GEOLOGICAL SURVEY of WESTERN AUSTRALIA

ANNUAL REPORT 1979

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ANNUAL REPORT

FOR THE YEAR

1979

EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

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

Under Secretary: B. M. Rogers

Director, Geological Survey: J. H. Lord

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1979

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REPORTS

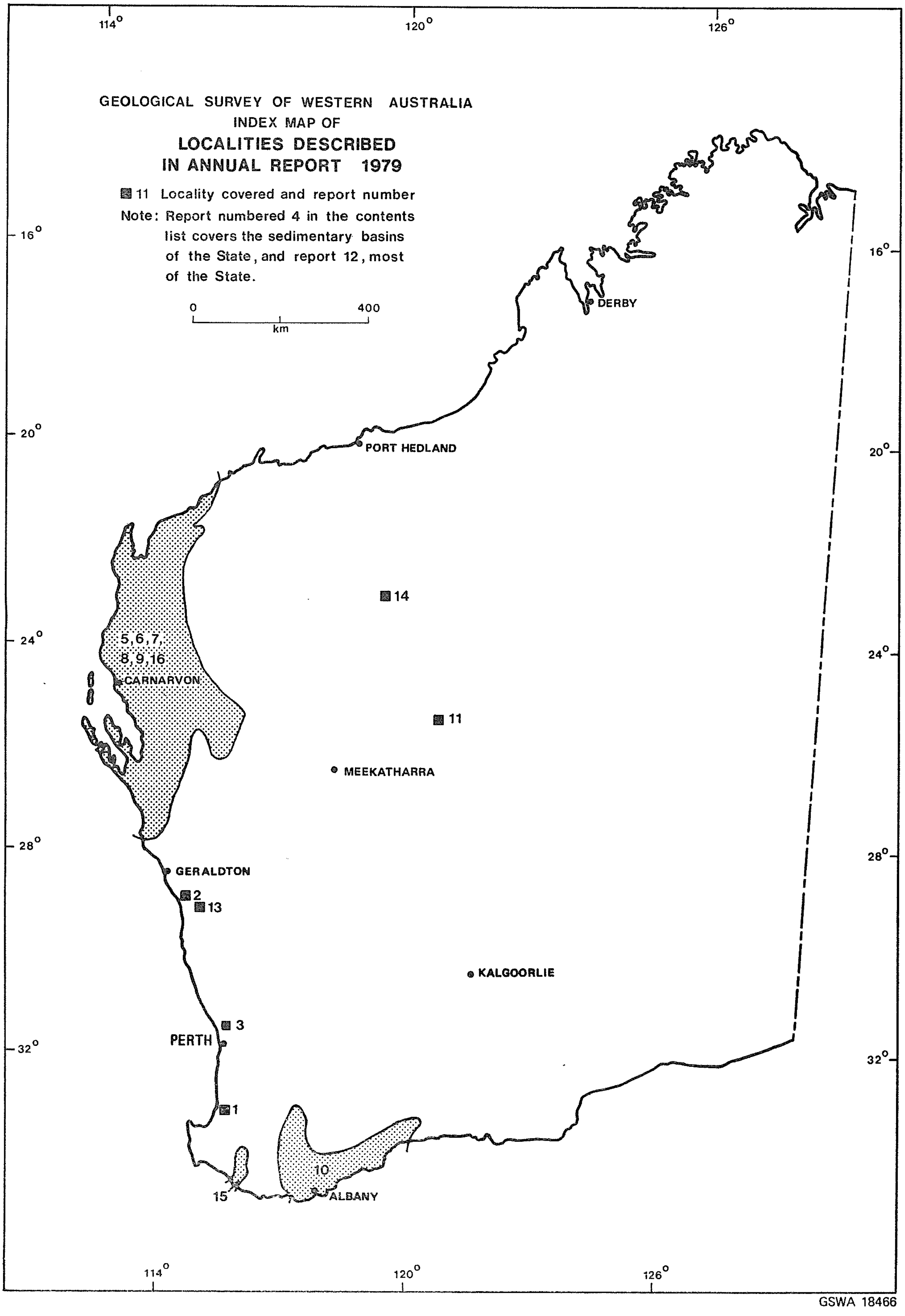

Figure 1 Index map showing areas and localities described in the Annual Report for 1979.

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1979

Under Secretary for Mines:

It is my privilege to present a report on the activities of the Geological Survey of Western Australia during 1979, together with selected reports on investigations and studies made for Departmental purposes, for the information of the Honourable Minister for Mines.

INTRODUCTION

The interest and expansion of exploration activities continued to gain momentum during 1979, and boom conditions were approaching by the end of the year. The increased mineral prices, particularly for energy minerals and gold, were the main stimulus. Also improved metal prices regenerated interest in the search for base metals.

The demand for temporary reserves as prospecting tenements increased as shown in the following statistics:

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

Year	New applications	Renewals	Total
1973	182	....	182
1974	47	28	75
1975	20	18	38
1976	117	11	128
1977	92	37	129
1978	228	33	281
1979	290	112	402

Uranium remains the most sought mineral being included in 233 of the 290 new applications approved, while diamond was included in 170. These new temporary reserves approved cover an area of 47 386 km² with a minimum exploration expenditure commitment of $9·477 million during the first 12 months of tenure.

In addition to the above temporary reserves at the end of 1979, 75 were held for gold, 166 for iron ore and 115 for coal. This is a total of 759 temporary reserves held compared with 463 in 1978, an increase of 64 per cent.

Exploration for uranium continues on both Precambrain areas and in the Phanerozoic basins. While traces of mineralization have been located in several localities none has yet shown sufficient promise to suggest a major deposit. Preparations for the development of the Yeelirrie deposit continues but the development of the Lake Way occurrence near Wiluna has been abandoned.

Diamonds continue to be the glamour mineral sought in many parts of the State. While diamond indicator minerals have been found elsewhere, the Kimberley remains the area of major activities. The Ashton Syndicate, with Conzinc Riotinto of Australia (CRA) as operator, continues to expend millions of dollars on exploration in the Kimberley particularly in the Ellendale area, 120 km east-southeast of Derby where assessment work continues. In the latter part of the year the Syndicate made a very exciting discovery on Smoke Creek which now flows into Lake Argyle near Kununurra—formerly it flowed into the Ord River. Here a kimberlite pipe (AK1) has been discovered on the upper reaches of Smoke Creek covering some 45 ha and preliminary sampling is reported to give 150 carats per 100 tonne, The diamonds shed from this pipe have been located for some 32 km downstream to the edge of Lake Argyle in alluvials ranging from 50 m to some hundreds of metres wide and 1 to 5 m in depth. Preliminary sampling of the alluvial is reported to have produced up to 750 carats per 100 tonne near the pipe decreasing to 60 to 65 carats per 100 tonnes at more than 30 km from the pipe. The largest diamond found to date weighed 7·03 carats. The assessment of quality has not yet been made.

Detailed sampling has continued on the Ellendale pipes, in particular pipe B which has produced 4 706 carats from 34 560 tonnes (13·6 carats per 100 tonnes) and has been tested to a depth of 175 m. Ellendale diamonds as tested are 60 per cent gem quality, 37 per cent, near-gem quality and only 3 per cent industrial quality. The largest stone found is 6·23 carats from pipe D.

The results suggest that a rich diamond mine should be developed at Smoke Creek shortly followed by a mine in the Ellendale area.

Exploration for iron ore, particularly in the Hamersley Basin, continued at a similar level as in 1978. The number of temporary reserves held for iron ore increased from 127 to 166 at the end of the year. With the forecast of an increase in the world demand for iron ore it is hoped that arrangements can be made to develop a new mining complex in the Hamersley shortly

There was considerable interest in the coal potential of the State and many companies and consultants carried out regional assessments. A large number of temporary reserves (115) were taken up for coal particularly in the Fortescue valley, but to date there has been no report of success.

The spectacular increase in the price of gold particularly towards the end of 1979, stimulated even more the interest in gold. The Telfer, Central Norseman and Mount Charlotte mines remain the major producers together with many small operators who kept State Batteries fully occupied. Two other former major mines, North Kalgurli and Kalgoorlie Mining Associates (Golden Mile) have begun rehabilitation of workings in order to re-commence mining operations. It will probably be up to two years before the two operations are onstream

Plans are being implemented to re-open small mines with treatment plants at Mount Ida, Marvel Loch and north of Bullfinch. Numerous other centres are being investigated such as Queen Margaret (Bulong), Mount Sir Samuel, Mount Magnet and Meekatharra.

Due to the lifting of water restrictions in the metropolitan area and probably as a result of advice given in recent years, the number of enquiries for hydrogeological advice dropped from over 4 000 in 1978 to 2 727 in 1979. In addition 107 inspections of properties outside the metropolitan area were made. Further work confirmed the major water resource of very good quality, located in the Quindalup area and eastwards. The resources of the Fortescue-Robe River area were further examined with satisfactory results. The Hydrogeological Division is becoming more and more involved in the study and monitoring of possible pollution of ground water aquifers, e.g. Laporte, Hertha Road, Kwinana red mud ponds, etc.

After many years of regional geological mapping on 1:250 000 scale, the field work required to give a complete coverage of the State was completed this year. It will probably take another 3 or 4 years to compile, to draw and to publish the remaining maps.

Even at this stage many sheets have been remapped where new information and ideas have shown that the original required re-interpretation. There are a number of sheets which require remapping and no doubt there will be many others in the future.

The activity on petroleum exploration continued during 1979 both offshore and onshore. While there was a decrease in seismic activity compared with the previous year, the number of holes drilled and the total depth of holes increased considerably.

Drilling in deep water on the Exmouth Plateau commenced and seven holes were completed with one (Vinck) still drilling at the end of the year. The deepest hole drilled was Jupiter 1 (Phillips) to 4 946 m while the site with the greatest water depth was the hole (Vinck) drilling in 1 383 m.

There was a considerable interest in the offshore Browse Basin and some onshore areas, particularly by the smaller operators.

Two holes Brecknock and Scarborough located gas but both were abandoned because of the locality and depth of water. These gas discoveries may be of interest in the longer term.

