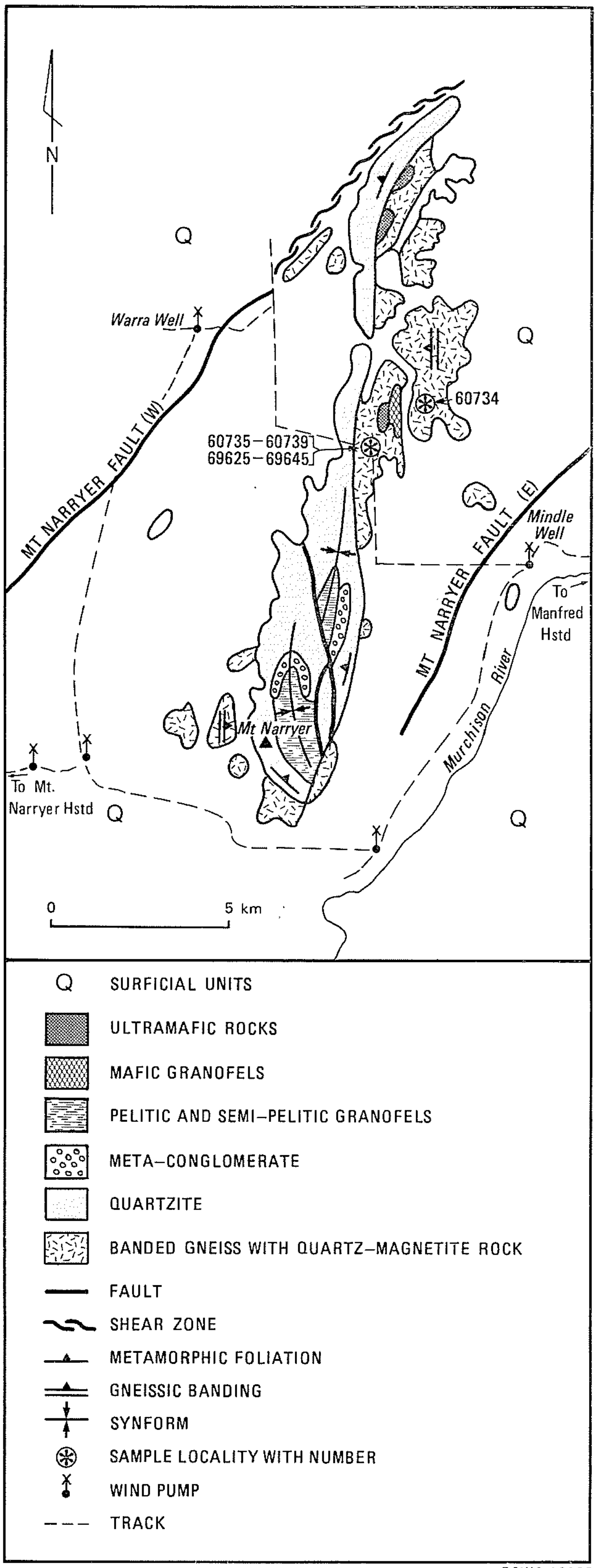

Figure 3 Simplified geological map of the Mount Narryer area.

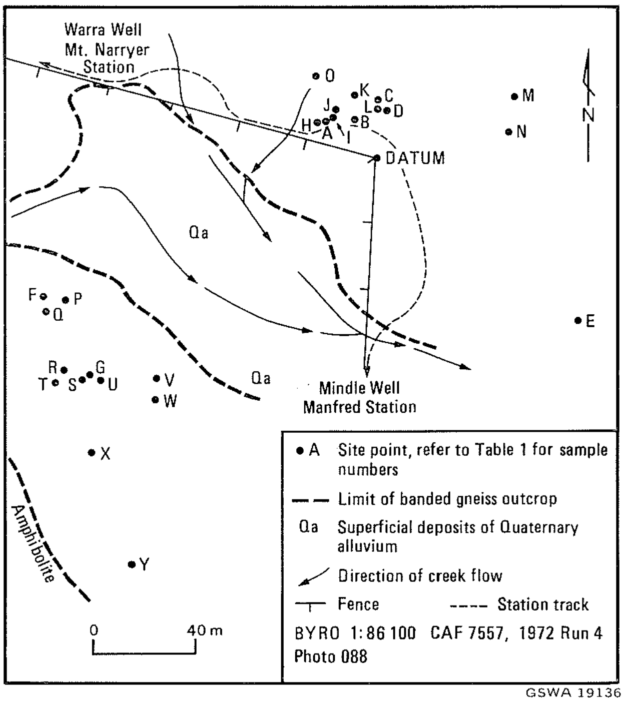

Figure 4 Detailed map of sampling localities, Mount Narryer area.

EXPERIMENTAL PROCEDURES

About 200 g of each sample was reduced to —200 mesh using a jaw crusher and a Tema-type mill. Approximately 0·4 g of each powdered sample was taken into solution using a HF-$HClO_4$ mixture. The solution was taken to dryness and the residue converted to the chloride form with 6M HCl. The concentration of the final solution was 1M HCl. After centrifuging, the supernate was transferred to a quartz ion-exchange column containing 2 g of BIORAD AG 50W-X8, 200–400 mesh cation exchange resin. Rubidium and strontium were eluted using conventional ion-exchange chemistry, and after being taken to dryness, mounted on a single zone-refined tantalum filament assembly ready for mass spectrometric analysis.

Blank determinations using the isotope dilution technique showed that the Rb and Sr contamination introduced by the chemical processing was less than 10^{-9} g and 10^{-8} g respectively. Full details of the isotope dilution technique used in this laboratory are given by de Laeter and Abercrombie (1970) and de Laeter (1976).

Isotope analyses were carried out in a 30·5 cm radius, 90° magnetic sector, solid-source mass spectrometer.

The Sr samples were loaded on to previously out-gassed tantalum filaments in dilute H_3PO_4. No evidence of Sr contamination from the ion source or filaments was observed. Microgram-sized samples produced an ion beam of approximately 10^{-11} amps for several hours. The resulting signals were amplified by an electron multiplier followed by a Model 401 Carey vibrating reed electrometer. After digitization using an integrating digital voltmeter, the signals were fed on-line to a mini-computer. Switching of the magnetic field was used to bring the centres of the isotopic ion beams to the collector. Switching was performed in a down-mass/up-mass sequence. Seven, one-second counts were taken on each peak with an eight-second delay after peak switching. Baseline measurements were taken on both the high-and low-mass sides of each peak. The non-linearity of the measuring system was established using a high accuracy potential divider, and a correction was made for this by the computer programme. During Sr analyses, mass 85 was monitored on a sensitive scale to ensure that no Rb was present.

Replicate analyses of the NBS 987 Sr standard were made, to give an average value of $^{87}Sr/^{86}Sr$ of 0·710 21 ± 0·000 08 normalized to a $^{88}Sr/^{86}Sr$ of 8·375 2. A decay constant for ^{87}Rb of $1{\cdot}42 \times 10^{-11}$ yr^{-1} was used to calculate the age (Steiger and Jäger, 1977).

X-ray fluorescence was used to select rocks with favourable Rb/Sr ratios and Rb and Sr concentrations for mass spectrometric analysis, and also to determine the precise value of Rb-Sr for the selected samples. A Siemen's SRS 200 fluorescence spectrometer equipped with a molybdenum tube, a lithium

TABLE 1. DESCRIPTION OF ROCK TYPES

Site No. (shown on Figure 4)	G.S.W.A. Sample No.	Isochron	Rock type	Remarks
A	60737	X	Quartz biotite adamellite gneiss	Partly recrystallized, deformed
B	60736	X	Biotite granodiorite gneiss	Recrystallized, deformed
C	60735	X	Boitite adamellite gneiss	Slightly recrystallized, deformed
D	69626	X	Biotite adamellite gneiss	Seriate, partly recrystallized, deformed
E	69625	X	Biotite adamellite gneiss	Seriate, partly recrystallized, weak deformation
F	60738	X	Biotite adamellite gneiss	Seriate, partly recrystallized, protomylonitic fabric
G	69627	X	Biotite adamellite gneiss	Seriate, partly recrystallized, protomylonitic fabric
H	69628	....	Biotite granodiorite gneiss	Recrystallized, deformed
I	69629	....	Quartz-biotite granodiorite gneiss	Recrystallized, deformed
J	69630	....	Biotite granodiorite gneiss	Recrystallized, deformed
K	69631	....	Biotite granodiorite gneiss	Recrystallized, deformed
L	69632	....	Biotite granodiorite gneiss	Recrystallized, deformed
M	69633	....	Quartz-rich adamellite gneiss	Recrystallized, deformed
N	69634	X	Biotite granodiorite gneiss	Recrystallized, deformed
O	69635	....	Biotite granodiorite gneiss	Recrystallized, deformed
P	69636	X	Biotite adamellite gneiss	Recrystallized, protomylonitic fabric
Q	69637	X	Biotite adamellite gneiss	Seriate, recrystallized, protomylonitic fabric
R	69638	X	Biotite adamellite gneiss	Recrystallized, protomylonitic fabric
S	69639	....	Biotite granodiorite gneiss	Recrystallized, protomylonitic fabric
T	69640	....	Biotite granodiorite gneiss	Recrystallized, protomylonitic fabric
U	69641	....	Biotite adamellite gneiss	Recrystallized, protomylonitic fabric
V	69642	X	Biotite adamellite gneiss	Recrystallized, protomylonitic fabric
W	69643	....	Biotite adamellite gneiss	Recrystallized, protomylonitic fabric
X	69644	....	Biotite granodiorite gneiss	Recrystallized, protomylonitic fabric
Y	69645	....	Biotite granodiorite gneiss	Recrystallized, protomylonitic fabric
2·1 km NE*	60734	X	Biotite-amphibole-cummingtonite granodiorite gneiss	Partly recrystallized
350 m WNW*	60739	....	Plagioclase-quartz-epidote gneiss	Intensely epidotized

* Not shown on Figure 4

TABLE 2. RUBIDIUM-STRONTIUM ANALYTICAL DATA, MOUNT NARRYER

Sample	Map Symbol	Rb	Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
60739*	....	3	670	0·004 5 ± 0·000 1	0·013 ± 0·001	0·719 48 ± 0·000 09
60734	....	6·7	310	0·022 ± 0·000 2	0·064 ± 0·001	0·707 03 ± 0·000 12
60736	B	17	680	0·024 ± 0·000 2	0·069 ± 0·001	0·707 20 ± 0·000 07
60737	A	60	387	0·150 ± 0·002	0·433 ± 0·005	0·724 39 ± 0·000 12
69634	N	71	485	0·154 ± 0·002	0·445 ± 0·005	0·725 03 ± 0·000 11
69626	D	61	313	0·195 ± 0·002	0·564 ± 0·005	0·731 86 ± 0·000 15
60735	C	67	265	0·254 ± 0·003	0·736 ± 0·007	0·740 07 ± 0·000 08
69625	E	97	284	0·342 ± 0·003	0·991 ± 0·009	0·750 86 ± 0·000 14
69638	R	108	195	0·554 ± 0·005	1·61 ± 0·01	0·782 63 ± 0·000 05
60738	F	112	155	0·720 ± 0·007	2·10 ± 0·02	0·803 90 ± 0·000 11
69637	Q	138	153	0·905 ± 0·009	2·64 ± 0·02	0·832 25 ± 0·000 09
69636	P	134	139	0·959 ± 0·009	2·81 ± 0·02	0·842 61 ± 0·000 08
69627	G	123	123	1·00 ± 0·01	2·93 ± 0·03	0·846 02 ± 0·000 12
69642	V	139	134	1·05 ± 0·01	3·08 ± 0·03	0·854 82 ± 0·000 14

* Sample 60739 has been omitted from the regression because of petrographic evidence of intense epidotization which may indicate chemical mobility.

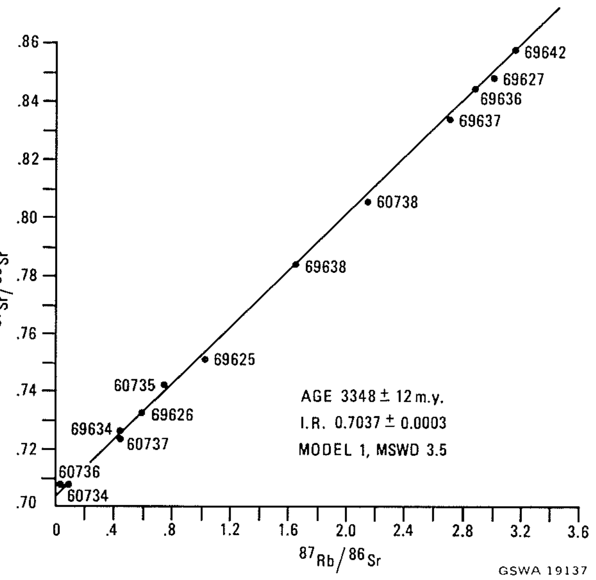

Figure 5 Rubidium-strontium isochron, Mount Narryer.

fluoride (200) crystal and a scintillation detec o was used. The spectrometer was calibrated against a set of geochemical reference samples whose Rb and Sr concentrations have been determined by isotope dilution (de Laeter and Abercrombie, 1970). Although the Rb/Sr ratios are accurate to better than 1 per cent, the individual Rb and Sr concentrations are only accurate to ± 7 per cent. Thus the Rb and Sr concentrations given in Table 2 do not necessarily correspond exactly to the stated Rb/Sr ratios. All errors are reported at the 95 per cent confidence level.

Regression analyses of the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ ratios were carried out using the least squares programme of McIntyre and others (1966). If the mean square of the weighted deviates (MSWD) is <1, the regression fits within experimental error (a Model 1 isochron). An MSWD of greater than unity indicates a departure from the geological assumptions of homogenous initial $^{87}Sr/^{86}Sr$ ratios and subsequent chemical closure of all samples to Rb and Sr. The programme then tests the assumption that the geological variance, in excess of the assigned experimental errors, is proportional to the $^{87}Sr/^{86}Sr$ value for each sample. This implies that the samples have a real spread in ages (Model 2). The third model tests the assumption that the excess geological variation of $^{87}Sr/^{86}Sr$ is independent of $^{87}Rb/^{86}Sr$. This model is more appropriate for samples which have the same age but a difference in initial $^{87}Sr/^{86}Sr$ ratios. In some regressions neither Model 2 nor Model 3 is preferred, and the programme then distributes the excess geological variance as a compromise between Models 2 and 3 (Model 4).

RESULTS AND DISCUSSION

The Rb-Sr data for the Mount Narryer samples are listed in Table 2, and the rubidium-strontium isochron is shown in Figure 5.

A Model 1 regression of the analytical data yields an age of 3 348 ± 12 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0·703 83 ± 0·000 08 and MSWD of 10·8. Alternatively, a Model 4 date of 3 348 ± 43 m.y. with an initial ratio of 0·703 7 ± 0·000 5 m.y. is indicated.

The age and initial ratio of the data strongly supports earlier suggestions (Arriens, 1971; Gee, 1979; and Gee and others, in press) that the Western Gneiss Terrain is substantially older than the 2 500 to 2 700 m.y. dates normally recorded from elsewhere in the Yilgarn Block.

The substantial variation in dynamic metamorphism among samples seems not to have greatly disturbed the precission of the isochron. This suggests either that dynamic metamorphism is more pervasive than is apparent from petrography, almost totally resetting the isochron, or that the dynamic phase followed closely the principal phase of dynamothermal metamorphism.

Strontium evolution analysis (Libby and de Laeter, 1981) using the determined age (3 350 m.y.), the initial $^{87}Sr/^{86}Sr$ ratio (0·703 7) and the arithmetic mean of measured $^{87}Rb/^{86}Sr$ ratios (1·32) suggests a mantle evolution date of about 3 550 m.y., assuming a single-stage model. This is equivalent to a prior crustal residence time of approximately 200 m.y. Even using the highest $^{87}Sr/^{86}Sr$ value which was measured (3·08), the calculated crustal prehistory is still nearly 100 m.y.

This substantial crustal residence time is compatible with the multistage metamorphism suggested above, but is also consistent with simpler models of single stage metamorphism, of either igneous or sedimentary rocks with the indicated, or greater, crustal prehistory. The Mount Narryer rocks are interpreted, on field evidence, to be metasedimentary.

Further work is planned to document in more detail the sedimentological, metamorphic, structural and chronological history of these gneisses in the Narryer Metamorphic Belt.