Year	Total holes drilled	Total metrage drilled	Seismic (km)	
			Land	Marine
1971	29	70 620	2 744	19 933
1972	29	102 876	3 266	43 218
1973	22	63 612	1 776	14 904
1974	21	48 172	559	11 815
1975	6	17 115	484	2 733
1976	6	22 171	443	2 599
1977	8	35 339	Nil	5 994
1978	15	48 110	1 143	38 996
1979	17	66 428	909	26 312

Public lectures: Three half days of public lectures were presented on 19 and 20 April. Attendance varied greatly according to the topics, the maximum present being 75. The main public interest is obviously associated with Precambrian geology geochronology and exploration potential.

Field excursions: An excursion to the Nabberu Basin was organized. On the evening of 23 April lectures on the basin were presented in Meekatharra. This was followed by a 4-day field trip observing the general geology and type sections and localities of the basin. Despite the remoteness of the area concerned some 70 geologists and prospectors attended.

On 26 November lectures were presented at the departmental theatrette on the geology of the Collie and Pemberton 1:250 000 sheets. This was followed by a 4-day field excursion. While over 70 attended the lecture only 44 could be accommodated on the tourist bus used for transport.

These excursions continue to be well-patronized and it is proposed to continue to organize one or two each year.

Microfilm library: For the second year this has been a very popular and well-used public facility. The demand for open-file material grows as the exploration boom develops. At the end of 1979 there were 118 rolls (35 mm 500 frame per roll) of company reports on mineral exploration and 95 rolls on oil and gas exploration available in the library.

A printer-reader has been installed in the Kalgoorlie office together with a set of film on mineral exploration.

All Records produced are being made available on microfiche form as are some of the frequently asked for out-of-print bulletins.

STAFF

The stability of geological staff experienced in recent years came to an end in 1979 with the development of the exploration boom. There were seven resignations and more are expected early in the new year. As well as the booms creating a shortage of geologists in this State, a number of our geologists have been dedicated regional Precambrian geological mappers for 5 to 7 years, so it is appropriate time at the end of the first edition of mapping to broaden their experience, as they cannot all be promoted within the Survey.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Smith, R. A., B.Sc. (Hons)	Geologist L1	11/1/79
Hall, J. W., B.Sc. (Hons)	Geologist L1	28/5/79
Moore, P. S., B.Sc. (Hons)	Geologist L1	21/6/79
Tuckson, M., B.Sc. (Hons), M.A. (Hons), Ph.D.	Geologist L1	4/7/79
Martin, M. W., B.Sc. (Hons)	Geologist L1	17/12/79

Promotions

Hocking, R. M.	Geologist L2	26/1/79

Resignations

Green, K. H.	Geologist L1	23/2/79
Leech, R. E. J.	Geologist L2	16/3/79
Briese, E. H.	Geologist L1	6/4/79
Elias, M.	Geologist L1	21/9/79
Bunting, J. A.	Geologist L2	28/9/79
Lavaring, I. H.	Geologist L1	30/11/79
Moore, P. S.	Geologist L1	18/12/79

CLERICAL AND GENERAL

Appointments

McKenzie, J.	Clerk	3/1/79
Bryce, A.	Laboratory Assistant	5/2/79
Brzusek, M.	Laboratory Assistant	19/3/79
Hazel, T.	Typist	19/3/79
Munz, R.	Technical Assistant	2/4/79
Toohey, J.	Technical Assistant	2/4/79
Mountier, A.	Typist	8/6/79
Watt, M. S.	Geological Assistant	3/9/79
Wilson, C.	Laboratory Asssitant	25/10/79
Wall, H.	Technical Assistant	10/12/79

Transfer In

Healy, J.	Clerical Assistant	10/8/79

Transfer Out

Stevens, M.	Laboratory Assistant	6/7/79
Cusan, M.	Clerical Assistant	15/8/79
Monaghan, R.	Technical Assistant	19/10/79

Resignations

Pritchard, D.	Technical Assistant	2/2/79
McDonald-Goodall, A.	Technical Assistant	23/2/79
Graham-Sutton, P.	Geological Assistant	20/4/79
Hammill, N.	Technical Assistant	26/4/79
Brown, T.	Geological Assistant	4/5/79
Hazel, T.	Typist	24/5/79
Kerr R.	Laboratory Assistant	23/11/79
Willis, B.	Technical Officer	27/12/79

ACCOMMODATION

During the year the required extensions to the store at Russell Street, Morely were commenced and completed to provide additional space, particularly for storage of publications and company reports.

Additions to the Dianella core library will be required within the next 1 or 2 years.

The proposed extension to Mineral House would be a welcome addition, allowing the Hydrogeology and Engineering Geology Divisions to return to the main office and to expand our library facilities.

OPERATIONS

HYDROGEOLOGY DIVISION

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.

Drilling for water resources investigations has been maintained at about the same level as last year. Three deep bores that have been drilled in, and east of, Busselton, together with five shallow bores, complete the programme of exploration on the Quindalup line of bores across the southern part of the Perth Sedimentary Basin. One of these bores (No. 9A), located 8 km south of Donnybrook, was completed to a depth of 1 469 m, a record depth for a water bore in the Perth Basin. This important line of bores has proved very large storages of fresh groundwater between Busselton and Donnybrook.

In the metropolitan area a further eight bores have been drilled to between 421 and 908 m to aid exploration of the deeper aquifers and provide information on the geological structure and recharge relations. Three shallow drilling projects have also been undertaken in the Perth Basin: the Bunbury shallow aquifer investigation has been completed with the construction of a further eight bores and an extensive programme of test pumping, 51 bores have been drilled in the Southwest coastal groundwater area to complete the first phase of that project and north of Perth the Metropolitan Water Board has drilled 11 bores at Lake Mariginiup to aid a water balance study.

The effects of bauxite mining and of the woodchip industry on groundwater and stream salinities continue to be studied on an inter-departmental basis. Other salinity studies include the interpretation of groundwater monitoring in the Harvey-Waroona irrigation schemes, Lake Toolibin, and close to Lake Muir.

In the west Pilbara, seven new bores have been drilled and an extensive programme of test pumping has been carried out. This completes work in the upper part of the Robe catchment.

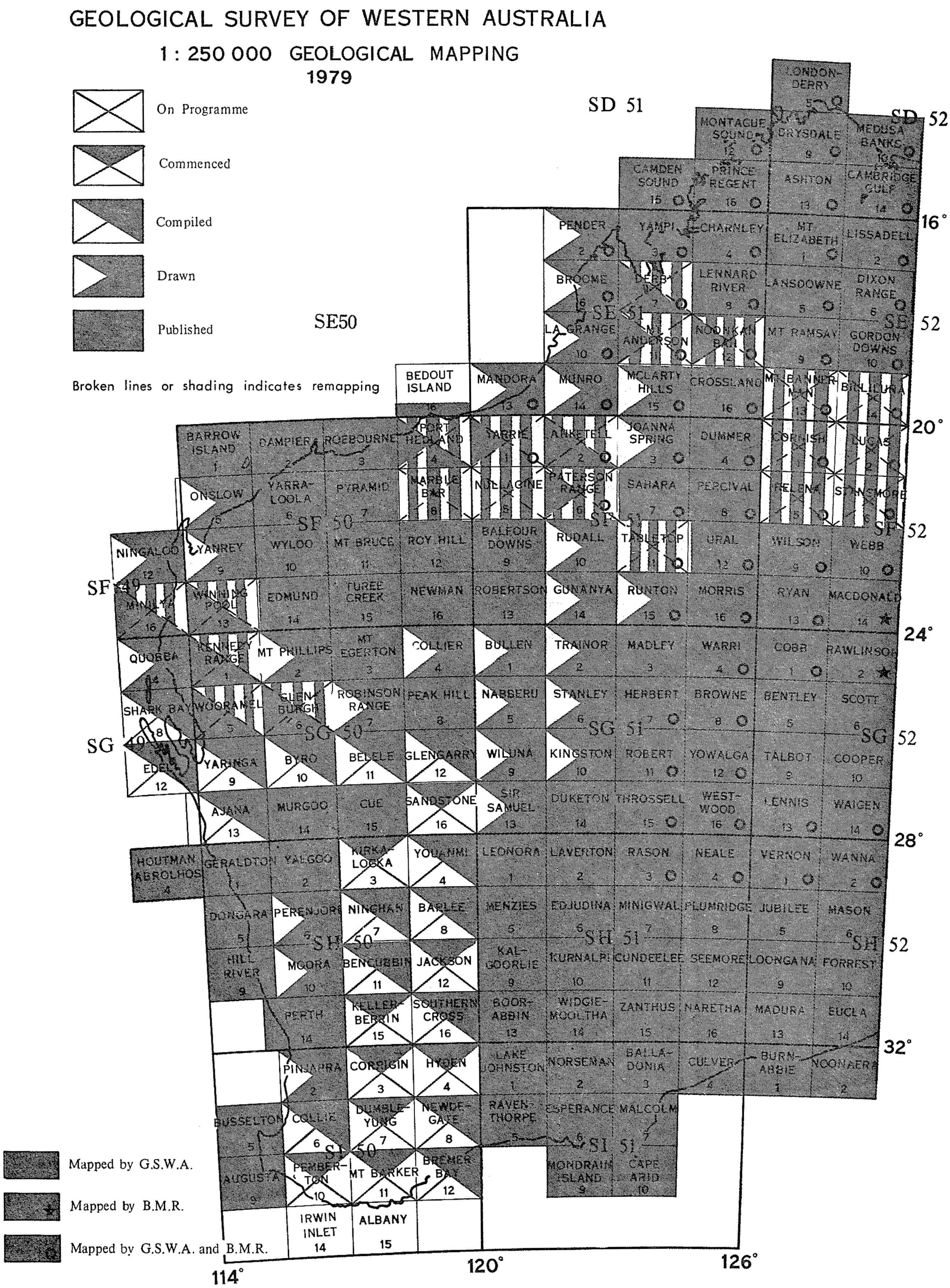

Figure 2 Progress of 1:250 000 and 4 mile geological mapping to the end of 1979.

GSWA 18467

The lifting of water restrictions in the metropolitan area and the consequent reduction in demand for private bores, resulted in a marked fall in the number of enquiries to 2 727 for advice on prospective drilling depth and other details. A similar fall to 107 was experienced in the demand for bore site selection by farmers.

Groundwater pollution surveys have been undertaken in several areas at the request of the Public Works Department, and hydrogeological studies of acid effluent disposal at Australind continue. Advice has been provided to the Main Roads Department regarding sources of compaction water for three road-improvement schemes and 23 reports have been written in response to requests for investigations or advice by other Government departments. The compilation of bore records throughout the State continues.

ENGINEERING GEOLOGY DIVISION

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

Activities were confined to investigations for other Government Departments and instrumentalities including.

Department of Public Works:

(a) Further investigations made at Harding River dam site in the Pilbara, at two dam sites near Manjimup, and at two damsites on Marrinup Brook.

(b) Geological reconnaissance made of dam sites on the Tone and Kent Rivers.

(c) Foundation studies for several tank sites between Millstream and Karratha and a study of the foundations of the Kokardine tank, damaged by the Cadoux earthquake.

(d) Minor investigations carried out including a rock quarry site for the proposed breakwater at Rocky Point near Dunsborough.

Metropolitan Water Board:

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

(b) Continued studies on South Canning, New Victoria and Bickley dam sites.

(c) Reports completed on Wungong and Bibra tunnels.

(d) Studies commenced on Little Dandalup dam site.

Westrail:

(a) Geological advice given on the selection of quarry sites and rail routes.

Miscellaneous:

(a) Geological mapping of surface features associated with the Cadoux earthquake.

REGIONAL GEOLOGY DIVISION

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

Regional mapping, at 1:250 000 scale, saw the completion of field work for the Precambrian portion of the State. Field work was completed on Barlee, Jackson, Bencubbin, Kellerberrin, Corrigin and Dumbleyung. Field mapping on Sandstone and Youanmi was completed with the assistance of three geologists from the Bureau of Mineral Resources, Canberra.

One regional mapping officer has been positioned in the regional office at Kalgoorlie to re-map the Widgiemooltha sheet.

Work on the Bangemall Basin and Nabberu Basin Bulletins is almost complete. Preliminary work has begun on a Gascoyne Province Bulletin.

SEDIMENTARY DIVISION

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

The processing of data submitted by petroleum companies continued. In 1979, wells located by the extensive seismic surveys of 1978 were drilled but none produced hydrocarbons in economic quantities. Seismic surveys continued offshore (but at a lower rate than in 1978) and onshore, mainly to detail structures for drilling. An extensive seismic survey was completed in deep water off the southern Eucla Basin, but most seismic and drilling activity continued to be on the Northwest Shelf and the Exmouth Plateau.

Field work in the Carnarvon Basin was completed in 1979 with the mapping of the Kennedy Range 1:250 000 Sheet and the northeastern corner of the Wooramel Sheet. Preparation of a bulletin covering both the onshore and the economically important offshore portions of the basin commenced. Preparation of the explanatory notes for the remaining Winning Pool, Kennedy Range, and Wooramel map sheets proceeded.

MINERAL RESOURCES DIVISION

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

Compilation of the Collie and Kirkalocka Sheets were completed and draft Explanatory Notes prepared. Compilation of Pemberton is continuing.

Mapping of the Warriedar fold belt at a semi-regional scale began and, together with associated specialist studies, will continue into 1980. Preliminary work on a detailed study of the Mount Monger area has started.

A bulletin on the State's nickel deposits is near completion. A first report on Ministerial Iron Ore TRs was written and a second is in preparation. An inspection of Jennings Mining Ltd's operation at Eneabba was made before the mine closed.

An assessment of the State's reserves and resources of nickel, bauxite and mineral sands was completed while work continues on a compilation of gold resources.

During 1979, 27 rolls of microfilm were produced for the open-file library.

COMMON SERVICES DIVISION

Petrology

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

Demand for petrographic services remained at the same high level of the past two years; 85 petrological reports were completed, on a total of 1 860 rock samples. Further thin sections were studied for incorporation into the computer based petrological data system.

The co-operative geochronology programme with WAIT continued, with one paper published and four others prepared for publication. Fifteen projects are in various stages of completion and have been carried over the 1980 programme.

The laboratory prepared 2 400 thin sections, 292 polished thin sections, and 223 rocks were cut and faced for further examination. In addition 372 samples were crushed for geochronology and chemical analysis, 350 specimens were stained for carbonate and potash feldspar identification and a number of specimens were subject to grain size analysis, and heavy mineral separation.

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

Palaeontology

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

Thirty-four reports were written during the year and 820 samples were added to the Survey fossil collection. In addition 16 000 palaeontological samples from relinquished petroleum tenements were catalogued. As in previous years most of the reports covered three main fields (a) Perth Basin palynology (for the Hydrogeology Division), (b) Precambrian palaeontology (for the Regional Geology Division) and (c) Carnarvon Basin invertebrate fossils (for the Sedimentary Division).

A long-term study of the stromatoporoids from the Devonian reef complexes of the Canning Basin was completed and a report prepared. A record summarizing the stratigraphical distribution of Proterozoic stromatolites was published during the year.

Geophysics

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

The decline in exploratory drilling by the Metropolitan Water Board was reflected by lower well-logging activity in 1979 when only 77 logging operations were carried out by comparison with 144 in 1978. Aggregate total depths were 28 396 m and 25 720 m respectively indicating a trend towards exploitation of deeper aquifers. The deepest water bore yet logged by the Section, Quindalup 9A to 1 469 m, encountered potable formation water over an interval in excess of 1 100 m.

Seismic refraction surveys were undertaken at two prospective dam sites at Manjimup, and at Victoria and Wungong dams. Seismic sections were also obtained across four forestry coupes at Manjimup to augment groundwater salinity projects and on the coastal plain environs of the Robe and Fortescue Rivers in the Pilbara to aid selection of exploratory waterbore sites. Experimental seismic work to delineate the "channel sand" aquifer in the Mirrabooka area was unsuccessful, apparently because of inadequate velocity contrasts with the Osborne and superficial formations.

In conjunction with MRD the search for unexploded artillery shells at Warnbro was resumed and a proposed roadway area amounting to 14 ha was investigated. The proton magnetometer was discarded in favour of equally sensitive but more manoeuvrable commercial metal detectors.

The high demand for field salinity determinations continued; salinity monitoring projects involved 510 measurements and the public submitted about 320 water samples, mainly from metropolitan bores, for testing. Normal laboratory and electronic servicing facilities were maintained and some 70 public enquiries on geophysical matters answered.

Environmental Geology

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

A study of Perth's sand resources, supply and demand was completed and the results published as a Survey Record. The examination of Perth's aggregate requirements was completed and a map and report supplied to the Darling Escarpment Aggregate Resources Committee. Maps have been drawn showing the areal extent of basic raw materials for the construction industry in Perth.

Geological information has been supplied for nine Town or Shire planning schemes and for several other projects including development at Joondalup and Herdsman Lakes. Appraisal of environmental review and management programme reports continues an important part of the section's activities, as do committees and liaison meetings.

Geochemistry

R. Davy.

Reconnaissance exploration of the Saddleback greenstone belt, and a literature survey on the possible use of geochemistry for prospecting for chromite have been completed.

Work has continued, in co-operation with the Petrology Section, on the study of the granitoids of the Mount Edgar and Corunna Downs batholiths.

Liaison has been maintained with the Government Chemical Laboratories.

Technical Information

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

During the year the Survey undertook, for the first time, the publication of the 1:250 000 geological series with explanatory notes which have previously been published by the Bureau of Mineral Resources. Of the 6 sheets with explanatory notes sent to press, 5 have been published and sell for $5.00 each. Eleven sheets with explanatory notes were published by the BMR who are finalizing their publishing commitment.

This year the annual report, one mineral resources bulletin, two reports and one Urban Geology map were published. One bulletin was sent to press and two bulletins were already in press. Five explanatory notes were edited and proof read. Nine records were published and also issued on microfilm. Two information pamphlets were revised and one is in progress.

Requisitions raised on the Surveys and Mapping Branch for drafting, photography and copying totalled 1 306.

Rising gold prices and the success of prospecting with metal detectors have led to an influx of gold prospecting enquiries from the general public. The section answered 1 653 requests for information including rock identifications 308 of which entailed detailed research; and 4 511 members of the public visited the library for research purposes. Book loans to the staff totalled 7 782, and loans to and from other libraries 601.

The open file system for the "M" series reports continued to expand, 1 011 public users and 122 staff visited the microfilm library.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

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

(i) three geologists joined our geologists on the mapping of the Sandstone and Youanmi sheet.

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

PROGRAMME FOR 1980

HYDROGEOLOGY DIVISION

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling on the Boyanup line, completion of report on the Quindalup line and planning of the Harvey and Gillingarra lines.
2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) Completion of work in the Millstream-Weelumarra area and continuation of work on the Robe and Fortescue flood plains.
   (b) Re-assessment of the groundwater resources along Gascoyne and Arrowsmith Rivers, on Rottnest Island, Eneabba, Pinjarra, Dawesville, and the Swan Valley.
   (c) Continuation of the investigation of the water resources of the Collie Basin.
3. Town water supply investigations and/or drilling for the following: Salvado, Busselton, Lake Clifton, Port Gregory, New Norcia, Bunbury.
4. Hydrogeological investigations for the Metropolitan Water Supply Board:
   (a) Deep drilling for artesian monitoring scheme.
   (b) Shallow drilling at Mirrabooka and East Mirrabooka.
   (c) Continuation of pollution studies at Gnangara and Kwinana.
   (d) Continuing study of water balance in coastal lakes.
5. Interdepartmental studies concerning groundwater salinity problems in the Darling Range bauxite and woodchip areas.
6. Continuation of bore census of selected areas, salinity and pollution studies and supervision of consultant's work.
7. A preliminary study of the occurrence and the feasibility of using any moderate to high temperature water which may occur in the Perth Basin, for energy purposes.
8. Miscellaneous investigations and inspections as required by Government departments and the public.

ENGINEERING GEOLOGY

1. South-West Division dam sites investigations: Wungong (completion report), South Canning, North Dandalup, Little Dandalup, Dirk Brook, Manjimup, Brockman River and on the Tone, Frankland, Kent and Denmark Rivers.
2. North West dam site and pipeline investigations: Harding River.
3. Geological studies and advice during construction of the Wungong and Bibra Lake tunnels.
4. Geological advice to Westrail on quarry sites and railway construction.
5. Geological advice on miscellaneous problems for Public Works and other Government departments and authorities.