ACKNOWLEDGEMENTS

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REFERENCES

Arriens, P. A., 1971, Archaean geochronology of Australia: International Archaean Symposium, First, Perth 1970, Geol. Soc. Australia Special Publication No. 3, p. 1–23.

Baxter, J. L., 1974, Murgoo, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Baxter, J. L., and Lipple, S. L., 1979, Explanatory notes on the Perenjori 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1978/16.

Blight, D. F., and Barley, M., 1981, Estimated pressure and temperature conditions from some Western Australian Precambrian metamorphic terrains: West. Australia Geol. Survey Ann. Rept 1980, p. 67–72.

de Laeter, J. R., 1976, Rb-Sr whole-rock and mineral ages from the Gascoyne Province: West. Australia Geol. Survey Ann. Rept 1975, p. 126–130.

de Laeter, J. R., and Abercrombie, I. D., 1970, Mass spectrometric isotope dilution analyses of rubidium and strontium in standard rocks: Earth and Planetary Sci. Letters v. 9, p. 327–330.

de Laeter, J. R., Libby, W. G., and Trendall, A. F., in press, The older Precambrian geochronology of Western Australia: International Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Special Publication No. 7.

Elias, M., and Williams, S. J., 1977, Explanatory notes on the Robinson Range 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1980/4.

Gee, R. D., 1979, Structure and tectonic style of the Western Australian Shield: Tectonophysics v. 58, p. 327–369.

Gee, R. D., Baxter, J. L., Wilde, S. A., and Williams, I. R., in press, Crustal development in the Archaean Yilgarn Block, Western Australia: International Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Special Publication 7.

Libby, W. G., and de Laeter, J. R., 1979, Biotite dates and cooling history at the western margin of the Yilgarn Block: West. Australia Geol. Survey Ann. Rept. 1978, p. 79–87.

Libby, W. G., and de Laeter, J. R., 1981, Rb-Sr geochronology of alkaline granitic rocks in the Eastern Goldfields Province: West. Australia Geol. Survey Ann. Rept. 1980, p. 98–103.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research v. 71, p. 5459–5468.

Muhling, P. C., and Low, G. H., 1977, Yalgoo, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explanatory Notes.

Nieuwland, D. A., and Compston, W., 1980, The geological history of part of the Jimperding Metamorphic Belt, west Yilgarn Block: International Archaean Symposium, Second, Perth 1980, Geol. Soc. Australia Extended Abstracts, p. 12–13.

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on use of decay constants in Geo- and Cosmochronology: Earth and Planetary Sci. Letters, v. 36, p. 359–362.

Wilde, S. A., and Low, G. H., 1978, Perth, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Williams, I. R., 1979, Recent fault scarps in the Mount Narryer area, Byro 1:250 000 Sheet: West. Australia Geol. Survey Ann. Rept 1978, p. 51–55.

Williams, S. J., Elias, M., and de Laeter, J. R., 1978, Geochronology and evolution of the Eastern Gascoyne Province and the adjacent Yilgarn Block: West. Australia Geol. Survey Ann. Rept 1977, p. 50–56.

Williams, S. J., Williams, I. R., Chin, R. J., Muhling, P. C., and Hocking, R. M., 1978, Explanatory notes on the Mount Phillips 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1978/13.

Williams, I. R., Walker, I. W., Hocking, R. M., and Williams, S. J., 1980, Explanatory notes on the Byro 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1980/5.

Williams, S. J., Williams, I. R., and Hocking, R. M., 1980, Explanatory notes on the Glenburgh 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1980/4.

Rb-Sr GEOCHRONOLOGY OF ALKALINE GRANITIC ROCKS IN THE EASTERN GOLDFIELDS PROVINCE

by W. G. Libby and J. R. de Laeter*

ABSTRACT

Isochrons from two alkaline granitic masses in the Eastern Goldfields Province of Western Australia give Rb-Sr whole-rock dates near 2 500 m.y. Rocks from Twelve Mile Well (lat. 29°55′S, long. 122°05′E) yield a model 1 date of 2 489 ± 82 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio (Ri) of 0·701 2 ± 0·000 3, and a mean square of weighted deviates (MSWD) of 0·97. Samples from Woorana Well (lat. 27°30′S, long. 121°15′E), 270 km to the north, yield a model 1 date of 2 520 ± 113 m.y., with an Ri of 0·701 4 ± 0·001 7, and a MSWD of 0·70. All samples from both localities regressed together give a model 1 date of 2 512 m.y., with an Ri of 0·701 1, and a MSWD of 0·78.

Rubidium-strontium dating in general seems to be establishing alkaline plutonism as a distinctively late Archaean phenomenon in the Eastern Goldfields, and data from the present study do not support substantial crustal prehistory. Nevertheless, scattered results from other sources suggest that very mildly alkaline rocks may have been present in the area as early as 2 600 m.y. or even before 2 700 m.y.

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INTRODUCTION

Mildly alkaline plutonic, hypabyssal and perhaps volcanic igneous bodies are scattered through the gneissic, granitoid and supracrustal rocks of the Eastern Goldfields Province. Most alkaline masses lie within a north-trending belt which is 70 km wide and nearly 700 km long. Compositions range from syenite and monzonite to alkali granite. Mildly sodic clinopyroxene is characteristic, and aegirine or aegirine-augite and arfvedsonitic amphibole are present at a few locations. Libby (1978) has summarized previous studies of these rocks and has explained the terminology that will be used in this report.

The present study indicates that the alkaline suite was emplaced late in the Archaean tectonic cycle. It also suggests that some members of the suite were derived from rocks of mantle composition late in the Archaean and have been little contaminated by older crustal rocks. However, other members appear to have been injected into the crust earlier in the Archaean, and were later reworked to give the late Archaean dates which they now show.

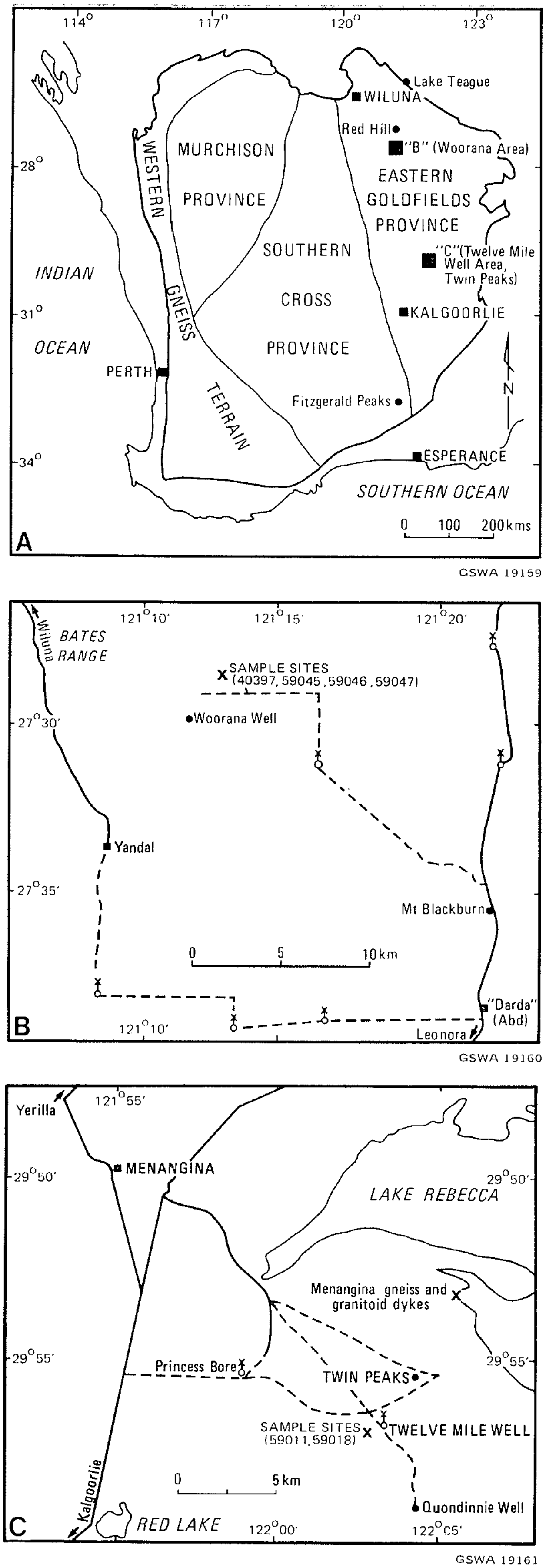

Figure 1 Index and location maps.
(A) Index map of the Yilgarn Block.
(B) Woorana Well area.
(C) Twelve Mile Well area.

New data presented here are based on two sets of samples, one from near Twelve Mile Well (lat. 29°55'S, long. 122°05'E) at the southern margin of the Edjudina 1:250 000 sheet; and the other from the vicinity of Woorana Well (lat. 27°30'S, long. 121°15'E) in the east-central part of the Sir Samuel 1:250 000 sheet. The localities are shown in Figure 1.

REGIONAL GEOLOGY

The Eastern Goldfields Province is a typical Archaean granite-greenstone terrain consisting of north-northwesterly trending belts of supracrustal rocks, separated by large masses of gneiss and granitoid plutons, and cut by smaller granitoid plutons. The regional geology has been summarized recently by Gee (1979) and Gee and others (in press), and in two guides to field excursions associated with the 1980 International Archaean Symposium in Perth (Groves and Gee, 1980; and Hallberg, 1980). The alkaline rocks have been described by Libby (1978) and by Lewis and Gower (1978). Stuckless and Bunting (written communication) have dated alkaline (2 760 m.y.) and subalkaline Mount Boreas type (2 371 m.y.) granitoids in the northern part of the Eastern Goldfields Province by Pb-Pb isochron techniques. Local geology has been mapped by Williams and others (1976) on the Edjudina sheet, and by Bunting and Williams (1979) on the Sir Samuel sheet. Further study of the chemistry of the alkaline plutonic rocks is in progress.

PETROGRAPHY

All samples are allotriomorphic seriate sodic syenite or quartz syenite, with the exception of 59011C which has similar minerals but is mafic. All samples contain albite, microcline, sphene, and variably green, mildly sodic clinopyroxene. Only three of the 13 samples have more than 10% normative quartz, and only one of these exceeds 20% normative quartz. Normative albite is low, exceeding 3% in only a single sample. Only sphene and, in rare cases, clinopyroxene achieve an approximation to crystal form. Where microcline insets are appreciably coarser than average grains, they are perthitic. Most samples have a weak preferred grain orientation.

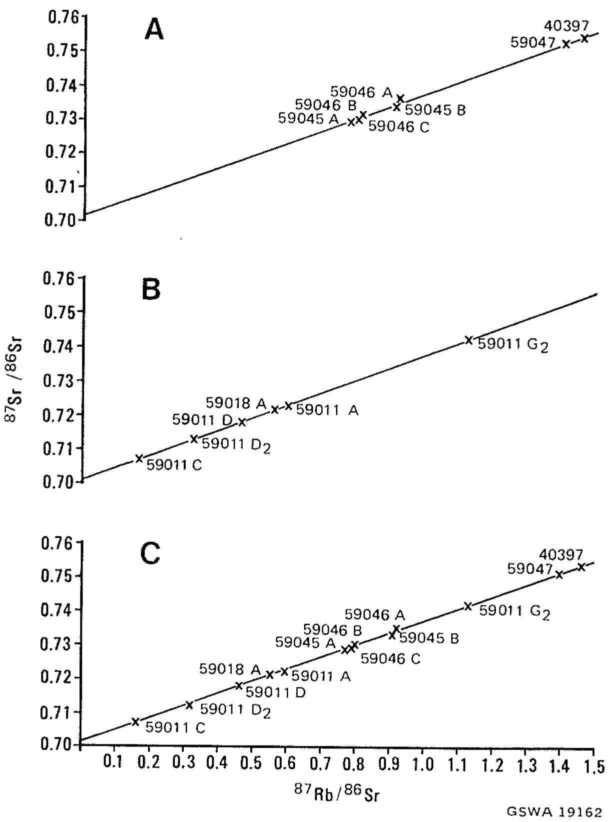

Figure 2 Isochrons
(A) Samples from Woorana Well, including 40397. Age 2520 ± 113, Ri 0.7014.
(B) Samples from Twelve Mile Well. Age 2489 ± 82, Ri 0.7012.
(C) Combined isochron of samples from Twelve Mile and Woorana Wells. Age 2512 ± 42, Ri 0.7011.

Note: For clarity in presentation the isochrons are arranged by replicating the $^{87}Sr/^{86}Sr$ axis, but all have initial ratios close to 0.701.

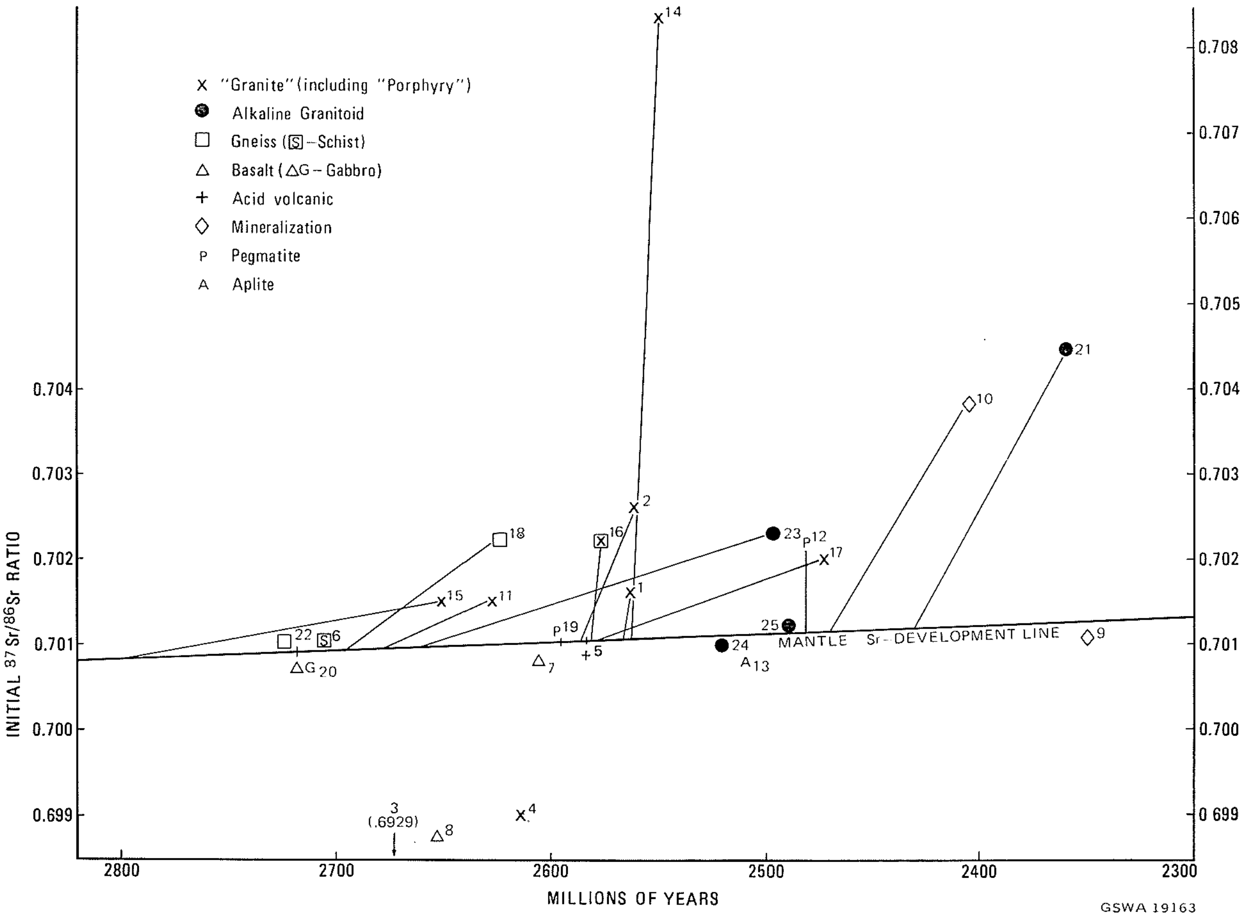

Figure 3 Strontium-evolution diagram of samples from the Eastern Goldfields Province. Parentheses indicate the point of projection on to the mantle Sr-evolution line of samples which plot beyond the limits of the graph. Samples more than 0·000 5 (Ri) below the mantle-evolution line are not projected on to the line.

A key to sources of data follows:

Sample	Author	Rock Unit
1.	Turek (1966)	Internal granites
2.	do.	External granites
3.	do.	Acid flows
4.	do.	Kalgoorlie Mine Porphyry
5.	do.	Norseman porphyritic rhyolite
6.	do.	Penneshaw acid schist
7.	do.	Paringa Basalt
8.	do.	Golden Mile Dolerite
9.	do.	Norseman quartz reefs
10.	do.	Kalgoorlie gold mineralization
11.	Roddick and others (1976)	Mount Keith Granodiorite
12.	do.	Mount Keith pegmatite
13.	do.	Aplite veins
14.	Worden and Compston (1973)	Mertondale granite
15.	Cooper and others (1978)	Lawlers tonalite
16.	do.	Lawlers Leucogranite
17.	do.	Lawlers Well Leucotonalite
18.	do.	Perseverance Gneiss
19.	do.	Perseverance pegmatite
20.	do.	Kathleen Valley Gabbro
21.	de Laeter and Lewis (1978)	Fitzgerald Peaks granitoids
22.	de Laeter and others (1978)	Menangina gneiss (Twin Peaks)
23.	do.	Menangina granite (Twin Peaks)
24.	This paper	Woorana Well
25.	do.	Twelve Mile Well

ANALYTICAL METHODS

The samples from Woorana and Twelve Mile Wells were prepared in the laboratory of the Geological Survey of Western Australia and analysed at the Department of Physics, Western Australian Institute of Technology. The methods of analysis are essentially as reported by de Laeter and others (1981). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0·710 2 ± 0·000 1, normalized to a $^{88}Sr/^{86}Sr$ value of 8·375 2.

Measured Rb and Sr values and Rb/Sr ratios, determined by x-ray fluorescence spectrometry, are listed with mass spectrometric determinations of $^{87}Sr/^{86}Sr$ in Table 1. Errors accompanying the data are at the 95% confidence level. We believe the values of Rb and Sr are accurate to ± 7 per cent; however, the measured Rb/Sr ratios may not correspond precisely with ratios which would be derived from the separate Rb and Sr values listed.

RESULTS

Analytical results listed in Table 1 are plotted as isochrons on Figure 2. Sample 40397 is included in the results as it is from the Woorana Well locality, though analytical data are included in an earlier report (Bunting and others, 1980). The data for these samples have been regressed using the least squares programme of McIntyre and others (1966). The value $1·42 \times 10^{-11} yr^{-1}$ was used for the decay constant of

TABLE 1. ANALYTICAL DATA FOR WHOLE-ROCK SAMPLES FROM TWELVE MILE AND WOORANA WELLS

Sample	Rb	Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Twelve Mile Well:					
59011 C	31	590	0·055 ± 0·001	0·160 ± 0·002	0·707 03 ± 0·000 20
59011 D_2	105	940	0·112 ± 0·001	0·324 ± 0·003	0·712 86 ± 0·000 13
59011 D	98	600	0·162 ± 0·002	0·468 ± 0·004	0·718 38 ± 0·000 28
59018 A	91	465	0·194 ± 0·002	0·561 ± 0·005	0·721 61 ± 0·000 14
59011 A	100	480	0·208 ± 0·002	0·601 ± 0·006	0·722 38 ± 0·000 07
59011 G_2	188	485	0·395 ± 0·003	1·14 ± 0·01	0·742 55 ± 0·000 34
Woorana Well:					
59045 A	160	590	0·273 ± 0·002	0·790 ± 0·008	0·729 95 ± 0·000 11
59046 C	137	490	0·281 ± 0·002	0·813 ± 0·008	0·730 15 ± 0·000 21
59046 B	173	615	0·282 ± 0·002	0·816 ± 0·008	0·730 33 ± 0·000 23
59045 B	202	640	0·316 ± 0·002	0·915 ± 0·008	0·724 38 ± 0·000 31
59046 A	175	555	0·319 ± 0·002	0·924 ± 0·009	0·735 07 ± 0·000 10
59047	180	370	0·488 ± 0 004	1·42 ± 0·02	0·752 67 ± 0·000 10
40397*	195	380	0·510 ± 0·005	1·48 ± 0·02	0·754 96 ± 0·000 21

* See Bunting and others (1980) for details.

^{87}Rb (Steiger and Jäger, 1977). To provide proper comparison, dates from sources using a different decay constant have been recalculated before inclusion in the present work.

All samples from the Woorana Well and Twelve Mile Well areas regressed together yield a model 1 date of 2 512 ± 42 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio (Ri) of 0·701 1 ± 0·000 5, and a mean square of weighted deviates (MSWD) of 0·78. However, as the localities of the two suites are separated by 270 km, they are more reasonably considered separately. Thus samples, including 40397, from the locality near Woorana Well yield a model 1 age of 2 520 ± 113 m.y., with an Ri of 0·701 4 ± 0·001 7, and a MSWD of 0·70. The samples near Twelve Mile Well give a model 1 age of 2 489 ± 82 m.y. with an Ri of 0·701 2 ± 0·000 3 and a MSWD of 0·97.

The range of $^{87}Rb/^{86}Sr$ ratios among the samples from Twelve Mile Well is sufficiently great for this set to dominate the combined data from Twelve Mile Well and Woorana Well. The more clustered data from Woorana Well yield an age which is slightly older than that from Twelve Mile Well but well within the error limits of both data sets. Addition of the previously determined sample 40397 strengthened the Woorana Well isochron without appreciable effect on the date or initial ratio.

DISCUSSION

Geochronological data are now available from five suites of alkaline rocks from the Eastern Goldfields Province. At three localities, Woorana Well, Twelve Mile Well and Fitzgerald Peaks (de Laeter and Lewis, 1978), the isochron ages are unequivocal. Data from Lake Teague are difficult to interpret (Bunting and others, 1980). The fifth suite is a group of four granitoid samples collected from Twin Peaks, 3 km northeast of Twelve Mile Well, and recorded by de Laeter and others (1978). The rocks at Twin Peaks are reported to consist of alkaline granitoid (Williams and others, 1976; Libby, 1978) but the analysed samples are not avaialbe for direct verification of their alkalinity. Other samples from Twin Peaks do not seem greatly different from the analysed alkaline samples from Twelve Mile Well. Hence the isochron reported by de Laeter and others would seem to be from alkaline rock.

The low MSWD from the isochron on combined data from Twelve Mile and Woorana Wells suggests that both bodies were derived from materials of similar isotopic ratio at about the same time. The distance between the two localities would seem to preclude derivation from the same crustal source but is consistent with simultaneous derivation from homogenous mantle.

The alkaline rocks from all the localities have late Archaean radiometric dates, but strontium evolution anylsis and Pb-Pb isochron whole-rock studies suggest that the various bodies may have different histories.

Strontium evolution analysis is the study of the change with time of the ratio of ^{87}Sr to ^{86}Sr. The purpose of the study commonly is to date events which occurred prior to the isochron date of the rock. The $^{87}Sr/^{86}Sr$ ratio changes with time because the absolute amount of ^{87}Sr increases through radioactive decay of ^{87}Rb. Thus, the rate of change of $^{87}Sr/^{86}Sr$ depends on the $^{87}Rb/^{86}Sr$ ratio and the decay constant of ^{87}Rb.

Of particular interest is the rate of change of $^{87}Sr/^{86}Sr$ at the time given by the isochron date of the rock. The $^{87}Sr/^{86}Sr$ ratio at that time is given by the initial $^{87}Sr/^{86}Sr$ ratio read from the isochron, the decay rate of ^{87}Rb is a known constant, and the $^{87}Rb/^{86}Sr$ ratio can be approximated from the present ratio.

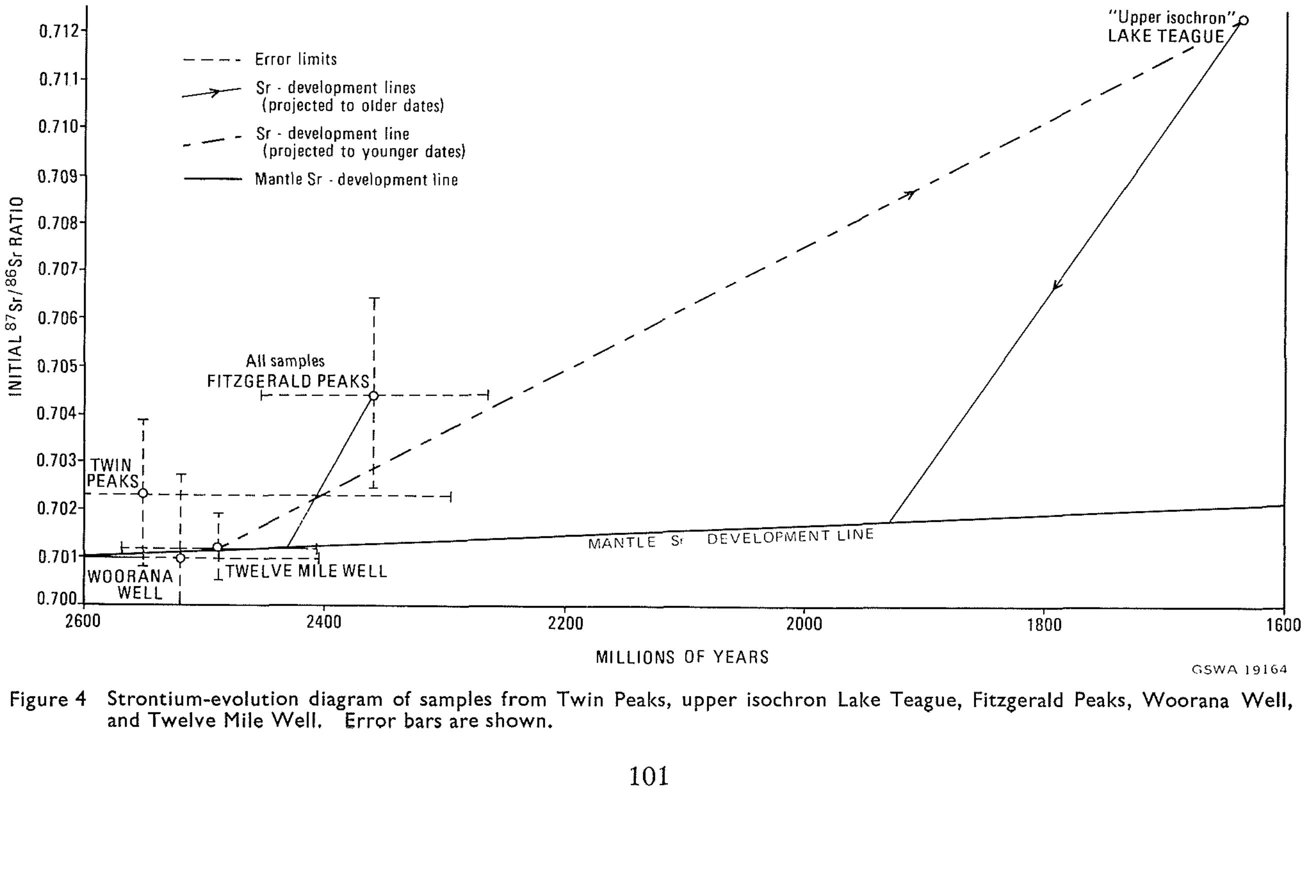

Figure 4 Strontium-evolution diagram of samples from Twin Peaks, upper isochron Lake Teague, Fitzgerald Peaks, Woorana Well, and Twelve Mile Well. Error bars are shown.

Knowing the rate of change of $^{87}Sr/^{86}Sr$ at a time in the past, the $^{87}Sr/^{86}Sr$ ratio can be projected farther backward. Thus the value of $^{87}Sr/^{86}Sr$ can be estimated for any time back to its original differentiation from materials of mantle composition, if the rock has not experienced a gross change in chemical composition (e.g. bulk metasomatism or further magmatic differentiation) which would change the $^{87}Rb/^{86}Sr$ ratio in the rock. A rock which meets this criterion is said to have experienced single-stage evolution. Metamorphism or melting would not disturb the system as long as bulk composition has remained unchanged.

The $^{87}Sr/^{86}Sr$ ratio in the mantle evolved similarly but more slowly than in crustal rocks because of a lower $^{87}Sr/^{86}Sr$ ratio than in the crust. Changes in mantle $^{87}Sr/^{86}Sr$ follow a development line which can be approximated by measuring the $^{87}Sr/^{86}Sr$ ratio in primitive rocks and again in modern, mantle-derived rocks (Faure and Powell, 1972). The intersection of the mantle development line and the backward projection of the $^{87}Sr/^{86}Sr$ ratio of a rock sample will give the date of differentiation of the sampled rock from material of mantle composition, assuming: that the rock is a product of single-stage evolution, that the mean of reported $^{87}Rb/^{86}Sr$ values is a close approximation to the bulk value of the rock body, that the mantle evolution line is correct, and that in each case the true ages and initial ratios of the samples are closely approximated by the isochron values.

The assumption of single-stage evolution is seldom capable of direct testing by the isotopic data, but even where this assumption cannot be accepted, the age of mantle evolution may sometimes be bracketed.

A multi-stage Sr-evolution line will consist of straight segments connecting points at which bulk composition has changed. The overall shape of the curve will be concave upward because young, evolved rocks will have a higher Rb/Sr ratio, and hence a higher $^{87}Rb/^{86}Sr$ ratio, than more primitive rocks. Consequently, the slope of the Sr evolution curve becomes steeper as age decreases.

From the upward concavity of the evolution curve, it follows that (1) straight-line projection to the mantle development line gives a minimum age for mantle evolution, (2) if the composition of the first stage is known, projection at the slope calculated from this composition will give the maximum age of mantle derivation.

Figure 3 summarizes whole-rock Rb-Sr analyses of a variety of granitoids, including the alkaline rocks, within the Eastern Goldfields Province on a Sr-evolution diagram. Six sources of data are utilized in addition to the present work; these are: Turek, 1966; de Laeter and others, 1978; Worden and Compston 1973; Roddick and others, 1976; Cooper and others, 1978; and de Laeter and Lewis, 1978. A further isotopic study, that of the syenitic rocks of the Teague Ring Structure (Bunting and others, 1980), which failed to establish a convincing isochron, is omitted from Figure 3, but some of these data are plotted in Figure 4.

All studies on Archaean metamorphic and igneous rocks of the Eastern Goldfields Province which include dates with error limits, initial $^{87}Sr/^{86}Sr$ ratios with error limits, and present-day $^{87}Rb/^{86}Sr$ ratios for individual samples are included in Figure 3. The mantle Sr-development curve was calculated assuming linear evolution from a $^{87}Sr/^{86}Sr$ ratio of 0·699 at 4 600 m.y. to 0·703 7 at the present (Faure and Powell, 1972, p. 130). The part of that line between 2 800 and 2 300 m.y. is plotted on Figure 3. A model Sr-development line for each sample is generated by the relationship:

$$S = (^{87}Rb/^{86}Sr)\ \lambda,$$

where S is the slope of the projection and λ is the ^{87}Rb decay constant ($1{\cdot}42 \times 10^{-11} yr^{-1}$). In this analysis the $^{87}Rb/^{86}Sr$ ratio which was used is the mean of the set of ratios reported for each locality; where determinations were replicated on an individual sample, the mean of replications was used as the value for that sample.

Initial ratios from three rocks, "Penneshaw acid schist" of Turek (1966), "Norseman porphyritic rhyolite" of Turek, and "Perseverance pegamtite" of Cooper and others (1978) fall outside the range of the graph. Consequently, these points are not plotted, but the intersections of Sr-evolution lines from these samples with the mantle Sr-development line are marked with ticks and labelled. "Acid flows", "Kalgoorlie Mine Porphyry", and "Golden Mile Dolerite" fall well below the mantle growth line and are not considered further.

Samples plotting within 0·000 5 (initial $^{87}Sr/^{86}Sr$ ratio) of the mantle development curve are assumed to be on it.

Figure 4 is a simplified version of Figure 3 in the time range of 2 600 to 1 600 m.y., and includes data from the Woorana Well, Twelve Mile Well, and Fitzgerald Peaks suites, as well as the younger age of the upper reference isochron from the Lake Teague suite.

Figure 5 shows that all ages are contained between 2 725 m.y. and 2 350 m.y., possibly in three groups: (1) gneiss and schist at an age slightly greater than 2 700 m.y., (2) the bulk of non-gneissic granitoids in an interval between 2 650 and 2 550 m.y., and (3) mainly alkaline and dyke rock together with gold mineralization at less than 2 550 m.y. Projection of dates along Sr-evolution lines to the mantle Sr-evolution line has little effect on the gross grouping, but in detail tightens the grouping in the younger age zone and loosens it in the older age area.