SEDIMENTARY GEOLOGY

1. Maintain an active interest in the progress and assessment of exploration and potential for fossil fuels in Western Australia including the checking and assessing of all company reports on exploration.
2. Continuation of the study of the surface and sub-surface geology and geophysics of the Carnarvon Basin.
3. Preparation and commencement of the mapping and study of the Bonaparte Gulf Basin.
4. Continuation of the compilation of a bulletin on stratigraphic studies of Devonian reef complexes in the Canning Basin.
5. Minor geological investigations as required.

REGIONAL GEOLOGY DIVISION

1. Completion of compilation and explanatory notes for the remaining 1:250 000 first edition geological maps of Western Australia. All field work having been completed.
2. Geological synthesis of the Gascoyne Province.
3. Commence re-mapping of Balfour Downs, Wyloo and eastern portion of Cue 1:250 000 sheets.
4. Detailed mapping of the Fraser Front in the Ravensthorpe and Bremer Bay area.
5. Completion of the re-mapping of Peak Hill 1:250 000 sheet.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral potential and resources in Western Australia.
2. Completion of mapping and study of the Warriedar fold belt.
3. Commence bulletin on the geology and bauxite occurences of the Darling Range area.
4. Completion of assessment of iron ore on Ministerial Reserves.
5. Prepare a mineral deposit map of Western Australia.

6. Prepare geological map of the southwest mineral sands area.
7. Review of the Mortimer Hills uranium prospect.
8. Miscellaneous investigations as required.

COMMON SERVICES DIVISION

Petrology

1. Carry out petrological investigations as required by other Divisions.
2. The following topics to be investigated:
   (a) Alkaline granitoids of the Eastern Goldfields.
   (b) Rb:Sr geochemistry in and about the Black Range dolerite.
   (c) Proterozoic effects on the petrology of the Archaean rocks in the southwestern corner of Western Australia.
   (d) Petrology of the kimberlites and related rocks of the Kimberley division.
   (e) Petrology of the Corunna Downs and Mount Edgar batholiths.
3. Miscellaneous minor petrological studies.

Palaeontology

1. Carry out palaeontological investigations as required by other Divisions.
2. Completion of the study of Precambrian stromatolites and micro-fossils.
3. Continuing palynological study of the Early Cretaceous of the Perth Basin.
4. Biostratigraphy and systematics of the Devonian radiolarians from the Canning Basin.
5. A study of the Gneudna stromatoporoids (Carnarvon Basin).

Geophysics

1. Well-logging on groundwater drilling projects as required.
2. Seismic surveys for numerous potential dam sites in South-West and for railway construction purposes.
3. Gravity survey to define the Southern Cross-Bullfinch greenstone belt.
4. Gravity and magnetic surveys of
   (a) Warriedar fold belt
   (b) Mount Monger area
   (c) Fossil drainages.
5. Miscellaneous geophysical investigations as required.

Geochemistry

1. Continuation of the study of the Corunna Downs and Mount Edgar batholiths.
2. Completion of the study on:
   (a) Mount McRae Shales
   (b) Mercury in sulphides
   (c) Yarrie ironstones.
3. Commence geochemical studies on:
   (a) Warriedar fold belt
   (b) Mount Monger area
   (c) Kimberlites.

Environmental Geology

1. Continue the compilation of urban geology maps for the Roebourne, Port Hedland and Bunbury areas.
2. Assessment of environmental reports as required.
3. Studies of the basic raw material resources of the metropolitan area.
4. Examination of miscellaneous environmental geological problems as required

Regional Offices

Kalgoorlie

1. Re-mapping of the Widgiemooltha 1:250 000 sheet.
2. Detailed mapping and mineral study of the Mount Monger area.
3. Study of the Phanerozoic sediments and fossil drainages of the Kalgoorlie-Norseman area.

Karratha (It is hoped to establish this office in the latter part of 1980)

1. Re-mapping Wyloo 1:250 000 sheet.
2. Detailed study of the mineralized parts of the Wyloo sheet.
3. Hydrogeological studies for the Pilbara region.

PUBLICATIONS

Issued during 1979

Annual Report 1978.

Mineral Resources Bulletin 11: Molybdenum, tungsten, vanadium and chromium in Western Australia.

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

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

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

Geological map of Marble Bar 1:250 000 sheet (SF/50-8 International Grid) with explanatory notes.

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

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

Geological map of Mount Egerton 1:250 000 sheet (SG/50-3 International Grid) with explanatory notes.

Geological map of Nullagine 1:250 000 sheet (SF 51-5 International Grid) with explanatory notes.

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

Geological map of Perth 1:250 000 sheet (SH/50-14 International Grid) with explanatory notes.

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

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

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

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

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

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

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

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

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

Urban geological maps 1:50 000: Pinjarra, Baynton, Karratha, Nickol Bay-Legendre, Point Samson-Delambre Island.

(Available in microfiche form)

Record 1979/1 Wells drilled for petroleum exploration in Western Australia to the end of 1978, by K. A. Crank.

Record 1979/2 Preliminary results for biostratigraphic studies of Proterozoic stromatolites in Western Australia, by Kathleen Gray.

Record 1979/3 Explanatory notes on the Glengarry 1:250 000 geological sheet, Western Australia, by M. Elias, J. A. Bunting, and P. H. Wharton.

Record 1979/4 Prospecting for chromite, by R. Davy.

Record 1979/5 Explanatory notes on the Southern Cross 1:250 000 geological sheet, Western Australia, by R. D. Gee.

Record 1979/6 Sand in the Perth metropolitan area, by E. R. Biggs.

Record 1979/7 Explanatory notes on the Ajana 1:250 000 geological sheet, Western Australia, by R. M. Hocking, W. J. E. van de Graaff, J. G. Blockley, and B. P. Butcher (in prep.).

Record 1979/8 Geochemical exploration Saddleback Greenstone Belt, by R. Davy.

Record 1979/9 Geology and groundwater resources of the south-western Canning Basin, Western Australia, by R. E. J. Leech.

Record 1979/10 A geophysical study of the south-central Carnarvon Basin, by M. N. Megallaa (in prep.).

Record 1979/11 Explanatory notes on the Collie 1:250 000 geological sheet, Western Australia, by S. A. Wilde and I. W. Walker (in prep.).

Record 1979/12 The geology and hyrdogeology of the Moora Borehole Line and adjacent area, Perth Basin, by E. H. Briese (in prep.).

Record 1979/13 A reassessment of the effects of bauxite mining on groundwater hydrology at Del Park, by E. H. Briese.

In Press

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.

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 Yanrey-Ningaloo 1:250 000 sheet (SF/50-9, SF/49-12 International Grid) with explanatory notes.

Urban Geological maps 1:50 000: Baynton, Karratha, Nickol Bay-Legendre, Point Samson-Delambre Island, Dampier, Roebourne.

Mineral Resources of Western Australia.

In preparation

Bulletin 127: Geology of the Pilbara Block and its environs.

Bulletins: The geology of the Bangemall Basin; The geology of the Earaheedy Group, Nabberu Basin.

Mineral Resources Bulletin: Nickel.

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Gee, R. D., 1979, Structure and tectonic style of the Western Australian Shield: Tectonophysics v. 58, p. 327–369.

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J. H. LORD,
Director.

21st January, 1980.

THE GEOLOGICAL SURVEY OF WESTERN AUSTRALIA OVER TWO DECADES 1960-1979

by J. H. Lord

INTRODUCTION

Every continuing activity or organization should be reviewed from time to time to ensure that it is developing along the desired lines, and that its achievements are in keeping with its objectives. It is appropriate that on entering the eighties one should review the past two decades of development and achievements of the Geological Survey of Western Australia. Why these two decades? This has been the period required to redevelop the Survey and to achieve most of the objectives formulated when a major expansion of the Survey was planned in 1960.

In late 1959 and early 1960 the Government was interested in the development of mineral resources other than gold, which was then declining rapidly in production. The Minister for Mines, the Hon. A. F. (now Sir Arthur) Griffith, M.L.C., and the Under Secretary for Mines, the late A. H. Telfer, investigated ways and means of expanding and developing the Survey. This included an inspection of other State Surveys, in particular South Australia, which was reputed to be one of the best in Australia at that time.

As a result, a new position, Deputy Government Geologist, was created and was advertised throughout Australia, with the proviso that the successful applicant should succeed the then Government Geologist, H. A. Ellis, who was due for retirement in mid-1961. The main purpose of this early appointment was for the appointee to plan the redevelopment of the Survey into a much larger organization. I was appointed to this position on 12 December 1960. During 1961 the Government approved a proposal to divide the Survey into divisions and to increase the professional staff establishment from 13 to 29.

DEVELOPMENT

The proposed five divisions were: Hydrology and Engineering, Mineral Resources, Regional Geology (for Precambrian mapping), Sedimentary (Oil), and Common Services. The Common Services Division was divided into petrology, palaeontology, geophysics, technical information, and clerical sections.

This basic structure has survived until now, except for some expansion. The Hydrology and Engineering Division has been divided into separate Hydrogeology and Engineering Geology Divisions, and the Common Services Division has had additional sections added, namely the geochemistry, environmental geology, laboratory and geological service sections.

STAFF

During the decade of the 1960s the professional staff increased from 29 in the initial reorganized structure to 51. During the 1970s the staff establishment increased further to 63.

The non-professional staff grew from 4 in 1960 to 36 in 1979 (Fig. 1).

In the early part of the expansion there were insufficient geologists available in Australia, and many were recruited from overseas, particularly from the United Kingdom. A very good group of geologists was assembled which developed considerable expertise; then came the mineral boom of 1968–72. This caused many staff to resign, mostly for more lucrative positions in industry. As a result the Survey had to recruit and train new staff, and it was 1973 before it was stabilized again.