AGES OF THE ALKALINE ROCKS

The reported isochron ages of the alkaline rocks are among the youngest Archaean granitoid ages recorded from the Eastern Goldfields, all being 2 520 m.y. or younger (Fig. 5).

Most alkaline rocks also project to the mantle Sr-development line at relatively young Archaean ages (Figs. 3 and 5). Data from Twelve Mile Well and Woorana Well plot close to the mantle-development line, hence the projected dates are close to the isochron dates for these localities; and data from Fitzgerald Peaks project to the mantle-development line at 2 431 m.y. In contrast, data from Twin Peaks project to the mantle-development line at 2 660 m.y., a date considerably earlier than that of the other alkaline sets.

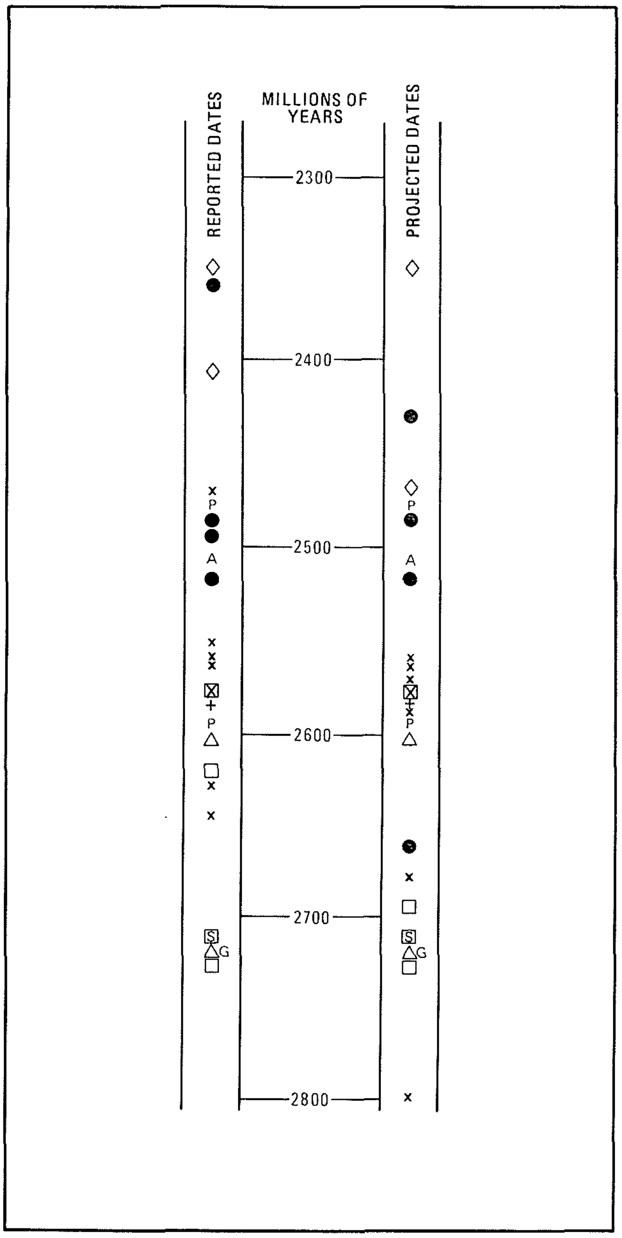

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Figure 5 Bar graph showing the age of various rock types and their displacement upon projection to the mantle Sr—evolution line. Symbols are those in Figure 3.

The Woorana Well and Twelve Mile Well sample sets were, therefore, derived from rocks of mantle composition near the time of their isochron age, that is, about 2 500 m.y. ago. If the rocks at Fitzgerald Peaks were derived from the mantle in a single stage, Sr evolution suggests an age for this event which, at 2 431 m.y., is younger than the rocks from Woorana and Twelve Mile Wells; but if two-stage evolution is assumed, the data are compatible with derivation from rocks of the age and isotopic composition of Twelve Mile Well.

It might be noted in passing that the upper isochron of alkaline rocks from Lake Teague (Bunting and others, 1980), though post-Archaean (1 636 m.y.) and projecting to the mantle-development line at about 1 930 m.y., is also compatible with evolution from rocks of the same age and Rb-Sr composition as the Twelve Mile Well samples, if multiple-stage evolution is accepted.

The position of the Lake Teague sample on the projection of the Sr-evolution line for the Tewlve Mile Well samples suggests that the Lake Teague material may have been derived at 1 636 m.y. by differentiation from a pre-existing alkaline rock with the composition and age of the Twelve Mile Well rock (Fig. 4).

Thus two of the sets of alkaline rocks (Woorana and Twelve Mile Wells) seem to be derived from materials of mantle composition about 2 500 m.y. ago. A further two sets of data, from Fitzgerald Peaks and Lake Teague, are compatible with this date of mantle derivation, but data from Twin Peaks project to an earlier date (2 660 m.y.). This earlier date could be explained as an artifact of calculation of the average $^{87}Rb/^{86}Sr$ value from only four samples, which may not be representative of the rock as a whole; however, the possibility of the appearance of alkaline rocks in the Eastern Goldfields Province before 2 600 m.y. is supported by a Pb-Pb whole-rock isochron date (Stuckless and Bunting, written communication) of 2 760 m.y.

Most of the samples providing the Pb-Pb data were collected from the vicinity of Red Hill, 300 km north of Twin Peaks but only 35 km north of the Woorana Well Rb-Sr sampling site. None of the Pb-Pb sampling sites is more than 35 km from Woorana Well and one (sample 40397) is from the alkaline mass at Woorana Well. On petrographic evidence, neither the rocks from Red Hill nor from Twin Peaks are strongly alkaline but both sets of rocks conform to the criteria for inclusion in the alkaline suite used by Libby (1978), and no independent criterion for excluding them has been found.

Thus, as the Twelve Mile Well and Woorana Well samples seem fixed at a date of mantle derivation of about 2 500 m.y. by their position on the mantle Sr-evolution line and, as the Twin Peaks and Red Hill rocks seem considerably older than this date, alkaline rocks may have originated at more than one period in the Archaean.

An unresolved problem is the presence of sample 40397 both in the set of Rb-Sr samples from Woorana Well, providing apparently clear evidence of mantle derivation near 2 500 m.y., and in the set of Pb-Pb samples, providing an age of 2 760 m.y.

CONCLUSIONS

The new data establish a late Archaean date for differentiation of two bodies of alkaline rock from material of mantle composition, despite evidence that other alkaline bodies may have had longer prior crustal residence. Rb-Sr isochron dates continue to be late Archaean, establishing a pattern which is apparently characteristic of the alkaline suite in the Eastern Goldfields Province.

ACKNOWLEDGEMENTS

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REFERENCES

Bunting, J. A., and Williams, S. J., 1979, Sir Samuel, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Bunting, J. A., de Laeter, J. R., and Libby, W. G., 1980, Evidence for the age and cryptoexplosive origin of the Teague Ring Structure: West. Australia Geol. Survey Ann. Rept 1979, pp. 81–85.

Cooper, J. A., Nesbitt, R. W., Platt, J. P., and Mortimer, G. E., 1978, Crustal development in the Agnew region, Western Australia, as shown by Rb/Sr isotopic and geochemical studies: Precambrian Research, v. 7, pp. 31–60.

de Laeter, J. R., Compston, W., and Chappell, B. W., 1978, An internal whole-rock age from an Archaean gneiss: West. Australian Inst. of Tech. Dept of Physics Report No. PD147/1978/EP18.

de Laeter, J. R., and Lewis, J. D., 1978, The age of the syenitic rocks of the Fitzgerald Peaks, near Norseman: West. Australia Geol. Survey Ann. Rept 1977, pp. 56–60.

de Laeter, J. R., Williams, I. R., Rosman, K. J. R., and Libby, W. G., 1981, A definitive 3 350 m.y. age from banded gneiss, Mount Narryer area, Western Gneiss Terrain: West. Australia Geol. Survey Ann. Rept 1980, p. 94–98.

Faure, G., and Powell, J. L., 1972, Strontium isotope geology: Berlin, Springer-Verlag, 188 pp.

Gee, R. D., 1979, Structure and tectonic style of the Western Australian Shield: Tectonophysics, v. 58, pp. 327–369.

Gee, R. D., Baxter, J. L., Wilde, S. A., and Williams, I. R., in press, Crustal development in the Yilgarn Block, Western Australia: Geol. Soc. Australia Special Publication.

Groves, D. I., and Gee, R. D., 1980, Regional geology and mineral deposits of the Kalgoorlie-Norseman region: Geol. Soc. Australia, W.A. Division, 2nd Int. Archaean Symposium, Perth, Excursion Guide, 112 pp.

Hallberg, J. A., 1980, Archaean Geology of the Leonora-Laverton area: Geol. Soc. Australia, W.A. Division, 2nd Int. Archaean Symposium, Perth, Excursion Guide, 37 pp.

Lewis, J. D., and Gower, C. F., 1978, Syenitic rocks of the Fitzgerald Peaks, near Norseman: *in* Contributions to the geology of the Eastern Goldfields Province of the Yilgarn Block: West. Australia Geol. Survey Report 9, pp. 139–161.

Libby, W. G., 1978, The felsic alkaline rocks: *in* Contributions to the geology of the Eastern Goldfields Province of the Yilgarn Block: West. Australia Geol. Survey Report 9, pp. 111–137.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys, Research, v. 71, pp. 5459–5468.

Roddick, J. C., Compston, W., and Durney, D. W., 1976, The radiometric age of the Mount Keith Granodiorite, a maximum age estimate for an Archaean greenstone sequence in the Yilgarn Block, Western Australia: Precambrian Research, v. 3, pp. 55–78.

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on use of decay constants in Geo- and Cosmochronology: Earth and Planetary Sci. Letters, v. 36, pp. 359–362.

Turek, A., 1966, Rubidium-strontium isotopic studies in the Kalgoorlie-Norseman area, Western Australia: Australian National University, Ph.D. thesis (unpublished).

Williams, I. R., Gower, C. F., and Thom, R., 1976, Edjudina, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Worden, J. M., and Compston, W., 1973, A Rb-Sr isotopic study of weathering in the Mertondale Granite, Western Australia: Geochim. Cosmochim. Acta, v. 37, pp. 2567–2576.

FELSIC DYKES OF THE MOUNT EDGAR BATHOLITH

by J. D. Lewis and R. Davy

ABSTRACT

A petrographic and chemical study has shown that a wide variety of felsic dykes, including andesitic, trachyandesitic, granophyric, and rhyolitic types, intrude the Mount Edgar batholith. The andesites are the oldest dykes and are possibly related to the Archaean Duffer Formation; they intrude only the alkali granite, which forms the oldest part of the batholith. The trachyandesite dykes are related to the Bridget Adamellite, of early Proterozoic age. Three types of rhyolite can be distinguished and most specimens are highly potassic, the dykes are confined to the batholith and probably related to it. The rhyolites and trachyandesites are intruded along the same fracture system as the widespread dolerite dyke swarm of the Pilbara and were intruded late in the Archaean and early in thr Proterozoic.

INTRODUCTION

The Mount Edgar batholith, which is located east of Marble Bar (lat. 21°10′S long. 119°45′E,), is roughly rhombic in outline, and has a maximum north-south dimension of 52 km and a

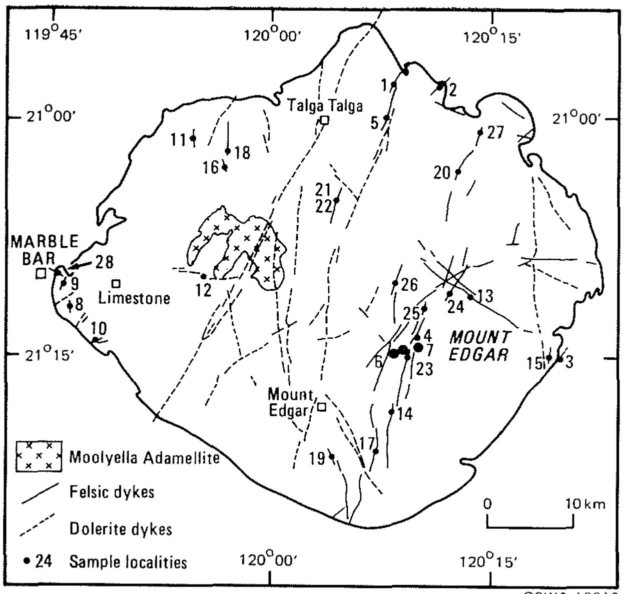


Figure 1 Dykes in the Mount Edgar Batholith.

maximum east-west dimension of 55 km. Its shape is structurally controlled along the southeast margin by a compressed and sheared greenstone belt, and along the southwest margin by a major lineament. Elsewhere the margin of the batholith shows cross-cutting intrusive relationships. The batholith consists of a large mass of granodiorite-tonalite into which are intruded a number of smaller granodioritic and adamellitic bodies. It is cut by large dolerite dykes belonging to the north-northeast trending Black Range dyke suite, which is prominent throughout the Pilbara Block, and by numerous felsic dykes which form the substance of this study. The regional geology of the Mount Edgar batholith has been described by Hickman (in press).

The felsic dykes follow two dominant trends; the principal set trends north-northeast, parallel to the dolerites of the Black Range suite, and a lesser set trends northwest. The dykes range in thickness from 5–20 m and are exposed over strike distances of up to 15 km. Dykes are found throughout the batholith, but the largest number are found in a belt centred on Mount Edgar in the eastern part of the batholith (Fig. 1). In addition, Mount Edgar itself and a number of small tors in the vicinity, are formed by small plugs of felsic material similar to the dyke rocks.

This study is concerned mainly with the petrography and geochemistry of the felsic dykes and arises out of a major geochemical study of the Mount Edgar batholith (Davy and Lewis, in prep. a).

METHODS OF STUDY

Twenty-four samples of felsic dykes, each of 2–3 kg, were collected, mostly in the vicinity of station tracks (Fig. 1). In addition, samples were collected from two small plugs of hornblende-bearing rock (thought to be related to some of the dykes) at Mount Edgar itself and, for comparative purposes, from two dolerite dykes.

Analyses for SiO_2, Al_2O_3, Fe_2O_3, CaO, TiO_2 and K_2O were carried out by X-ray fluorescence on fused discs using lithium tetraborate flux, and on Ba, Ce, La, Mn, Nb, Rb, Sr, Th, Sn, V, Y and Zr by X-ray fluorescence on pressed powder pellets. Determinations of MgO, Na_2O, Cu, P, Li, Ni and Zn were made by atomic absorption analysis after a perchloric-hydrofluoric acid digestion and extraction into 5% HCl. F was determined using a specific ion electrode. Analytical results are given in Tables 1, 2 and 3.

PETROGRAPHY

Visual inspection of the felsic dykes in outcrop and hand specimen reveals two major groupings depending on the phenocryst phase present. The largest group carries phenocrysts of quartz and feldspar, but a number of specimens contain hornblende phenocrysts. Samples from the Mount Edgar plugs appear similar to the hornblende porphyries, but there are a few dykes which cannot easily be assigned. As the groundmass in all the dyke rocks is fine grained, rock nomenclature is on the basis of major-element chemistry (Tables 1 and 2). On the outline classification of Cox and others (1979), based on silica and total alkali content, the quartz feldspar porphyries are rhyolites, while the hornblende-bearing varieties are trachyandesites and andesites.

HORNBLENDE PORPHYRIES

Trachyandesite

This group of major north-northeast trending dykes (Table 1, samples 1–5) in the eastern half of the batholith is characterized by a fine-grained feldspathic groundmass and small phenocrysts of hornblende up to 4 mm long.

The groundmass consists of small feldspar prisms and laths, often strongly sericitized. In some specimens, the laths were probably sanidine, and the rock has a sub-trachytic texture; in others, small prisms of calcic oligoclase are surrounded by low-relief potash feldspar. In all specimens, there

TABLE 1. CHEMICAL ANALYSES OF HORNBLENDE PORPHYRY, ANDESITE AND DOLERITE DYKES MOUNT EDGAR BATHOLITH

	1	2	3	4	5	6	7	8	9	10	11	12
SiO_2	52·7	54·2	56·0	58·3	58·3	54·1	61·6	59·9	62·5	63·5	47·9	54·5
Al_2O_3	14·3	14·1	14·9	14·8	16·0	13·8	15·5	15·9	14·7	15·8	13·6	15·7
Fe_2O_3	9·7	7·29	7·2	7·6	7·4	9·0	6·4	7·2	5·94	7·1	14·9	9·8
FeO	....	3·5	....	....	....	....	3·1	....	3·6	....	....	....
MgO	2·7	3·3	3·1	3·6	2·6	5·0	1·9	3·2	3·3	2·2	5·9	3·1
CaO	6·5	5·2	5·5	5·7	5·7	6·8	4·5	5·4	4·7	2·0	7·4	6·7
Na_2O	2·6	3·4	4·5	3·9	3·8	3·0	4·6	3·5	3·7	4·3	0·78	2·8
K_2O	3·6	3·6	1·1	3·1	3·1	3·3	3·2	1·5	1·8	0·7	0·89	1·8
TiO_2	0·75	0·65	0·46	0·64	0·74	0·67	0·69	0·66	0·56	1·06	2·78	1·03
P_2O_5	....	0·21	....	....	....	....	0·18	....	0·07	....	....	....
CO_2	....	3·80	....	....	....	....	0·02	....	0·14	....	....	....
$H_2O\pm$	....	1·89	....	....	....	....	0·35	....	1·16	....	....	....
$H_2O\pm$	....	0·09	....	....	....	....	0·03	....	0·03	....	....	....
LOI (*a*)	6·94	(5·43)	6·57	2·48	1·58	4·21	(0·09)	1·75	(0·97)	2·65	5·45	4·00
Total	99·79	101·23	99·53	100·02	98·88	99·88	102·07	99·01	102·2	99·31	99·60	99·33
Ba	2 000	1 200	1 000	1 000	1 200	900	1 000	400	500	240	1 000	1 200
Ce	80	80	40	60	80	80	100	60	<20	100	40	80
Cu	120	70	25	75	65	15	30	35	35	20	30	110
F	870	800	760	890	80	1 080	800	450	610	730	820	890
La	40	40	40	40	40	40	60	20	40	60	20	40
Pb	30	20	25	25	50	40	<10	<10	<10	<10	<10	20
Li	110	45	30	15	35	25	18	40	45	40	60	205
Mn	1 200	1 200	970	970	1 090	1 130	940	875	750	950	1 500	1 150
Ni	30	30	10	20	15	20	10	45	70	5	45	90
Nb	<5	<5	<5	<5	<5	<5	10	5	<5	10	10	5
Rb	130	140	65	110	85	150	120	90	90	20	40	95
Sr	500	480	400	800	900	750	750	320	260	150	180	420
Th	10	10	10	10	<10	<10	10	<10	<10	<10	<10	<10
Sn	<2	2	<2	<2	<2	<2	<2	2	2	6	<2	4
V	210	160	150	150	140	180	100	130	100	<10	320	170
Y	15	20	10	15	15	15	25	25	25	45	60	30
Zn	110	90	75	90	100	105	96	65	60	70	120	95
Zr	90	105	90	105	90	90	150	150	165	210	255	180

a) Bracketed L.O.I. are calculated; 1–5: Hornblende porphyry dykes; 6, 7: Hornblende porphyry plugs; 8–10: Andesite dykes; 11, 12: Dolerite dykes. For locations see Fig. 1,

TABLE 2. CHEMICAL ANALYSES OF QUARTZ-FELDSPAR PORPHYRY DYKES

	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
SiO_2	70·2	71·7	73·4	74·1	74·4	74·5	75·4	75·4	75·5	76·7	76·1	76·5	76·7	76·8	81·9	74·6
Al_2O_3	13·4	13·1	12·5	13·6	12·1	13·3	11·9	12·7	12·6	13·0	12·5	11·8	11·8	11·2	11·8	12·8
Fe_2O_3	4·1	3·6	1·4	1·8	2·1	2·0	2·3	2·2	2·2	1·6	1·9	1·7	1·6	1·8	1·2	2·7
FeO	....	....	....	....	1·3	....	1·3	....	....	....	....	....	....	1·2	....	....
MgO	0·69	0·53	0·27	0·50	0·30	0·33	0·33	0·33	0·22	0·05	0·39	0·16	0·38	0·12	0·32	0·27
CaO	2·4	1·4	2·4	0·65	0·52	1·3	0·37	0·89	0·18	0·14	0·60	0·53	0·33	0·52	0·21	1·1
Na_2O	1·6	3·7	7·1	3·9	2·8	1·6	2·7	1·0	3·3	3·6	2·7	1·6	2·6	3·3	0·05	4·5
K_2O	7·5	4·7	0·8	5·6	5·4	5·9	5·2	6·6	5·4	5·1	5·7	7·5	6·4	4·0	3·5	3·0
TiO_2	0·63	0·55	0·77	0·21	0·24	0·25	0·27	0·27	0·27	0·08	0·20	0·07	0·12	0·17	0·15	0·17
P_2O_5	....	....	....	....	0·02	....	0·03	....	....	....	....	....	....	0·01	....	....
CO_2	....	....	....	....	0·27	....	0·20	....	....	....	....	....	....	0·05	....	....
$H_2O\pm$....	....	....	....	....	0·61	....	0·67	....	....	....	....	....	....	0·44	....	....
$H_2O\pm$....	....	....	....	....	0·06	....	0·06	....	....	....	....	....	....	0·02	....	....
LOI (*a*)	1·45	1·50	2·37	0·69	(0·81)	2·01	(0·80)	1·54	0·90	0·66	0·57	0·93	0·83	(0·39)	1·75	1·65
Total	102·0	100·8	101·0	101·1	100·1	101·2	100·7	100·9	100·6	100·9	100·7	100·8	100·8	99·6	100·9	100·8
Ba	1 200	900	350	500	600	500	500	800	700	60	450	300	450	700	300	800
Ce	140	180	140	120	140	140	160	160	180	120	140	140	120	160	40	140
Cu	10	5	5	25	15	15	20	2·5	10	10	10	10	10	10	20	5
F	100	1 150	270	310	900	850	270	1 450	440	1 570	590	320	1 630	1 840	220	430
La	100	80	60	60	80	80	100	100	120	60	60	80	60	100	<20	80
Pb	<10	10	10	<10	10	10	<10	35	15	25	20	70	15	<10	20	<10
Li	20	15	10	15	11	40	9	10	15	70	10	15	20	11	15	10
Mn	400	445	135	180	220	240	220	240	185	115	220	205	160	150	60	190
Ni	<5	5	<5	10	<10	<5	10	<5	<5	<5	<5	<5	<5	<10	<5	<5
Nb	5	10	5	15	10	10	10	15	15	30	15	10	20	10	10	5
Rb	140	210	25	340	300	420	240	340	220	440	260	400	360	190	280	60
Sr	190	100	170	85	180	45	80	30	45	15	80	40	30	120	10	70
Th	20	30	20	50	30	50	50	40	30	50	50	50	50	30	50	20
Sn	<2	2	<2	2	4	2	4	2	4	8	4	40	6	4	2	2
V	30	20	40	10	20	10	<10	10	<10	<10	<10	<10	<10	<10	<10	10
Y	35	50	30	45	50	50	50	45	60	100	50	50	60	60	45	60
Zn	70	55	50	20	34	30	34	85	45	25	35	35	35	38	15	35
Zr	420	380	400	180	225	195	255	270	285	180	210	150	210	225	180	340

(*a*) Bracketed L.O.I. are calculated. 13–26: Quartz-feldspar porphyry dykes; 27: Silicified quartz-feldspar porphyry; 28: Granophyre dyke.

are prominent small euhedra of apatite and magnetite. Hornblende phenocrysts occur as euhedral prisms or acicular crystals up to 4 mm long, and more rarely as large anhedral grains and aggregates. Hornblende comprises about 15% of the rock and is often altered to an aggregate of chlorite and carbonate. Where fresh, the hornblende is rhythmically zoned, dark green and often has a narrow darker outer rim.

Most of the rocks contain sericite, chlorite, and carbonate. This alteration is related to the introduction of CO_2 rather than to weathering. Specimen 5, however, which contains rounded phenocrysts of oligoclase in addition to hornblende, has been epidotized rather than carbonated.

Trachyandesite plugs

The small intrusions (Table 1, samples 6 and 7) in the vicinity of Mount Edgar, have a similar chemical composition and show the same hornblende phenocrysts as the trachyandesite dykes described above. The two samples examined are from Mount Edgar itself (sample 7) and a smaller plug (sample 6) 2 km to the southwest.

Both specimens are similar to the dyke rocks and contain numerous small phenocrysts of dark green rhythmically zoned hornblende, but are distinctive in carrying minor amounts of strongly coloured sphene. Specimen 6 is a medium-grained, hypidiomorphic assemblage of euhedral prisms of andesine (An_{32}), rhythmically zoned to marginal albite, containing minor interstitial microperthite, quartz and calcite. In addition to approximately 15% of hornblende phenocrysts, there are a few flakes of brown biotite, prominent accessory apatite, and magnetite.

Specimen 7 is fine grained, and the groundmass to the hornblende phenocrysts consists of closely packed prisms of rhythmically zoned andesine (An_{32}), from 0·2–0·8 mm long, and minor interstitial potash feldspar and quartz. The rock contains a few larger phenocrysts (or xenocrysts) of altered plagioclase, a small amount of biotite, apatite and magnetite, and a little diopside. The pyroxene occurs in two forms, as ragged partially resorbed crystals up to 2 mm long, and as clots of small prisms. One such clot surrounds a distinctive patch of probably xenocrystic quartz.

Andesite

These dykes (Table 1, samples 8, 9 and 10) from the western margin of the batholith, probably belong to a different suite from the other hornblende-bearing dykes. Specimens 8 and 9 are similar and contain saussuritized phenocrysts of plagioclase, aggregates of pale-green hornblende, and green biotite in a fine-grained plagioclase-quartz-amphibole matrix. Both specimens are extensively altered and recrystallized, but specimen 9 preserves a sub-trachytic texture.

TABLE 3. ANALYSES OF SOME FELSIC ROCKS OF THE PILBARA REGION

	29	30	31	32	33	34	35	36	37	38
SiO_2	56·5	63·54	58·44	71·8	75·6	72·9	77·15	62·0	60·92	74·5
Al_2O_3	14·8	14·67	14·08	13·0	12·4	13·9	11·21	15·5	15·29	12·9
Fe_2O_3	8·6	3·67	3·44	3·0	2·3	2·2	0·55	7·9	1·71	2·3
FeO	....	2·53	4·72	....	....	....	0·30	....	3·40	....
MgO	3·17	2·35	4·41	0·50	0·28	0·37	0·42	2·9	2·74	0·23
CaO	5·7	4·19	6·11	2·07	0·55	1·6	0·68	4·0	4·55	0·50
Na_2O	3·7	3·51	3·02	4·13	2·6	4·0	0·81	3·8	4·50	4·5
K_2O	3·0	4·15	3·44	4·33	5·7	3·5	7·45	1·3	1·35	4·1
TiO_2	0·66	0·45	0·53	0·65	0·20	n.d.	0·05	0·76	0·59	0·14
LOI	4·10	0·67	1·06	1·77	0·99	0·90	1·62	2·08	4·44	0·92
Ba	1 200	900	970	815	500	985	90	380	460	536
Ce	75	....	....	150	140	76	58	60	47	127
Cu	55	26	100	7	12	32	1	30	30	12
F	770	....	....	500	925	196	....	600	....	487
La	40	....	....	80	80	50	25	40	23	69
Pb	25	....	....	8	20	10	16	<10	7	10
Li	40	....	....	15	20	14	7	40	8	5
Mn	1 070	1 300	1 200	330	195	209	300	850	1 100	154
Ni	20	....	....	3	<5	<5	2	40	35	<5
Nb	<5	....	....	7	15	<5	10	6	3	21
Rb	115	132	104	125	320	84	191	65	39	106
Sr	650	670	690	150	70	216	14	240	364	45
Th	10	....	....	23	40	17	31	<10	6	23
Sn	<2	....	....	<2	4	4	8	3	<2	<2
V	150	....	....	30	8	6	2	80	81	<10
Y	15	20	19	38	55	9	26	30	13	41
Zn	95	74	97	60	38	44	15	65	64	22
Zr	100	123	103	400	215	175	82	175	127	288

29: Average trachyandesite dykes (Table 1, 1–7); 30, 31: Bridget adamellite and satellite plug of hornblende porphyry (Barley, 1980); 32: Average Ca-rich rhyolite dyke (Table 2, 13–15); 33: Average rhyolite dyke (Table 2, 16–26); 34: Mount Edgar Batholith, Pluton J (Davy and Lewis, in press); 35: Average rhyolite of Wyman Fm (Hickman, in press); 36: Average andesite dyke (Table 1, 8–10); 37: Average Duffer Fm (Hickman, in press); 38: Average alkali granite, Marble Bar (Pluton F *in* Davy and Lewis, in press).

Specimen 10 is more dacitic and consists of patches of epidote and small subhedral phenocrysts of oligoclase in a fine-grained recrystallized matrix of oligoclase prisms. The phenocrysts are notable for showing Baveno and Manebach twinning.

Quartz-feldspar porphyries

The dykes in this suite are chemically all rhyolitic (Table 2). Specimen 27 has been strongly silicified, and specimen 28 is a granophyre not belonging to the porphyry suite; specimens 15, 16 and 18 are also texturally distinctive and will be considered later.

The main group of potash-rich rhyolites all contain phenocrysts of quartz, perthite and oligoclase in a fine-grained quartzo-feldspathic groundmass. The quartz phenocrysts are 1–6 mm across, subhedral to rounded, and usually show resorption features. Feldspar phenocrysts are similar in size, euhedral to rounded, and often occur as glomeroporphyritic aggregates. The proportion of phenocrysts ranges from 20% to 40% of the rock.

The only mafic mineral present is cholrite, which sometimes occurs as aggregates enclosing numerous grains of apatite and ilmenite.

The groundmass of the rock is an indeterminate, quartzo-feldspathic devitrified glass. Some specimens preserve original spherulitic textures, whereas others have developed a fine-grained, vermicular, granophyric texture. Alteration of groundmass and phenocrysts consists of sericitization of the feldspars and the introduction of minor carbonate; a few specimens contain minor epidote.

Specimens 16 and 18, from the western part of the batholith, are from adjacent dykes and are distinctive in carrying apparent phenocrysts of granophyric perthite. The rock consists of small prisms of oligoclase, perthite, small euhedra of quartz, and flakes of chlorite in a sparse matrix of devitrified quartzo-feldspathic material. In addition to a number of larger phenocrysts of quartz and feldspar, there are large subhedral grains of perthite showing a coarse, granophyric texture. These do not appear as xenocrysts but probably represent material picked up by passage of the magma through a still-hot granophyre.

Specimen 15 is distinctive in that it is low in potash. In thin section, it is similar to the potash rhyolites except that the rare perthite crystals show strong resorption and are probably xenocrysts.

Specimen 28 is a coarse leucocratic granophyre, in which phenocrysts of quartz and oligoclase form the nucleus of granophyric growth. The dyke probably represents a portion of the same magma as the alkali granite which it intrudes.

DOLERITE

Two specimens (Table 1, samples 11 and 12), collected for comparison purposes, are of saussuritized basalt and dolerite which nevertheless retain a relict igneous texture.

CHEMISTRY

MAJOR ELEMENTS

Analyses of the hornblende porphyry dykes and plugs of the eastern part of the batholith (Table 1) fit closely the average values for trachyandesites compiled by Le Maitre (1976), and are not greatly dissimilar from those of Le Maitre's andesites, except for the relatively high K_2O content. The Mount Edgar plug (sample 7) is relatively high in silica and low in MgO and CaO but is within the range of analyses of similar rocks reported by Barley (1980) east of the Mount Edgar batholith (Table 3, samples 30 and 31).

The trachyandesites differ chemically from the andesite dykes of the western part of the batholith principally by virtue of their higher K_2O content, but they also have a slightly lower silica content. Between the andesitic rocks and the rhyolitic quartz-feldspar porphyries there is a silica gap, the least siliceous rhyolite containing nearly 7% more SiO_2 than the most siliceous andesite. The andesitic and trachyandesitic rocks contain more Al_2O_3 and total Fe (as Fe_2O_3), and less total alkalis, than the rhyolitic dykes.

The rhyolitic rocks (Table 2) are more K_2O-rich than the average rhyolite of Le Maitre, and values reach 7·5% K_2O on a volatile-free basis. However, the mean values (Table 3 samples 32, 33) are well within two standard deviations of the published mean. Le Maitre has no classification to fit the soda-rich rock (sample 15—7·1% Na_2O) although it is closest to dacite.