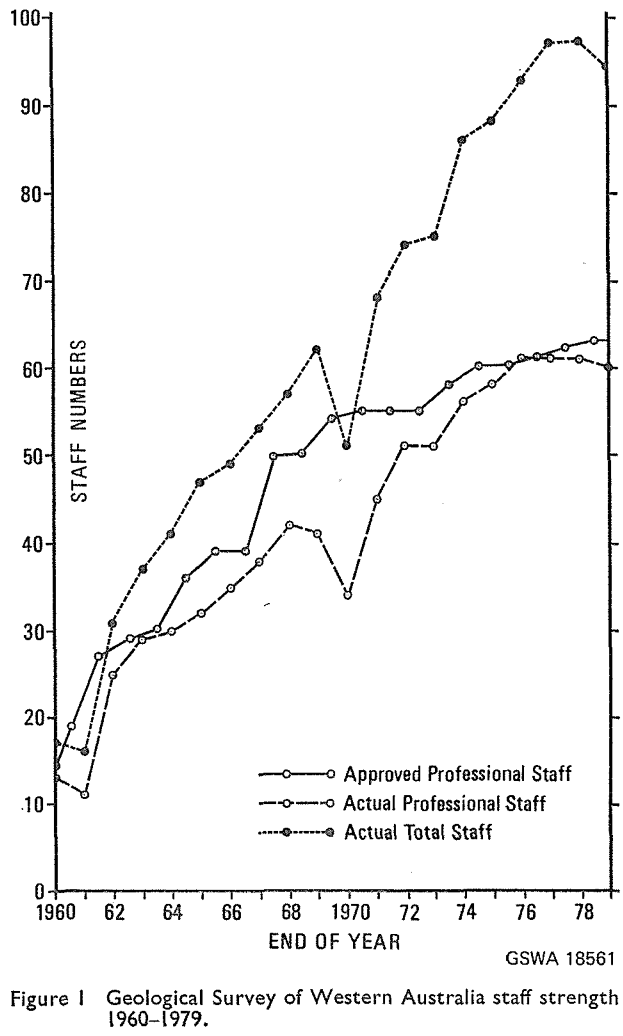


Figure 1 Geological Survey of Western Australia staff strength 1960–1979.

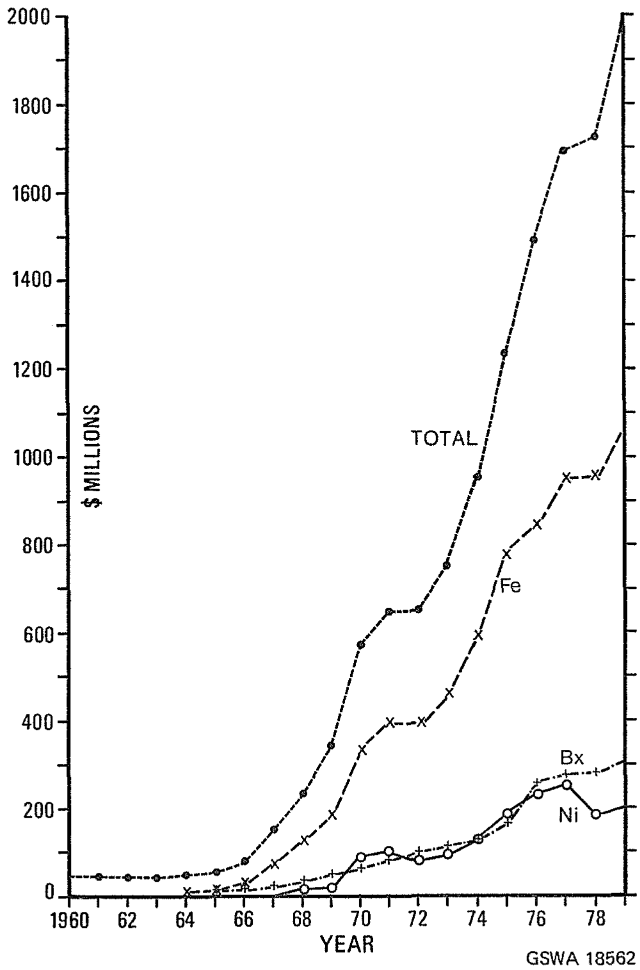


Figure 2 Value of total mineral production, also iron (Fe), bauxite (Bx), and nickel (Ni) over the period 1960–1979.

From 1973 to 1979 there was little movement of staff, but in 1979, with exploration beginning to boom and young staff of several years' experience being in demand, the movement of staff out of the Survey recommenced. This is to be expected, because geology is a profession which requires broad experience in different styles and places of work. Similarly it is believed that recruitment from different universities and countries is advantageous to a geological survey and prevents the possibility of local inbreeding of ideas and methods. During the two decades some 86 geologists have left the Survey, but the vast majority have contributed to the knowledge of the geology of this State and we have benefited from their time with the Survey.

One of the policies instilled into the staff has been that of service to industry. It is believed that for active exploration and prospecting to be attracted to Western Australia the Survey has to play its part by providing the basic geological data on which exploration is based, and by giving willing and courteous service and encouragement to industry. It is believed that this policy has materially assisted in the remarkable growth of the State's mineral industry, from a total production value of $44 million in 1960 to over $2 000 million in 1979 (Fig. 2).

ACCOMMODATION

Initially the Survey suffered badly from inadequate accommodation, situated in a depressed part of the city. By 1970 six different buildings were occupied as offices and laboratories, including a converted church and lodging house, and the upper floor of a warehouse.

In 1970, with the building of Mineral House, the Survey came together for the first time for many years, and also for the first time with the rest of the Department of Mines. This building provided ideal modern accommodation until 1977 when, due to the growth of the Department, it was necessary to move the Hydrogeology and Engineering Geology Divisions to another office block.

In 1960 the only storage available was a small shed at the rear of the Western Australian Museum. A small core library was built in late-1961 at Dianella and an adjacent shed was used for equipment and vehicle storage. The core library has since been extended twice. In 1969 it was necessary to move the equipment and vehicles to a larger new store built at Morley which houses geological equipment, publications, and a geophysical workshop and includes an adequate vehicle park.

ACHIEVEMENTS

In a number of fields of geology, the Survey can claim achievements over the past two decades. The critic may ask, "what mine did they find?". The answer in this case is "none", simply because it is not the task of the Survey to find mines. It has been Government policy during this period for the Survey to assist prospecting and exploration. This includes the provision of geological advice, basic maps, and services to encourage the search for new deposits, and at the same time to advise Government on development. This policy is based on the principle that the people should not have their taxes used for the very high-risk activity of exploration for mines.

The items described below are some in which it is considered the Survey's work and enterprise have assisted in the development of this State over the past two decades.

HYDROGEOLOGY

One of the first items to receive attention during the 1961 reorganization was hydrogeology. This was essential for Western Australia, the driest State within the driest continent. Rotary-drilling methods and electric-well-logging-processes were established by the Survey for water exploration, and in 1963 it was fortunate in attracting Mr E. P. O'Driscoll, one of Australia's leading hydrogeologists, to take charge of the Survey's Hydrogeology Division.

This Division was recognized by the Metropolitan Water Board and the Department of Public Works as their official source of geological advice and services in respect of groundwater exploration.

In 1962 the Survey, on its own initiative, drilled near Lake Gnangara, and this led eventually to the identification of the Gnangara Mound of groundwater, which now provides large supplies for Perth. Later the Jandakot Mound was located and developed. Groundwater from both deep and shallow aquifers now can supply at least 40% of the requirements of the Metropolitan area. This has been of immense value during the current four-year drought period.

All the coastal towns of the Pilbara area are drawing their supplies from sources of groundwater discovered and delineated by the Survey. Further potential supplies have been located along the Robe and Fortescue Rivers and in the West Canning Basin, and are available for future development in the Pilbara.

In the Perth Basin supplies have been proven at Allanooka (for Geraldton), Arrowsmith River (for Morawa), Agaton, Eneabba, Gingin and in the Bunbury-Busselton-Donnybrook areas.

During the drought of 1969 and 1970 in the wheatbelt the Survey helped with the crash programme of investigation and drilling for water in areas where the chances of success were very poor. This involved drilling 2 639 holes with an aggregate depth of 67 294 metres. The success rate was one hole in 10, locating poor-quality stock water or better.

The recent drought and water restrictions in the Metropolitan area resulted in the Survey being inundated with enquiries for advice on the water potential of Metropolitan lots. In 1978 advice was given on more than 4 000 enquiries.

REGIONAL GEOLOGY

In 1960 there was a lack of comprehensive regional geological maps to assist exploration. It was decided to map the whole State at the International scale of 1:250 000, a mammoth task involving some 163 map sheets with explanatory notes. The Bureau of Mineral Resources assisted by providing staff for joint field parties and earlier by printing all of the maps.

By the end of 1979 all the field work for this project was completed. A number of sheets still remain to be compiled, and these should be completed during 1980, while drafting will probably take another two years. Some 103 map sheets with explanatory notes have been published, while 60 sheets are in progress between compilation and printing.

Some sheets have already been remapped and there are many others waiting to be done.

GEOCHRONOLOGY

The rapid progress of Precambrian mapping during the sixties, particularly in the Pilbara and Hamersley Range, highlighted the need for age determination of rocks. Liaison was established in 1961 with Dr W. Compston, of the Australian National University, and he was encouraged by the Survey to continue work on Western Australian rocks. Later, in 1968, a suitable laboratory was established at the Western Australian Institute of Technology under Dr J. R. de Laeter, and arrangements were made for the Survey to co-operate in its geochronological studies. Through these two laboratories the Survey has played a significant part in establishing a firm time framework for the Precambrian rocks of this State. The published results have been of immense value for the work of the Survey.

EVALUATION SECTIONS

Originally it was not necessary to report results of exploration work to the Government, so that much valuable information was lost. It was often necessary for a person exploring an area to repeat work previously done. In 1968 the Department of Mines, at the instigation of the Survey, regulated under the Mining Act that all results of work on tenements should be reported on an annual basis. This had also been made a requirement under the Petroleum Act (1967) and the Petroleum (Submerged Lands) Act (1967).

The new data requirements coincided with the mineral boom of 1968–72, which resulted in the Survey being inundated with information and results of exploration.

The Survey established sections in the Mineral Resources and Sedimentary Geology Divisions to handle this information and to make it available to the public as permitted under the various acts.

This exercise has taken some considerable time to develop methods, procedures, indexes, etc. It was found that the only way to make such a mass of material readily available for the public was to photograph it all on 35 mm film. At the end of 1979, 213 rolls of such film had been made, with 500 frames on each roll. Many frames include two pages of reports and the others maps.

Evaluation sections also review the activity on each tenement to ensure that the programme of work is being done in accordance with the condition of granting. Also from these results Survey geologists can assess the mineral potential of a particular area or a particular mineral.

FILM LIBRARY

A film library has been established for the use of the public and staff, with 35 mm and 16 mm reader-printers available. These are used to consult roll film or microfiche of exploration reports and Survey publications.

This film library is in constant use by the public and was the first to be established in Australia by a Geological Survey. The results indicate that with the volume of reports being produced it will become more and more necessary to use film instead of hard copy.

URBAN GEOLOGY

In association with the creation of the environmental geology section, the production of urban geology map sheets at the scale of 1:50 000 was commenced. These sheets cover areas around development centres in the State to provide the extractive industry, town planners, engineers, etc. with information of a geological nature to assist development. Eight of these coloured maps have been published and seven more are proceeding towards that end.

REGIONAL OFFICES

Due to the mineral booms, regional mapping, and other activities, it was not until 1979 that a regional office was established. It is at Kalgoorlie, associated with the W.A. School of Mines. The purpose is to provide geological assistance to the mining industry in the field and also to establish, from the regional centre, a convenient base for detailed local studies.

PUBLICATIONS

There has been an expansion in the types of publications issued by the Survey. The new series of 1:250 000 geological maps with explanatory notes provides an outlet for a huge amount of geological information gathered in the field. Individual sets of notes range from 20 to 40 printed pages.

The Geological Bulletin and Mineral Resources Bulletin series were continued, and in these were published the results of many long and detailed studies, such as the Perth Basin, iron formations of the Precambrian Hamersley Group, the Blackstone region, and many others.

The Annual Report series was continued, but due to size problems could include only a selection of short reports prepared during each year.

A Report series has been commenced to include reports that are too long for the Annual Report, but are not of sufficient length for the Bulletin series, and also to save expense and time by using the offset printing method.

For small reports and those which require quick release a Record series was commenced. This is now considered as a publication because it is freely available to the public in microfiche form.

Probably the most ambitious publication attempted was Memoir 2, "The Geology of Western Australia". Unfortunately it was being prepared when the Survey suffered many staff resignations, which caused delays and other problems. The final text, which included sections by numerous authors within the Survey, was published in 1975.

Numerous other pamphlets and maps were published. The total publications issued during the two decades were:

Memoirs	1
Geological Bulletins	12
Mineral Resources Bulletins	5
Annual Reports	21
Reports	9
Records	445
Information Pamphlets	13
Maps: International scale—	
1:2 500 000	3
1:1 000 000	2
1:250 000 (with explanatory notes)	103
1:50 000	20

There were also about 130 papers published in outside journals.

In press there are three bulletins and a number of other publications, particularly maps.

CONCLUSION

The Survey has been through two waves of development during the period 1960 to 1979. The first was the enlargement of the Survey in the early 1960s and the recruitment and training of staff, so that an efficient organization had been established by the latter part of the decade. This situation was somewhat shattered by the mineral boom, when there was more than a 50% turnover of the professional staff between 1969 and 1971.

From 1972 onwards professional staff were more readily available, allowing for a second wave of development. It was necessary to recruit and train another group of geologists, who became highly productive in the latter part of the seventies.

Once again in 1979 a mineral boom commenced and staff began leaving to seek alternative employment in private enterprise. The Survey is a training ground for young geologists and is of such a size that all persons cannot be promoted to the higher levels justified by their ability and experience. Consequently a high staff turnover during periods of expanding exploration activity is to be expected.

Any achievements of the past two decades have resulted from the attracting and training of good professional staff from varying backgrounds. The Survey owes a debt of gratitude to many of these geologists who have contributed to its development in recent times.

With a third wave of development about to commence in the eighties, it is an opportune time for a change of leadership. The present operation of the Survey should be reviewed as there are probably areas where reconstruction and alteration of emphasis could be effected, remembering always that the Survey is required to serve the State and the people.

THE GEOLOGY AND HYDROGEOLOGY OF THE PICTON BOREHOLE LINE

by P. H. Wharton

ABSTRACT

The Picton Line of bores comprises seven bores at four sites drilled on an east-west line across the onshore Perth Basin, from Bunbury to south of Burekup. They were drilled to a maximum depth of 1 200 m (Picton Line 1) and had an aggregate depth of 4 069 m.

The drilling showed that the Leederville Formation (Early Cretaceous) fills an asymmetric syncline which is thought to have resulted from the compaction of Phanerozoic sediments over basement fault blocks. The Leederville Formation unconformably overlies an easterly dipping sequence of non-marine fluviatile sediments of the Yarragadee Formation (Late Jurassic) and Cockleshell Gully Formation (Early Jurassic).

Major groundwater flow systems are recognized in the Leederville Formation, and in the Yarragadee and Cockleshell Gully Formations. Both flow systems contain groundwater with a salinity generally less than 500 mg/L TDS, which extends to a depth of between 500 and 700 m below sea level. Below that depth the groundwater is saline, and there is almost no groundwater movement.

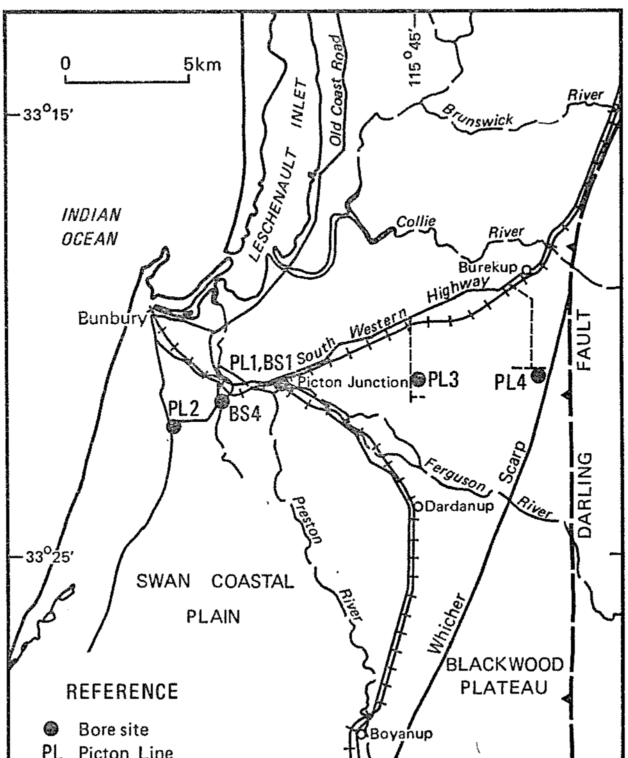
Large potable groundwater resources are available across the coastal plain, but principally in the central and western parts.

INTRODUCTION

The Picton Line consists of seven bores drilled at four sites on an east-west line across the coastal plain from Bunbury to south of Burekup (Fig. 1).

The bores were drilled as part of a long-term drilling programme to evaluate the deep groundwater resources of the Perth Basin. The nearest lines of deep bores are at Mandurah, approximately 100 km to the north (Commander, 1974), and the Quindalup Line, 32 km south (Probert, 1968). Bores drilled for the Bunbury Shallow Project (Commander, 1975, in prep.) in the vicinity of the Picton Line provided additional data for this report.

A more detailed account of the drilling procedures, geology and hydrogeology of the Picton Line is given by Wharton (in press).



GSWA 18452

Figure 1 Locality map, Picton Line.

PHYSIOGRAPHY

The Picton Line bores are situated on the Swan Coastal Plain (Saint-Smith, 1912), a low-lying, gently undulating area formed by coastal-dune and shoreline deposits. These sediments extend from the coast to the Whicher Scarp (Fig. 1), a late Tertiary or Pleistocene shoreline (Playford and others, 1976). The coastal plain has been divided into three physiographic units by Low (1972): the Pinjarra Plain, consisting of an alluvial plain formed by fine-grained alluvial and piedmont deposits; the Bassendean Dunes, of decalcified quartz sand; and the Coastal Belt, a band of fixed calcified dunes, with modern dunes along the coast.

INVESTIGATION PROGRAMME

A summary of drilling and bore information is given in Table 1.

The bores were drilled using a Franks Explorer Rocket (Picton Line 1, PL1) and a Midway Skytop (PL2 to PL4), both mud-flush rotary rigs. Two bores were drilled at each of sites 2 to 4: a deep bore, designated "A", was constructed to monitor two aquifer intervals separated by a compressible packer, and a second bore, designated "B", monitors a shallow aquifer. At site 1 only a deep bore was drilled, as Bunbury Shallow bores BS1B and BS1C, drilled for another project to depths of 84 m and 19 m respectively, are located about 30 m to the east. In PL1 compressible packers were used to isolate each of six intervals, to permit individual development, testing and sampling.

Sludge samples were collected at 3 m intervals from the deep bore at each site. On completion of drilling, gamma-ray and long- and short-normal resistivity logs were run on each bore, and other logs were obtained as required. Sidewall cores were recovered from shales or siltstones at about 30 m intervals in each deep bore.

All bores, except PL2B and PL4B, were completed with 155 mm casing to below the bottom aquifer interval to be tested, and the selected intervals were perforated with shaped explosive bullets. In PL2B and PL4B the test interval was screened with a 0·05 inch aperture 100 NB stainless-steel continuous-slot screen.

Each interval was developed by airlifting and surging until the water cleared and the salinity was constant, thus indicating that the sample was uncontaminated and suitable for analysis. Water samples taken after development were analysed by the Government Chemical Laboratories.

GEOLOGY

SETTING

The Picton Line of bores was drilled in the northern part of the Bunbury Trough, a structural subdivision of the Perth Basin (Playford and others, 1976). The Bunbury Trough is a deep graben, bounded to the east by the Darling Fault and to the west by the Busselton Fault. It probably contains at least 10 000 m of Phanerozoic sediments.

STRATIGRAPHY

Sediments encountered by the Picton Line bores range in age from Holocene to Early Jurassic. The formations recognized are given in Table 2, and are described below.

Subdivision of Mesozoic sediments

The Mesozoic sediments intersected by the Picton Line bores cannot be as readily subdivided into formations as they can in the northern Perth Basin. The upper part of the Yarragadee Formation in PL4A, where a younger section of the Yarragadee Formation is preserved, is lithologically indistinguishable from the overlying Leederville Formation. Similarly, in PL1 and PL2A, the Yarragadee Formation closely resembles the Cockleshell Gully Formation. Consequently, subdivision of the sediments into formations has been made primarily on biostratigraphic and geophysical evidence, rather than on lithology.