The granophyre dykes (sample 28) are chemically similar to the rhyolites, and to the alkali granite which they intrude (Table 3, sample 38). Although the dykes contain less K_2O (3·0%) than the adamellite (mean of 4·1% in 7 samples) it is almost certainly a variant of the same magma.

TRACE ELEMENTS

There is no study of the trace elements of rock types comparable to Le Maitre's (1976) study of the major components; thus, no comparison can be made with average trace-element contents of rhyolites and trachyandesites.

Within the groups outlined by the chemistry of the major elements, trace-element contents are not always internally consistent. For example, one of three andesites contains no detectable Ce, another no detectable Ni or V, while the other samples are relatively high. Similarly, one of the trachyandesites contains an order of magnitude less F than the remainder; sample 5 contains only 80 ppm F while the next lowest, sample 3, contains 760 ppm. These anomalies notwithstanding, the andesites always contain more Sn, Y and Zr, and less Ba, Pb and Sr than the trachyandesites. In addition, the andesites generally contain more Li and Ni, and less Cu, F, Mn, Rb, Th, V and Zn than the trachyandesites. The trachyandesite plugs differ from their associated dykes in containing less Cu, but are comparable in other respects.

The rhyolitic dykes are distinctly different from the andesitic and trachyandesitic dykes, particularly in their Rb and Sr contents. The rhyolites are rich in Rb and poor in Sr compared with the andesitic rocks. In addition the rhyolites are generally richer in Ce, La, Nb, Th and Zr, and poorer in Cu, Mn, Ni and V than the andesites. Within the rhyolitic group, there are individual specimens with widely different trace-element contents; F, for example, varies between 100 ppm and 1840 ppm, while individual samples are poor in Ba and Rb and rich in Cu, Pb and Sn.

Compared with other dyke rocks of the group, the silicified rhyolite, sample 27, has lost Ce, F, La, Mn, Sr and Zn, but other potentially mobile components such as Li, Ba and Rb appear unaffected. These components are possibly retained in the remaining K-feldspar and secondary mica.

The trace-element chemistry identifies a separate subgroup within the rhyolite dykes. Not only are samples 13–15 the least siliceous, but they contain significantly less Rb and more CaO, TiO_2, MgO, V, Zn and Zr than the remainder of the rhyolites. The two potassic samples (13 and 14) are also relatively enriched in Mn. Petrographically only the ultrasodic sample 15 is distinctive, although in each sample, small euhedra of ilmenite are relatively more common than in the remainder of the rhyolites. Despite the lack of petrographic distinctions, these samples should probably be treated as a separate group within the rhyolites. Conversely, samples 16 and 18, which are petrographically distinctive in containing xenocrysts of granophyre, are indistinguishable chemically from the main group of rhyloites.

The trace-element chemistry of the granophyre dyke (sample 28) is very close to that of the rhyolites, except for lower content of Rb and Th.

INTERPRETIVE DIAGRAMS

The data have been subjected to graphical interpretation to attempt to highlight similarities and differences between the various groups of dyke rocks. The plots presented in Figures 2 to 5 are Rb versus Sr, principal component analysis, and triangular diagrams of normative Or-Ab-An, and AFM components.

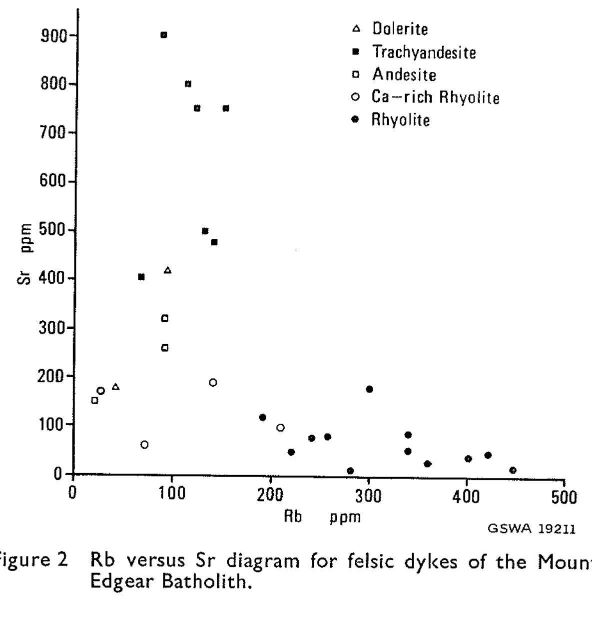
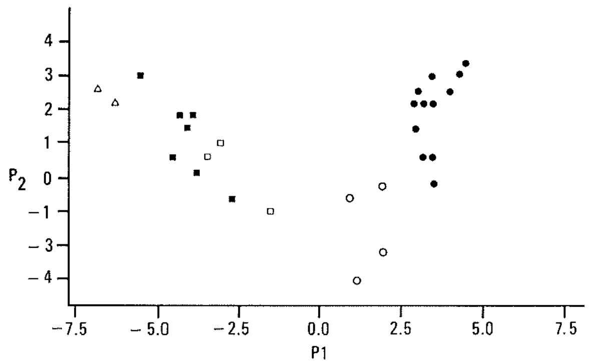


Figure 2 Rb versus Sr diagram for felsic dykes of the Mount Edgear Batholith.



Principal component loadings (standardized data) :

$$P_1 = 0.26\ SiO_2 + 0.19\ K_2O + 0.20\ Ce + 0.18\ La + 0.19\ Rb + 0.24\ Th + 0.16\ U + 0.19\ Y + 0.13\ Zr - 0.21\ Al_2O_3 - 0.26\ Fe_2O_3 - 0.27\ CaO - 0.25\ MgO - 0.19\ TiO_2 - 0.17\ Ba - 0.20\ Cu - 0.15\ Li - 0.26\ Mn - 0.19\ Ni - 0.21\ Sr - 0.25\ V - 0.24\ Zn$$

$$P_2 = 0.10 + 0.30\ K_2O + 0.14\ Cu + 0.20\ F + 0.19\ Li + 0.14\ Ni + 0.38\ Rb + 0.22\ Th + 0.32\ U + 0.13\ V + 0.10\ Y - 0.46\ Na_2O - 0.26\ B - 0.13\ Ca - 0.19\ La - 0.32\ Zr$$

GSWA 19212

Figure 3 Principal component analysis (symbols as in Figure 2).

The plot of Rb versus Sr (Fig. 2) clearly separates the Sr-rich trachyandesites from the Rb-rich rhyolite dykes. However, the dolerite, andesite and Ca-rich subgroup of the rhyolite dykes, all of which contain moderate amounts of Rb and Sr, are not clearly separated. Principal component analysis is intended to provide a multivariate comparison of samples using a wide range of chemical components. The resulting diagram (Fig. 3) demonstrates clearly two trends of groupings; the one includes the dolerites, trachyandesites and andesites, the other, the rhyolites. Except that they are distinct from the rhyolites, no clear subgroups appear within the more basic rocks, but within the rhyolites, the Ca-rich subgroup (samples 13–15) and the granophyre dyke form a distinct cluster separate from the bulk of the rhyolites.

The AFM diagram (Fig. 4) separates the trachyandesites and andesites from each other, but shows that both groups are within the field of Ringwood's (1974) calc-alkaline fractionation trends. The two dolerite samples, however, clearly follow a tholeiitic trend.

The normative plot of Q-Ab-An (Fig. 5) groups the rhyolites andesites and dolerites together, clearly separate from the trachyandesite dykes and plugs. The plot also indicates the possibility that a number of the rhyolites were near-eutectic melts although most must have been intruded at well above the eutectic temperature.

DISCUSSION

The limited data presented here show that there is far more diversity in the dyke rocks of the Mount Edgar batholith than might be expected, particularly when compared with the adjacent Corunna Downs batholith where only dolerite and microgranite dykes have been identified (Davy and Lewis, in prep. b). In the Mount Edgar batholith, geochemical and petrographic criteria suggest four groups of felsic dykes and two main types of intermediate dykes and plugs, as well as the dolerite dykes. There are, in addition, microgranite veins and dykes, quartz dykes, and pegamtites not discussed here (Davy and Lewis, in prep. a).

A major structural feature of the batholith is the presence of a well defined fracture pattern. The largest number and most clearly discernable fractures run in a north-northeast direction, parallel to the southeastern margin of the batholith. Landsat imagery indicates that this margin, together with the southeastern margin of the Corunna Downs batholith and the southeastern corner of the Shaw batholith, reflect a major deep-seated north-northeast-trending lineament. It is presumed, without direct evidence, that most of the fractures of the Mount Edgar batholith, now filled by dykes or quartz reefs, have been initiated by, or are related to this boundary lineament.

The north-northeast-trending fractures are accompanied by a lesser number of northwest trending fractures. From the offset of north-northeast-trending dykes, particularly the dolerites, there is evidence that some of these fractures may be younger than the main set of fractures. Both sets of fractures display an *en echelon* pattern.

The fractures are filled with dyke rocks of all types, but the distribution of felsic dykes is largely separate from the dolerite dykes. The western and eastern parts of the fracture pattern are predominantly filled by dolerite dykes while the central part contains rhyolite and trachyandesite dykes. The Mount Edgar plugs, of trachyandesite, lie close to north-northeast-trending fractures in the densest part of the felsic dyke swarm. Northeast of Talga Talga homestead both dolerite and trachyandesite dykes occupy *en echelon* portions of the same fracture (Fig. 1).

As far as is known, the rhyolitic dykes are restricted to the batholith proper. With their generally high K_2O/Na_2O ratio and high Rb and Rb/Sr, the presence of detectable Sn and moderate to high F content, it seems likely that the dykes are the last stage of the development of the granitoid rocks—the intrusion of residual magma along fractures. However, the high K_2O content of the dykes precludes the possibility of finding exact equivalents among the Mount Edgar granitoids. The high Ce and La of the dykes suggests that the only possible related granitoid is the granodiorite pluton located 5 km north of Mount Edgar (Table 3, sample 34). This pluton is geographically close to the main trend line of the dyke swarm but it seems an unlikely source as this would require severe fractionation to reverse the Rb/Sr ratio from 84/216 in the pluton to 319/68 in the dykes. The only other potassic rocks in the vicinity are the lavas of the Wyman Formation (Table 3, sample 35) but these form part of the Archaean layered succession into which the batholith is intruded and have an entirely distinct trace-element signature; there is no reason to suppose the dykes are related to this formation.

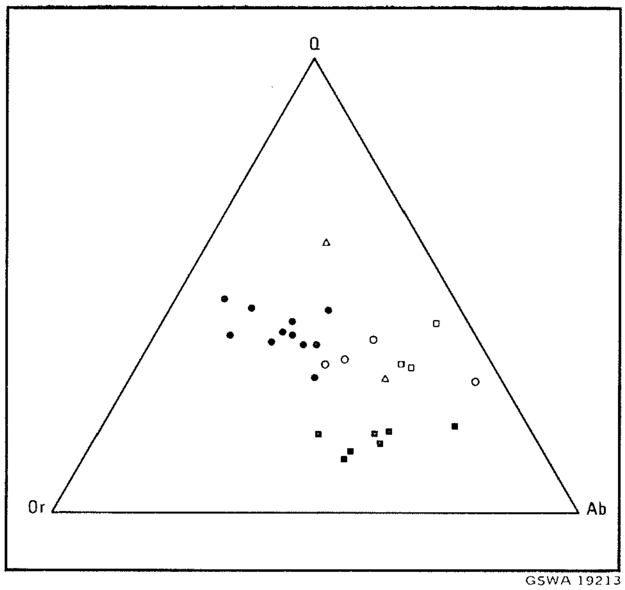


Figure 4 Normative Q-Or-Ab diagram (symbols as in Figure 2).

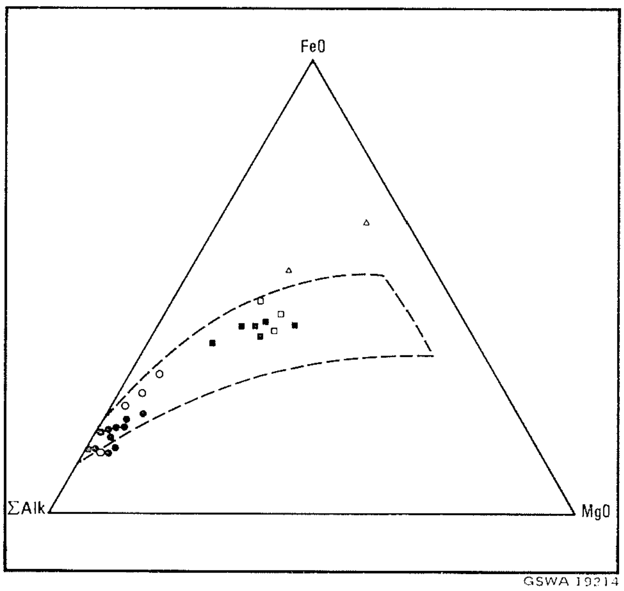


Figure 5 AFM diagram. The dashed line encloses calc-alkaline trends (Ringwood, 1974) (Symbols as in Figure 2).

Two of the Ca-rich rhyolite dykes (samples 13 and 14) occur with the main group of Ca-poor dykes. The rock appears to be a variant of the main rhyolite dyke magmas; the high CaO and TiO_2, and distinctive trace-element content may indicate a lesser degree of fractionation or perhaps minor contamination of the magma by basic material. The ultra-sodic dyke (sample 15) may be derived from the same magma source as some of the aplites, as these also contain highly sodic varieties (Davy and Lewis, in prep. b). The petrographically distinctive rhyolites containing xenocrysts of granophyre (samples 16 and 18) occur in the west of the batholith and have no known affinities.

The trachyandesite dykes and plugs occur in the same swarm as the rhyolites but are chemically and petrographically distinct from them. None of the granitoids of the Mount Edgar batholith are comparable with the trachyandesites, but similar dykes are known to occur southeast of the batholith associated with the Bridget Adamellite. The Bridget Adamellite is the largest of a number of small stocks which intrude the Mosquito Creek Formation; the composition of the stocks varies from adamellite to quartz monzonite (Table 3, samples 30, 31) and both stocks and dykes are characterized by prominent green euhedral hornblende. From the major-element chemistry, it is possible that the trachyandesites were formed by the contamination of doleritic magma with granitic material, but the trace element content of the rocks does not support this hypothesis.

The dolerite dykes are widespread throughout the region, rocks of similar type and composition occupy north-northeast-trending fractures cutting across many batholiths and greenstone belts.

No evidence has been found in this study for providing even a relative age for the dyke suites that intrude the Mount Edgar batholith, but there are a number of lines of evidence from other areas which suggest that, apart from the andesites in the eastern part of the batholith, the rhyolites are oldest, followed by the dolerites and trachyandesites. In the Shaw batholith, southwest of Mount Edgar, rhyolite dykes similar to those described here are cut by dolerites of the Black Range suite (Hickman, in press). Trachyandesite dykes associated with the Bridget Adamellite intrude Proterozoic lavas of the Fortescue Group (Hickman, 1978; Barley, 1980) for which the Black Range dyke swarm probably acted as feeders (Lewis and others, 1975). The absolute age of the dykes is also problematic: a lower limit is set by the age of the Moolyella Adamellite which is intruded both by dolerite and rhyolite dykes, and this pluton has been dated by the Rb-Sr method at 2 670 $\pm$ 95 m.y. by de Laeter and Blockley (1972). An upper age limit for the trachyandesite dykes is possibly provided by the Spinaway Porphyry, a dacite sill which intrudes the Hardey Sandstone, which was dated by Trendall (1975) at 2 124 $\pm$ 195 m.y. The Black Range Dolerite has been dated by Lewis and others (1975) at 2 329 $\pm$ 89 m.y., but the significance of this age is not certain as there is the possibility that the Hardey Sandstone, which unconformably overlies a dyke of the Black Range suite, is as old as 2 600 m.y. (Hickman and de Laeter, 1977). At all events, the three main dyke suites were intruded at the end of Archaean and in earliest Proterozoic times; in the Mount Edgar batholith they were intruded along a single fracture system and the time interval over which they were intruded may be relatively short. The availability of three distinctly different magmas over a single geographic area within a short space of time, remains a problem.