Jurassic

Cockleshell Gully Formation: The Cockleshell Gully Formation was encountered in bores PL1, PL2A, and PL3A, and extends beneath all the coastal plain. It consists of fine-sand to granule grade, mostly moderately sorted, angular to subrounded, weakly consolidated quartz sandstone, with accessory garnet and pyrite. The sandstone is interbedded with subordinate grey silty shale and carbonaceous shale in beds up to 12 m thick, which contain thin beds of soft lignite.

TABLE 1. SUMMARY OF BORE DATA

Bore	Latitude S	Longitude E	Drilling: Commenced	Drilling: Completed	Elevation (m) AHD: Surface	Elevation (m) AHD: Casing top	Total Depth (m)	Tested Interval (m bns)	Head (m) AHD Jan 1979	Salinity TDS by evap. (mg/L)	Aquifer (Formation)	Status
PL1	33°20′44″	115°41′36″	2/5/74	26/5/74	7·570	8·37	1 200	1 070–1 108	—21·77*	51 700	Cockleshell Gully	Abd
								829–837	—4·52*	14 800	Cockleshell Gully	Abd
								666–674	5·40	910	Cockleshell Gully	Obs
								599–607	6·59*	520	Cockleshell Gully	Abd
								414–422	6·97*	340	Yarragadee	Abd
								205–213	12·53	490	Leederville	Obs (flowing)
PL2A	33°22′07″	115°38′42″	3/1/78	7/3/78	5·82	6·682	772	576–586	4·78	460	Cockleshell Gully	Obs
								410–420	4·02	260	Cockleshell Gully	Obs
PL2B	33°22′07″	115°38′42″	8/3/78	15/3/78	5·81	6·662	207	192–201	3·37	310	Yarragadee	Obs
PL3A	33°20′55″	115°45′08″	22/3/78	20/4/78	18·07	18·941	794	440–446	7·55	360	Yarragadee	Obs
								308–314	8·01	370	Yarragadee	Obs
PL3B	33°20′55″	115°45′08″	19/5/78	26/5/78	18·10	18·674	228	126–132	16·45	300	Leederville	Obs
PL4A	33°20′59″	115°48′30″	18/6/78	15/8/78	44·03	44·855	823	699–705	....	360	Yarragadee	Abd
								669–675	7·82	720	Yarragadee	Obs
								564–570	8·25	410	Yarragadee	Obs
PL4B	33°20′59″	115°48′30″	13/7/78	14/7/78	43·93	44·840	45	38·5–44·5	24·51	490	Leederville	Obs

* Previous measurement, water level could not be re-measured.
bns—Below natural surface.
Abd—Abandoned test interval
Obs—Observation bore

TABLE 2. STRATIGRAPHIC SUCCESSION ENCOUNTERED IN THE PICTON LINE BORES

Age	Group/Formation	Thickness (m): PL1	PL2	PL3	PL4	Summary lithology	Remarks
Quaternary	Kwinana Gp	19	15	18	7	Sand and clay	Minor local aquifer
Early Cretaceous	Leederville Fm	261	....	244	?96	Sand, siltstone and shale	Multilayered aquifer
	Bunbury Basalt	....	....	....	....	Basalt	Aquiclude. Present between PL2 and PL1
Late Jurassic	Yarragadee Fm	?286	?187	471	>720	Sandstone, minor shale	Major aquifer
Middle to Early Jurassic	Cockleshell Gully Fm	>634	>570	>61	....	Sandstone and shale	Multilayered aquifer

Sidewall cores from PL1 and PL2A yielded palynomorph assemblages of a general Early Jurassic age. However, a sidewall core from a silty shale at the base of PL3A contained spores and pollen including *Lecaniella foveolatus*, previously only recorded from the Cadda Formation (Backhouse, 1978a). This indicates a mid-Jurassic age (Early to Middle Bajocian), the shale probably representing the uppermost part of the Cockleshell Gully Formation at this locality. The palynology of samples from the Cockleshell Gully Formation intersected in the Picton Line drilling is consistent with a nonmarine environment of deposition.

The Cockleshell Gully formation is about 2 000 m thick (Playford and others, 1976), of which a maximum thickness of about 635 m was intersected in PL1. The formation is conformably overlain by the Yarragadee Formation.

Yarragadee Formation: The Yarragadee Formation is composed of weakly consolidated, predominantly very coarse-grained sandstone, with minor shale beds. Although it is very similar lithologically to the Cockleshell Gully Formation at PL1 and PL2, the Yarragadee Formation varies from a clean sandstone with almost no shale at the base (PL2) upward to a very shaly section (PL4). The abundance of fine-grained sediments may indicate a low-energy environment towards the end of the Yarragadee Formation sedimentation.

The quantity of lignite and carbonaceous material in the formation increases from west to east. No lignite or carbonaceous material was recorded from the Yarragadee Formation in PL2. In PL1 carbonaceous material was common below a depth of 445 m, while in PL3A and PL4A bands of soft to moderately hard lignite were encountered; in PL4A the short-normal resistivity log indicated lignite at depths of 358·5 to 360 m, 400 to 402 m and 458 to 460·5 m, but geophysical logging in PL3 failed to give a similar indication.

The Yarragadee Formation extends beneath all the coastal plain, and ranges in thickness from ?187 m (PL2) to greater than 720 m (PL4). It is unconformably overlain by the Leederville Formation from PL1 eastwards, by the Bunbury Basalt between PL1 and PL2, and by the Kwinana Group from PL2 westwards (Fig. 2). The palynology of samples from the formation indicates a nonmarine environment of deposition.

Cretaceous

Bunbury Basalt: The Bunbury Basalt was not intersected by any of the Picton Line bores, but is known to occur between PL2 and PL1, where Bunbury Shallow bore BS4A intersected basalt from a depth of 30 to 49 m. The basalt varies from fresh with columnar jointing, to very deeply weathered, and is represented by clay where it has been completely weathered.

Leederville Formation: Sediments of the Leederville Formation were intersected at sites 1, 3 and 4, and consist of sand (or weakly consolidated sandstone), clayey sand, silt, and shale, with common to abundant thin layers of soft lignite and carbonaceous material. The sand is mainly coarse to very coarse grained and it may contain granules. Shales are commonly micaceous and carbonaceous. Accessory minerals include mica and pyrite.

Sludge samples from the 60 to 66 m depth interval in PL3A consist of 50% moderately hard lignite flakes and 50% calcareous shale. A conventional core was run from 58 to 67 m depth in PL3B to determine the characteristics of the lignite. There was no recovery, and sidewall cores and accurate geophysical logs could not be obtained because of washouts. However, from the platy nature of the lignite fragments it is likely that the lignite forms thin lenses of local extent.

Sidewall core samples from the Leederville Formation had unusually sparse assemblages of spores and pollen (Backhouse, 1978b). The palynomorphs indicate a general Late Neocomian to Aptian age, and a nonmarine environment of deposition.

Quaternary

Kwinana Group: Two formations of the Kwinana Group were intersected in the Picton Line drilling; the Guildford Formation (PL1, PL3 and PL4) and the Bassendean Sand (PL2).

The Guildford Formation consists of light-brown clay and clayey sand, commonly ferruginized. The sand is mostly fine to very coarse-grained and poorly sorted, although some

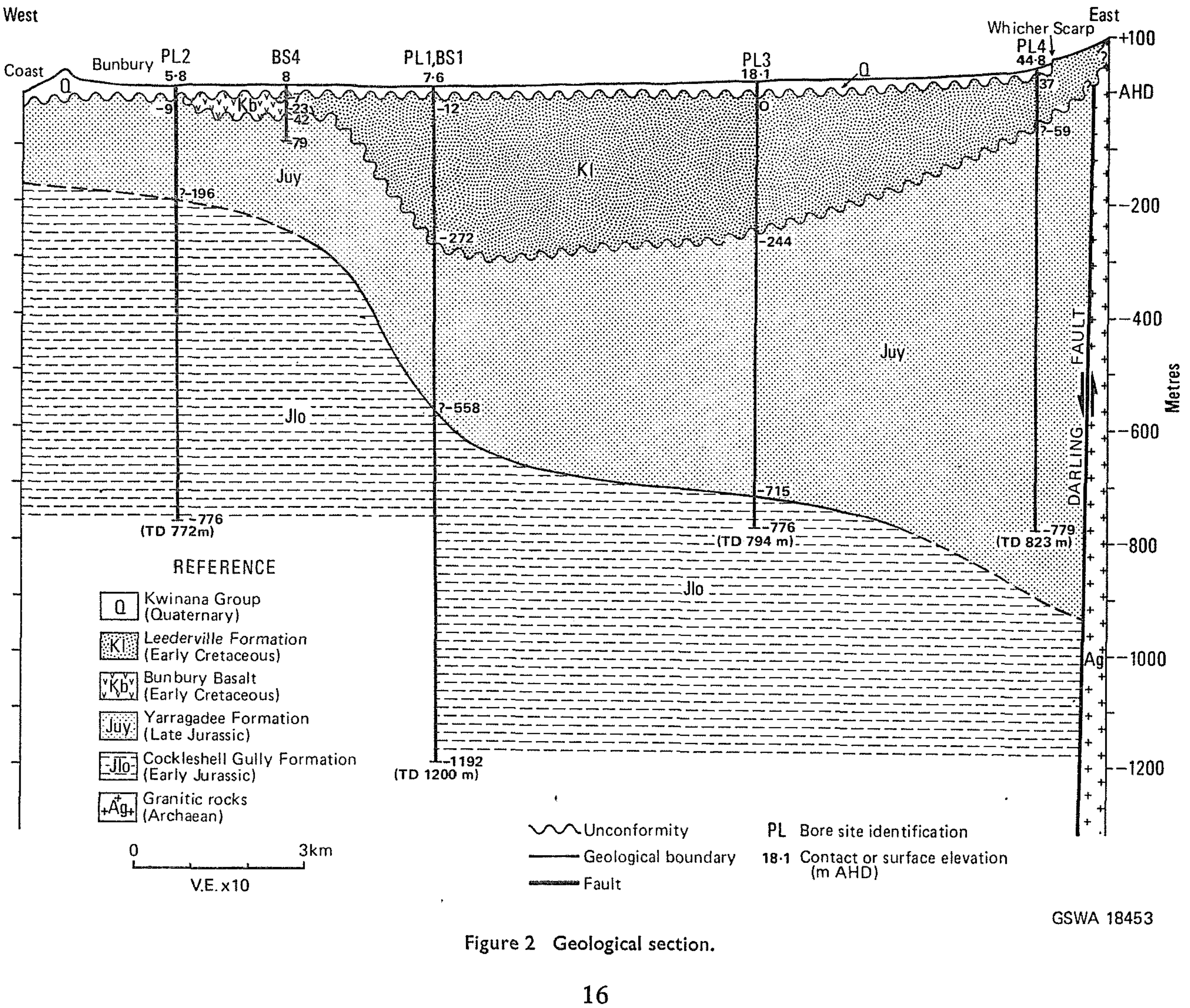


Figure 2 Geological section.