The last group of felsic dykes to be considered are the andesite which are restricted to a small area southeast of Marble Bar (Fig. 1). Though their dominant trend is northeast, the fractures are localized and do not appear to form part of the major fracture pattern occupied by dykes in the eastern part of the batholith. The fractures are confined to the alkali granite, which occupies the margin of the batholith, and there is some suggestion of a radial distribution with a centre close to the nearby 'Big Stubby' and 'Halley's Comet' lead-zinc mineralization. Hickman and Lipple (1978) and Hickman (in press) suggest that the alkali granite may be older than the Mount Edgar batholith and a magma source for the Duffer Formation. Xenoliths of this granitoid are present within the migmatite complex which is believed to be in the order of 3 280 $\pm$ 20 m.y. old (Pidgeon, 1978b), whereas the Duffer Formation itself is 3 452 $\pm$ 16 m.y. old (Pidgeon, 1978a); both ages were obtained by the U-Pb method on zircons.

A comparison of the chemistry of the andesite (samples 8-10) with that of felsic rocks within the Duffer Formation (Table 3, sample 37) indicates their overall similarity. The main differences are in SiO_2, Fe_2O_3 (total), MgO, and Li, but even here the differences are not great. While the similarities do not prove that the andesite dykes and the Duffer Formation are co-magmatic they are suggestive. That the andesite dykes are older than the other felsic dykes of the Mount Edgar batholith is also suggested by the fact that, unlike the rhyolites and trachyandesites, the andesite dykes have been metamorphosed and recrystallized.

In conclusion, this study has shown that there is a wide variety of felsic dykes intruding the Mount Edgar batholith and that their petrography and chemistry pose significant problems concerned with the availability of a variety of magmas over a wide area during a relatively short time interval. In the past little attention has been paid to dyke rocks in the Pilbara region, and it is suggested that a wider study is needed to solve the problems.

In particular the problems raised are:

(1) The relationship of the andesite dykes and alkali granite near Marble Bar to the Duffer Formation and the Mount Edgar batholith.

(2) The nature of the photolineament which marks the eastern margin of the Mount Edgar, Corunna Downs and Shaw batholiths and its relation to the fractures now filled by rhyolitic, trachyandesitic and doleritic dykes.

(3) The time-relationships and origin of the magmas which formed the dyke rocks.

REFERENCES

Barley, M. E., 1980, Evolution of Archaean calc-alkaline volcanics: University of Western Australia Ph.D. thesis (unpublished).

Cox, K. G., Bell, J. D., and Pankhurst, R. J., 1979, The Interpretation of igneous rocks: London, George Allen and Unwin.

Davy, R., and Lewis, J. D., in press, The geochemistry of the Mount Edgar batholith, Pilbara area, Western Australia: International Archaean Conference, 2nd, Perth, 1980, Geological Soc. Australia Spec. Publ.

Davy, R., and Lewis, J. D., in prep. a, The geochemistry and petrography of the Mount Edgar batholith, Pilbara region: West. Australia Geol. Surv.

Davy, R., and Lewis, J. D., in prep. b, The geochemistry and petrography of the Corunna Downs batholith, Pilbara region: West. Australia Geol. Surv.

de Laeter, J. R., and Blockley, J. G., 1972, Granite ages within the Archaean Pilbara Block, Western Australia: Geol. Soc. Australia, Jour. v. 19, p. 363–370.

Hickman, A. H., 1978, Nullagine, Western Australia: West. Australia Geol. Surv., 1:250 000 Geol. Series Explanatory Notes.

Hickman, A. H., in press, Geology of the Pilbara Block and its environs: West Australia Geol. Surv. Bulletin 127.

Hickman, A. H., and de Laeter, J. R., 1977, The depositional environment and age of a shale within the Hardey Sandstone of the Fortescue Group: West. Australia Geol. Surv. Ann. Rept 1976, p. 62–68.

Hickman, A. H., and Lipple, S. L., 1978, Marble Bar, Western Australia: West. Australia Geol. Surv., 1:250 000 Geol. Series Explanatory Notes.

Le Maitre, R. W., 1976, The chemical variability of some common igneous rocks: Jour. Petrology v. 17, p. 589–637.

Lewis, J. D., Rosman, K. J. R., and de Laeter, J. R., 1975, The age and metamorphic effects of the Black Range Dolerite dykes: West. Australia Geol. Surv. Ann. Rept 1974, p. 80–88.

Pidgeon, R. T., 1978a, 3 450 m.y.-old volcanics in the Archaean layered greenstone succession of the Pilbara Block, Western Australia: Earth and Planetary Sci. Letters, v. 37, p. 421–428.

——— 1978b, Geochronological investigations of granite batholiths of the Archaean granite-greenstone terrain of the Pilbara Block, Western Australia: Archaean Geochemistry Conference, Toronto, 1978, Proc. p. 361–362.

Ringwood, A. G., 1974, The petrological evolution in island arc systems: Geol. Soc. London, Jour. v. 130, p. 183–204.

Trendall, A. F., 1975, Preliminary geochronological results from two Pilbara porphyry bodies: West. Australia Geol. Surv. Ann. Rept 1974, p. 103–106.

Rb-Sr DATING OF TECTONIC EVENTS IN THE PROTEROZOIC MOUNT BARREN GROUP NEAR HOPETOUN

by R. Thom, J. R. de Laeter* and W. G. Libby

ABSTRACT

Samples of mica schist from the Mount Barren Group at Barrens Beach and West Beach, respectively about 9 km and 12 km west of Hopetoun, Western Australia, were sampled for Rb-Sr geochronology. Whole-rock samples from Barrens Beach provide a model 4 isochron at 1 077 ± 22 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0·790 3 ± 0·007 1. A single biotite sample has a radiometric age of 1 087 m.y., assuming an initial ratio of 0·79. The data from West Beach failed to define an isochron, but suggest older ages and a lower initial ratio. The 1087 m.y. date is believed to be associated with the latest folding in the area, as this folding is pervasive at Barrens Beach but only locally developed at West Beach. Muscovite—whole-rock pairs from the erratic data at West Beach may indicate an event between 1 200 and 1 300 m.y. Similarly, a low-precision isochron through whole-rock and biotite data at West Beach may reflect an event at about 1 790 m.y.

INTRODUCTION

The Mount Barren Group is a succession of arenaceous and shaley rocks forming an elongate outlier of Proterozoic metasediment in older gneiss, encompassing the peaks, East Mount Barren, Mid Mount Barren, and West Mount Barren, on the south coast of Western Australia (Fig. 1). The outlier straddles the boundary between the Yilgarn Block and the Albany-Fraser Province, and has undergone metamorphism and deformation, thought to be the effects of overprinting during development of the Albany-Fraser Province, a complex Proterozoic mobile belt. The intensity of metamorphism and deformation within the outlier decreases with distance from the mobile belt, northwestward toward the Yilgarn Block. This metamorphic gradient was first recognized by Sofoulis (1956), and has been described in more detail by Thom (1977).

The main aim of this study was to obtain a firm metamorphic age from the schist on the coast near East Mount Barren which would represent a reliable minimum age of deposition of the Mount Barren Group. A secondary aim was to examine whether interpretable differences in ages could be identified from metasediments of different structural history, and, therefore, elucidate the nature of the polyphase tectonic events in this area.

The Mount Barren Group has long been assigned to the Proterozoic on various lines of evidence:

(i) it is a stable-shelf sequence unconformably overlying, at a high angle, Archaean volcanic and sedimentary rocks of the Ravensthorpe Range;

(ii) it is younger than three dyke suites cutting the Ravensthorpe Quartz Diorite which has intruded the Archaean volcanics. An east-northeasterly trending mafic dyke suite is correlated with mafic dykes of the same trend in the Phillips River west of Ravensthorpe, dated at 2 447 ± 50 m.y. (Giddings, 1976);

(iii) where the effects of Proterozoic metamorphism and deformation are minimal, the Mount Barren Group is seen to post-date the main Archaean metamorphism and deformation;

(iv) stromatolites, but no other fossils, have been recognized within the succession (Thom and others, 1977);

(v) the Stirling Range Formation, 150 km to the west, with which the Mount Barren Group has long been correlated (Roe, 1852; Maitland, 1901; and Blatchford, 1919) has a metamorphic age of 1 126 ± 40 m.y. and an interpreted depositional age of 1 312 m.y. (Turek and Stephenson, 1966);

(vi) the metamorphic gradient within the Mount Barren Group has been attributed to overprinting during a tectonothermal event of 1 400–1 200 m.y. age within the Albany-Fraser mobile belt (Thom, 1980).

STRUCTURE OF THE MOUNT BARREN GROUP

The two locations (Fig. 1) which were sampled for geochronology represent different situations in the structural sequence, so that it is appropriate to summarize the structure of the repeatedly deformed Mount Barren Group.

On the basis of consistent structural relationships it is possible to recognize four generations of folds (F_1, F_2, F_3, and F_4), all with axial planar foliations (S_1, S_2, S_3, and S_4), which are assigned to four deformational events (D_1, D_2, D_3 and D_4). These relationships are summarized below:

D_1 The Fitzgerald Syncline, which is the major fold structure of the Mount Barren Group, is assigned to F_1. It is identified regionally (Fig. 1) by the distribution of younging directions of the various rock types within the outlier. Few associated mesoscopic structures are known (Thom and Chin, in press).

D_2 Thrusting was an important event in D_2, and recumbent F_2 folds were formed during this period. These folds are transected by a later cleavage, S_3, which is not axial planar to the F_2 folds.

D_3 Mesoscopic F_3 folds are ubiquitous throughout the Mount Barren Group, but the folded surface is commonly rendered indistinct by the strongly developed axial-planar foliation, S_3. This foliation is the most prominent planar surface in the metasediments of the Mount Barren Group.

D_4 F_4 folds are widespread and commonly have S_3 as the folded surface. F_4 folds have only poorly developed axial-planar foliation and are, therefore, the most conspicuous of the different generations of folds in the Mount Barren Group.

Folding is summarized schematically in Figure 2.

The Mount Barren Group is most strongly deformed and metamorphosed between Barrens Beach and West Beach. Quartz arenite has been metamorphosed to quartzite, and pelitic rocks have been metamorphosed to muscovite-biotite-kyanite-staurolite-garnet schist. A macroscopic F_4 fold train is clearly visible on aerial photographs and is mappable on the ground from varying younging directions in quartzite. These folds decrease in amplitude westward from several hundred metres near East Mount Barren to a few metres near Mylies Beach. This decrease in intensity of D_4 is reflected in the mesoscopic structures at the two sample locations, as described below:

(a) At West Beach, the most prominent feature is the foliation, S_3, which is planar and imparts a fissility or flagginess to the schists. This foliation is axial-planar to mesoscopic F_3 folds, and is so intense that F_3 folds are nearly obliterated, although evidence for them can always be found. F_3 folds are best preserved by quartz veins whose injection pre-dated the D_3 event. F_4 folds, which deform the S_3 foliation, are confined to discrete linear zones. The accompanying foliation (S_4, a crenulation cleavage) is widespread but is everywhere weaker than S_3. The samples were collected from a zone in which planar S_3 foliation is the dominant structure and F_4 folds are absent.

(b) At Barrens Beach, S_3 foliation is again the most prominent foliation, but here it is deformed into innumerable F_4 folds. These folds have an axial-planar crenulation cleavage (S_4) which is strongly developed and partially transposes the earlier foliation (S_3). Wide compositional bands, in which coarsely crystallized biotite alternates with bands of finer grained muscovite schist, have been deformed into F_3 folds, several metres in wavelength, and have been subsequently refolded in D_4. All samples from this locality contain recognizable F_4 folds. Except for the coarse-grained biotite schist, all of the samples contain abundant mesoscopic F_4 folds, usually with distinct axial-planar crenulation cleavage (S_4).

PETROGRAPHY

The Barrens Beach samples (55249A–F) are little-altered kyanite-biotite-muscovite-quartz schist with rutile and tourmaline, and, except for 55249E and F, opaque minerals and staurolite. Chlorite is present in all samples but is clearly secondary in at least some samples. Accessory apatite and zircon are present in most samples.

Biotite in sample 55249E ranges from fine to very coarse grained. Fine flakes of biotite tend to have a common orientation parallel to muscovite, whereas coarse, poikiloblastic grains have little systematic orientation and have grown post-kinematically to D_4. In this sample, chloride is interleaved

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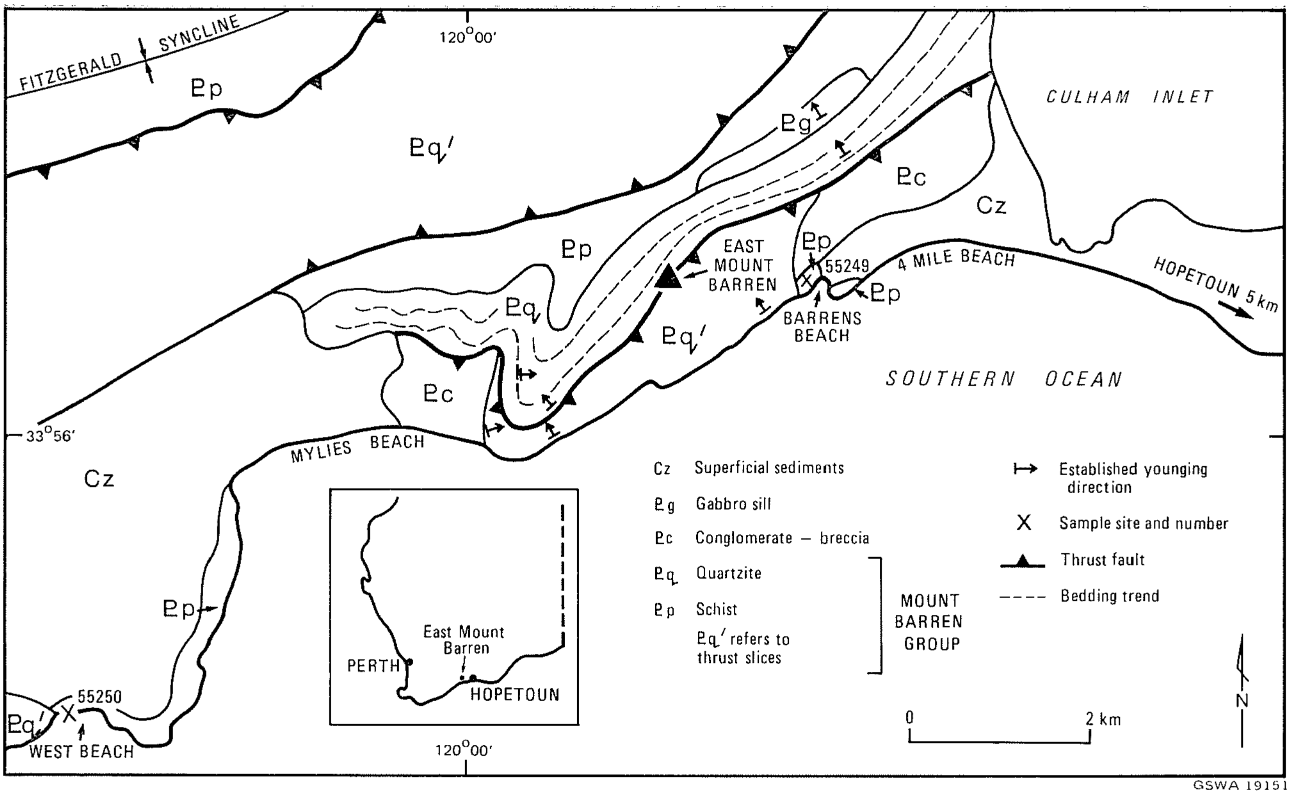

Figure 1 Structural and geological setting of the geochronology sample sites.

with biotite. Thus, as many as three stages of crystallization (synkinematic biotite, post-kinematic biotite and chloritization of biotite) are suggested by the sample.

Samples from West Beach (55250A–H) are fresh pelitic schists containing quartz, biotite, muscovite, tourmaline, and an opaque mineral which is probably graphite. Staurolite is present in five samples (55250A, B, C, F and G), of which three (55250A, B and F) contain kyanite. In contrast, garnet is present in samples 55250D, E and H, which are free of kyanite and staurolite. Iron oxide is present in some samples.

ANALYTICAL PROCEDURE

Geochronological samples were prepared mechanically in the laboratory of the Geological Survey of Western Australia and analyzed at the Department of Physics, Western Australian Institute of Technology.

Whole-rock samples were crushed and split, where appropriate, into subsamples for whole-rock and for mica analysis. Samples for whole-rock analysis were reduced to —200 mesh in a Tema-style mill.

Biotite and muscovite splits were further ground and the individual micas separated by a variety of techniques, primarily using the Frantz magnetic separator, then reduced to —200 mesh in an agate mortar.

The procedure for Rb-Sr analysis is essentially as described by de Laeter and others (1981). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0·710 2 ± 0·000 1, normalized to a $^{88}Sr/^{86}Sr$ value of 8·375 2.

RESULTS

Measured Rb and Sr values and Rb/Sr ratios, determined by x-ray fluorescence, are listed with mass-spectrometric determinations of $^{87}Sr/^{86}Sr$ in Table 1. We believe the measured values of Rb and Sr are accurate to within ± 7%; however, the measured Rb/Sr ratios may not correspond precisely with ratios which would be derived from the separate Rb and Sr values listed. Errors are reported at the 95% confidence level. The data listed in Table 1 have been regressed using the least-squares programme of McIntyre and others (1966). All dates reported have been calculated using an ^{87}Rb decay constant (λ) of $1{\cdot}42 \times 10^{-11}$ yr^{-1}(Steiger and Jäger, 1977). Dates

TABLE 1. ANALYTICAL DATA FOR BARRENS BEACH AND WEST BEACH

Sample	Rb	Sr	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Barrens Beach:					
$55249B_1$*	207	161	1·29 ± 0·02	3·78 ± 0·04	0·849 37 ± 0·000 30
55249A	143	57	2·51 ± 0·03	7·38 ± 0·07	0·897 00 ± 0·000 23
55249F	171	43	4·0 ± 0·04	11·9 ± 0·01	0·974 91 ± 0·000 41
55249E	198	36	5·50 ± 0·05	16·4 ± 0·02	1·051 19 ± 0·000 33
55249C	228	26·6	8·59 ± 0·08	26·0 ± 0·3	1·192 8 ± 0·000 51
55249D	177	7·9	22·4 ± 0·2	72·1 ± 0·8	1·888 03 ± 0·000 10
55249B	260	8·3	31·4 ± 0·3	105 ± 1·0	2·396 11 ± 0·000 4
$55249B_2$†	395	6·3	62·2 ± 0·6	250 ± 3	4·680 21 ± 0·000 70
West Beach:					
$55250C_1$*	345	170	2·03	5·95 ± 0·06	0·863 89 ± 0·000 5
55250F	187	84	2·23	6·54 ± 0·07	0·866 10 ± 0·000 35
55250A	222	89	2·50	7·35 ± 0·07	0·888 55 ± 0·000 34
55250B	230	91	2·53	7·43 ± 0·07	0·880 93 ± 0·000 32
55250G	187	72	2·60	7·65 ± 0·08	0·907 96 ± 0·000 49
55250C	216	81	2·66	7·82 ± 0·08	0·895 68 ± 0·000 30
$55250E_2$*	283	99	2·86	8·46 ± 0·09	0·962 78 ± 0·000 11
$55250E_1$*	247	84	2·94	8·70 ± 0·09	0·961 59 ± 0·000 30
55250D	180	45	4·04	12·0 ± 0·1	1·018 36 ± 0·000 09
55250H	181	43	4·21	12·5 ± 0·1	1·015 38 ± 0·000 48
55250E	235	46	5·08	15·2 ± 0·1	1·086 37 ± 0·000 46

* Separated muscovite
† Separated biotite

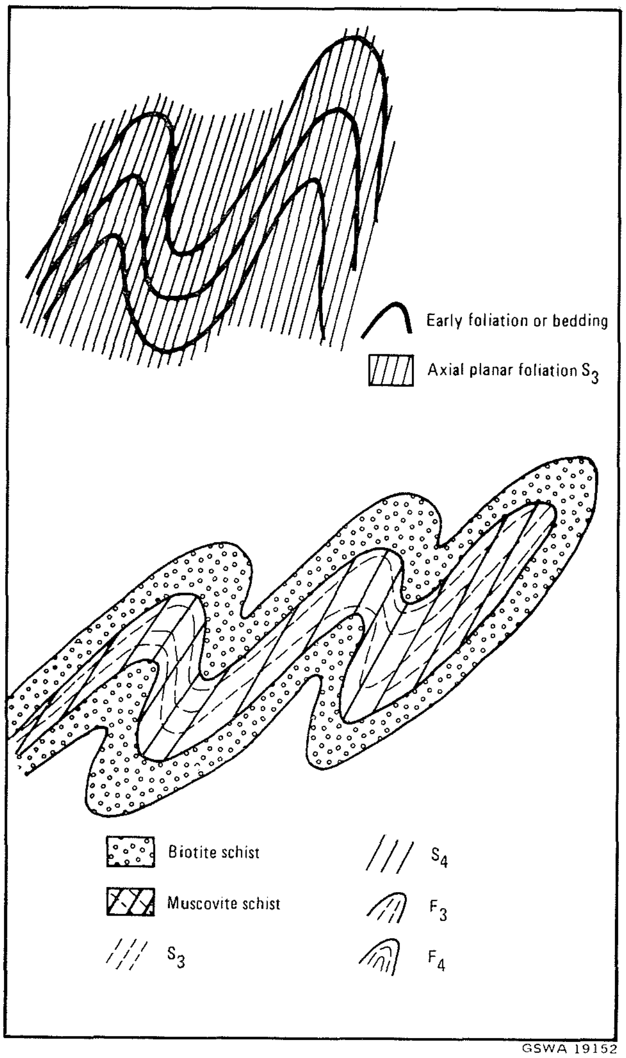

Figure 2 Schematic line drawing of fold types:—
(a) F_3 folds with strongly developed axial-planar foliation, S_3.
(b) F_4 folds in muscovite schist (with strongly developed S_3 and weaker S_4) and coarsely recrystallized biotite schist (no perceptible cleavages).

referred to here, from sources which used a different decay constant, have been recalculated before inclusion in the present work.

The six whole-rock samples plus one sample of separated muscovite and one sample of separated biotite from Barrens Beach provide a good model 4 isochron of 1 077 $\pm$ 22 m.y. with an initial $^{87}Sr/^{86}Sr$ ratio of 0·790 3 and a mean square of weighted deviates (MSWD) of 27·6. The isochron for these samples is plotted on Figure 3. Removing either biotite or both biotite and muscovite from the isochron changes the date slightly, but the deviation is well within the quoted error limits. The single biotite sample, $55249B_2$, provides a slightly older model date of 1 087 m.y., assuming an initial $^{87}Sr/^{86}Sr$ ratio of 0·79.

Samples from West Beach, plotted on Figure 4, failed to generate an intelligible isochron. There is, however, some order in the data which encourages an effort to extract some information.

The scatter of points can be reduced somewhat by deleting data based on separated muscovite (samples $55250C_1$, E_1 and E_2). A least-squares regression line on the remaining points corresponds to a model 4 age of 1 791 $\pm$ 184 m.y. with an initial ratio of 0·699 $\pm$ 0·024. This unrealistically low initial ratio may be attributable to the scatter in the data. A reference isochron drawn from an initial ratio of 0·702 to the mean of $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ values for whole-rock samples from the locality yields an age of 1 767 m.y., probably a better estimate than 1 791 m.y., and still well within the quoted error limits.

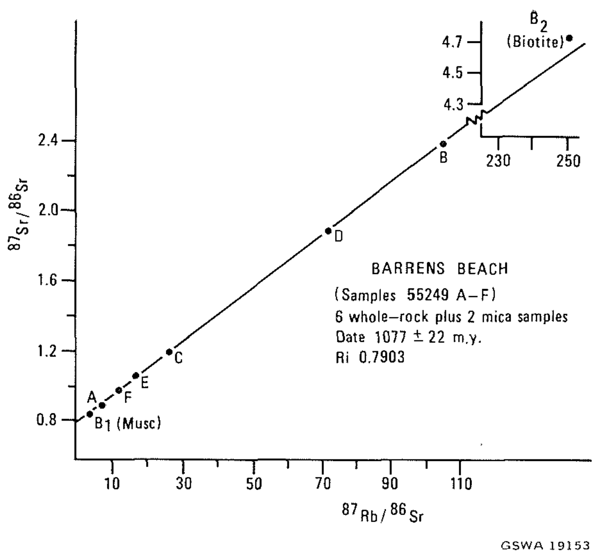

Figure 3 Rubidium-strontium whole-rock and mineral isochron from Barrens Beach.

If the scatter in points is due to partial re-equilibration of isotopes, separated minerals may be expected to be more completely reset than whole-rock samples, which were collected as much as 60 m apart. Two whole-rock samples with associated separated muscovite are available to test this possibility. Samples $55250E_1$ and E_2 are muscovite concentrates separated from whole-rock sample 55250E; sample $55250C_1$ is muscovite separated from 55250C. In both sets of samples the muscovite concentrate has a lower $^{87}Rb/^{86}Sr$ ratio than the whole-rock sample, implying that muscovite has retained or gained more radiogenic Sr than the other minerals in the rock, most notably biotite. Sample 55250E with its separated muscovite suggests an age of 1 307 m.y.; sample 55250C and separated muscovite indicates an age of 1 187 m.y. These dates may record an event at about 1 250 m.y.

DISCUSSION

Field mapping has established that the tectonic history of the area is complex, but has not indicated whether this complexity was concentrated in a single, polyphase orogenic event or was developed by a series of discrete unrelated events spread over substantial geological time. As a result of the tectonic complexity, the geochronological results are also

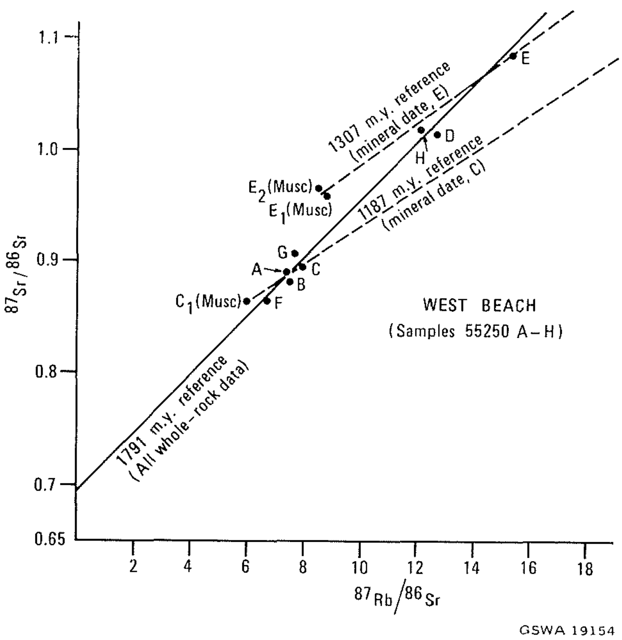

Figure 4 A plot of rubidium-strontium whole-rock and mineral data from West Beach, with reference isochrons.

largely ill defined. However, a single event seems well established at 1 077 m.y. at Barrens Beach, and discrete events extending back for several hundred million years before this date are suggested by the data from West Beach.

The 1 077 m.y. isochron at Barrens Beach probably is associated with the latest deformation (D_4) of the Mount Barren Group, as the substantial development of D_4 deformation is the only recognized geological difference between the rocks at Barrens Beach and at West Beach where no isochron is defined. The 1 077 m.y. date is similar to the metamorphic date of 1 126 $\pm$ 40 m.y. ($\lambda = 1{\cdot}42 \times 10^{-11}yr^{-1}$) obtained from the Stirling Range Formation by Turek and Stephenson (1966).

The less reliable dates of 1 187 and 1 307 m.y. calculated by joining muscovite data to whole-rock data cannot be confidently tied to specific events, but may be associated with the earlier events, F_2 or F_3, for which there is field evidence. The 1 767 m.y. whole-rock date is even more difficult to interpret. Candidates for the event generating this date are: (1) igneous or metamorphic activity in the provenance prior to sedimentation, (2) sedimentation of the unit, and (3) one of the metamorphic-tectonic events subsequent to deposition. Survival of provenance and sedimentary ages through medium-grade metamorphism seems unlikely, hence an early metamorphism of the Mount Barren Group in its present site probably has been dated.

If the low-precision isochron at 1 767 m.y. on whole-rock data from West Beach approximates the date of a real post-depositional event, and if the 1 077 m.y. date from Barrens Beach represents F_4, metamorphic and tectonic activity affecting the Mount Barren Group was spaced over 700 million years, probably as discrete periods of activity within that interval.

The 700 m.y. history of deformation of the Mount Barren Group includes the date of the Woodline Beds, measured by Turek (1966) at 1 586 $\pm$ 100 m.y. ($\lambda = 1{\cdot}42 \times 10^{-11}yr^{-1}$) which was interpreted as the time of deposition.

The dates of the Woodline Beds and the Mount Barren Group should be the same, within the limits of accuracy, if the two units are contemporaneous and both dates are depositional. However, 1 586 m.y. is not within the limits of the 1 791 m.y. date of the Mount Barren Group. Furthermore, a line through the midpoint of the data from the Mount Barren Group at a slope consistent with the date of the Woodline Beds clearly fails to fit the Mount Barren Group data.

These observations suggest either (1) 1 767 m.y. is not an adequate estimate of the age of either deposition or metamorphism within the Mount Barren Group, (2) the Mount Barren Group is older than the dated portion of the Woodline Beds, or (3) the 1 586 m.y. isochron from the Woodline Beds dates a post-depositional period of metamorphism rather than sedimentary deposition.

If the 1 767 m.y. date is accepted as an approximation to the age of a post-depositional event, and the Mount Barren Group correlates stratigraphically with the Stirling Range Formation, deposition of both groups was substantially earlier than the 1 312 m.y. ($\lambda = 1{\cdot}42 \times 10^{-11}yr^{-1}$) minimum depositional age suggested by Turek and Stephenson (1966) for the Stirling Range Formation.

This discussion serves to highlight the fact that at present, very little is known of the depositional age of the Proterozoic rocks that are scattered around the periphery of the Yilgarn Block.

CONCLUSIONS

The Mount Barren Group was substantially and penetratively deformed at about 1 077 m.y. providing a minimum depositional age of 1 077 m.y. Interpretation of imprecise and scattered data from West Beach suggests a tectonic event between 1 700 and 1 800 m.y., and again at about 1 250 m.y. These dates suggest that the Mount Barren Group, deposited 1 800 million years ago, was deformed in several discrete stages spanning several hundred million years.

Further work could explore the relation between the depositional ages of the Stirling Range Formation and Mount Barren Group. The results of the present study suggest that firm dates on the earlier tectonic events affecting these rocks could be obtained by careful selection of sampling localities on the basis of degree of development of each phase of deformation.

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REFERENCES

Blatchford, T., 1919, The country between Hopetoun and the Fitzgerald River: West. Australia Geol. Survey Ann. Progress Rept 1918, p. 11–12.

de Laeter, J. R., Williams, I. R., Rosman, K. J. R., and Libby, W. G., 1981, A definitive 3 350 m.y. age from banded gneiss, Mount Narryer area, Western Gneiss Terrain: West. Australia Geol. Survey Ann. Rept 1980, p. 94–98.

Giddings, J. W., 1976, Precambrian palaeomagnetism in Australia I: Basic dykes and volcanics from the Yilgarn Block: Tectonophysics, v. 30, p. 91–108.

Maitland, A. G., 1901, Phillips River Goldfield: West. Australia Geol. Survey Ann. Progress Rept 1900, p. 9–11.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A. 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research, v. 71, p. 5459–5468.

Roe, J. S., 1852, Report of an expedition to the south-eastward of Perth, Western Australia: Royal Geog. Soc. Jour., v. 22.

Sofoulis, J., 1956, Report on the broad geological structure of the Phillips River Goldfield, W.A.: West. Australia Geol. Survey Ann. Rept 1953, p. 28–32.

Steiger, R. H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in Geo- and Cosmochronology: Earth and Planetary Sci. Letters, v. 36, p. 359–362.

Thom, R., 1977, The evolution of Proterozoic rocks near the Fraser Front at Ravensthorpe, Western Australia: Univ. London Ph.D. thesis (unpublished).

——— 1980, Clastic dykes near the south coast of Western Australia: West. Australia Geol. Survey Ann. Rept 1979, p. 78–81.

Thom, R., and Chin, R. J., in press, Explanatory notes on the Bremer Bay 1:250 000 geological sheet, Western Australia: West. Australia Geol. Survey Record.

Thom, R., Lipple, S. L., and Sanders, C. C., 1977, Ravensthorpe, Western Australia: West. Australia Geol. Survey 1:250 000 Geol. Series explan. notes.

Turek, A., 1966, Rubidium-strontium isotopic studies in the Kalgoorlie-Norseman area, Western Australia: Australian National University Ph.D. thesis (unpublished).

Turek, A., and Stephenson, N. C. N., 1966, the radiometric age of the Albany Granite and the Stirling Range Beds, southwest Australia: Geol. Soc. Australia Jour., v. 13, p. 449–456.

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