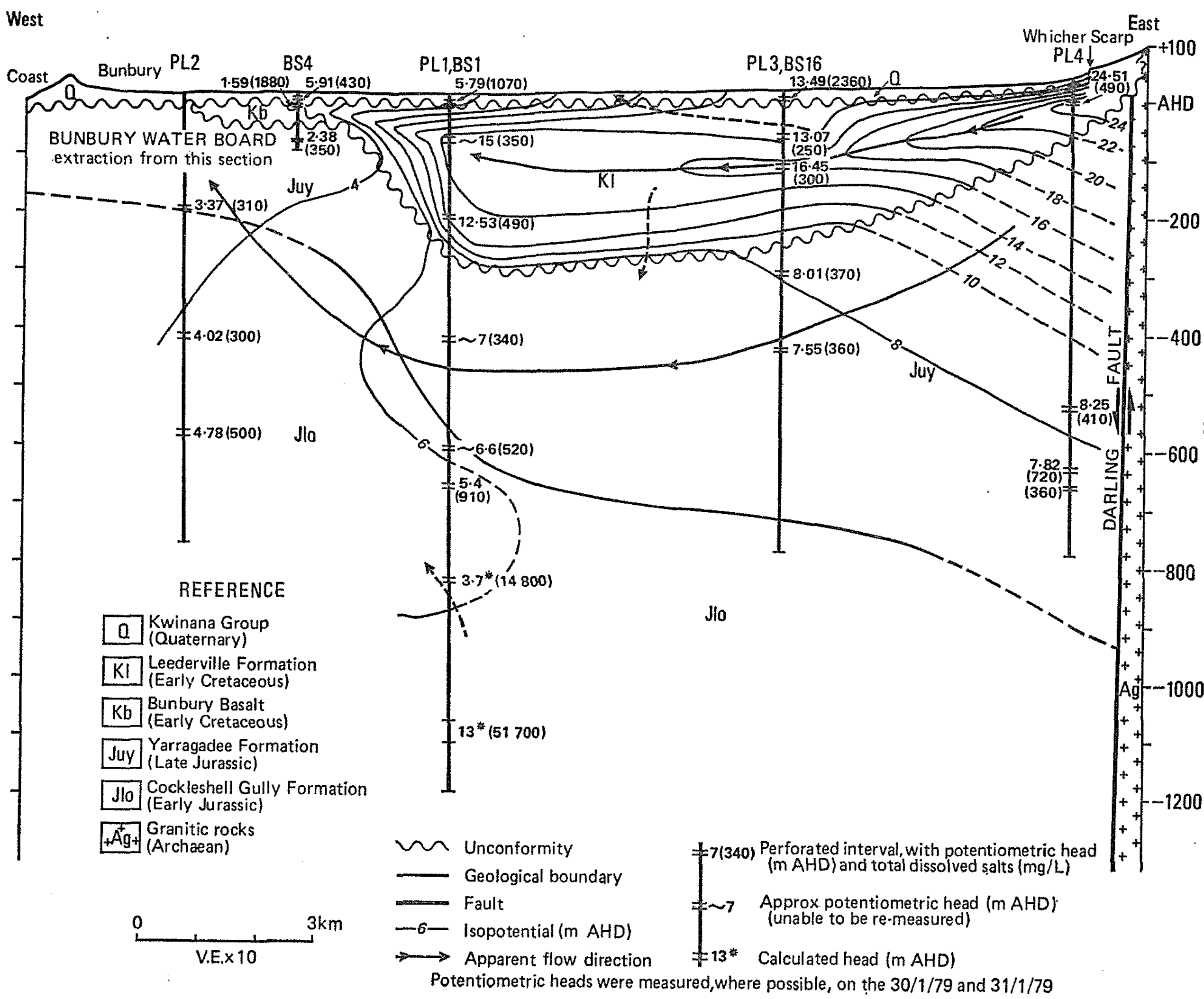


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Figure 3 Section showing apparent flow systems.

well-sorted very coarse-grained sand was encountered in PL3. Sand grains are often iron stained. Heavy minerals were common in the Guildford Formation at PL1.

The Bassendean Sand intersected at PL2 is medium to coarse grained, poorly sorted, angular to subrounded, with some iron staining of the quartz grains.

STRUCTURE

The inferred geological structure in the section through the Picton Line bores is shown in Figure 2.

The Cockleshell Gully and Yarragadee Formations dip gently eastwards with an average dip of about 3°. The Yarragadee Formation is locally unconformably overlain by the Bunbury Basalt, and regionally by the Leederville Formation.

The Leederville Formation occupies an asymmetric synclinal depression which is presumed to be either a fault angle depression, resulting from vertical movements on a fault between PL1 and PL2, or a downwarp resulting from the differential compaction of sediments over faulted Precambrian basement. The latter explanation is preferred as it more readily explains the shape of the unconformity at the base of the Leederville Formation west of PL1, and because Cope (1972) has claimed that differential compaction may have controlled deposition of all the Cretaceous sediments in the onshore Perth Basin.

HYDROGEOLOGY

AQUIFER RELATIONSHIPS

A section showing the apparent direction of groundwater flow in the Leederville Formation and the Yarragadee and Cockleshell Gully Formations is given in Figure 3. The two flow systems are separated by shale beds within the Leederville Formation, and by the impermeable Bunbury Basalt.

In the Leederville Formation the section shows an apparent east-to-west component of groundwater flow with possible minor recharge from the Kwinana Group west of PL1, minor leakage into the underlying Yarragadee Formation, and upward discharge into the Kwinana Group east of PL1.

The groundwater flow in the Yarragadee and Cockleshell Gully Formations flow system also has an east-west component, with discharge via the Kwinana Group to the sea in the vicinity of Bunbury. Water-level measurements made by the Public Works Department (Boyd, 1979) indicate that abstraction from the Yarragadee Formation may seasonally reverse the hydraulic gradient, inducing some recharge to the Yarragadee Formation from the Kwinana Group.

Groundwater movement at depth in the Cockleshell Gully Formation is probably negligible, as shown by the presence of highly saline groundwater, and the high vertical hydraulic gradient in PL1 (Fig. 3).

KWINANA GROUP

The Kwinana Group is 10 to 20 m thick, and consists of sand and limestone with some clay in the Coastal Belt and Bassendean Dunes, and clay with minor sand beneath the Pinjarra Plain. These sediments form an unconfined aquifer in which the groundwater is derived from the direct infiltration of rainwater, and west of PL1, by upward leakage from the Leederville Formation. Groundwater movement is to the west, with discharge to the Collie, Ferguson and Preston Rivers, and along the coast. Large evapotranspiration losses are presumed to occur, especially from the Pinjarra Plain where the water table is close to the surface, with the result that extensive areas have brackish groundwater.

The Kwinana Group sediments are unimportant as a major groundwater source because of the extensive area underlain by clayey sediments (Pinjarra Plain). Supplies of fresh groundwater are sometimes obtained from the Bassendean Dunes,

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and are usually available from the sand and limestone of the Coastal Belt. Groundwater from the Kwinana Group is used for some small farm supplies, and for garden reticulation along the Coastal Belt.

LEEDERVILLE FORMATION

The Leederville Formation is a multi-layered aquifer system, consisting of sand, clayey sand, silt, and shale, with the proportion of sand, or clayey sand, to shale decreasing from about 80% at PL1 to less than 50% at PL4. The formation ranges in thickness from 260 m at PL1 to approximately 95 m at PL4.

Groundwater in the formation is confined by shale beds, and local artesian flows may be encountered, as in PL1.

Groundwater movement is from the southeast (Commander, in prep.), where much of the recharge probably originates from the infiltration of rainfall on the Blackwood Plateau. There may be minor recharge from the overlying Kwinana Group west of PL1.

Vertical isopotentials (Fig. 3) indicate an east to west component of groundwater flow along the Picton Line section, and a low vertical permeability, resulting from sand/shale stratification.

Discharge from the Leederville Formation is presumed to occur from the upper part of the flow system via the Kwinana Group to the sea in the vicinity of the Leschenault Inlet, and by downward leakage from the lower part of the flow system into the underlying Yarragadee Formation, except in areas where the Bunbury Basalt is present.

All water samples taken from the Leederville Formation had a salinity of less than 500 mg/L TDS (Fig. 4), apart from one, of 1 880 mg/L, from Bunbury Shallow bore BS4C, which was possibly a result of local brackish groundwater recharge from the Kwinana Group.

Ferrous iron in sufficient concentrations to cause staining occurs in groundwater from the Leederville Formation, and it is likely that groundwater would require treatment for iron before being used for domestic, industrial or public water-supply purposes. One sample, from PL4B, had the very high iron concentration of 38 mg/L.

The extent of the formation, the high proportion of sand, and the low salinity of the groundwater in it, make the Leederville Formation an important aquifer system. The formation has been utilized for farm and some industrial supplies, but is still virtually undeveloped.

YARRAGADEE FORMATION

The Yarragadee Formation consists of weakly consolidated, mostly very coarse-grained sandstone, with minor shale beds. Shale becomes more common towards the east, notably in the upper part of the formation (PL4).

Head measurements indicate that the Yarragadee and Cockleshell Gully Formations form a single flow system (Fig. 3). The east-to-west component of groundwater flow along the Picton Line results from recharge in the south or southeast, with discharge via the Kwinana Group to the sea near Bunbury.

The salinity of groundwater in the Yarragadee Formation, where intersected by the Picton Line bores, ranges from 300 to 8 000 mg/L TDS (Fig. 4). The groundwater is fresh in the upper part of the flow system (above −500 to −700 m AHD), with the salinity generally less than 500 mg/L TDS. Groundwater in the lower part of the flow system is brackish to saline. Brackish groundwater at shallow depths near the coast at Bunbury may be associated with a salt-water interface which has moved inland as a result of overpumping (Commander, 1975).

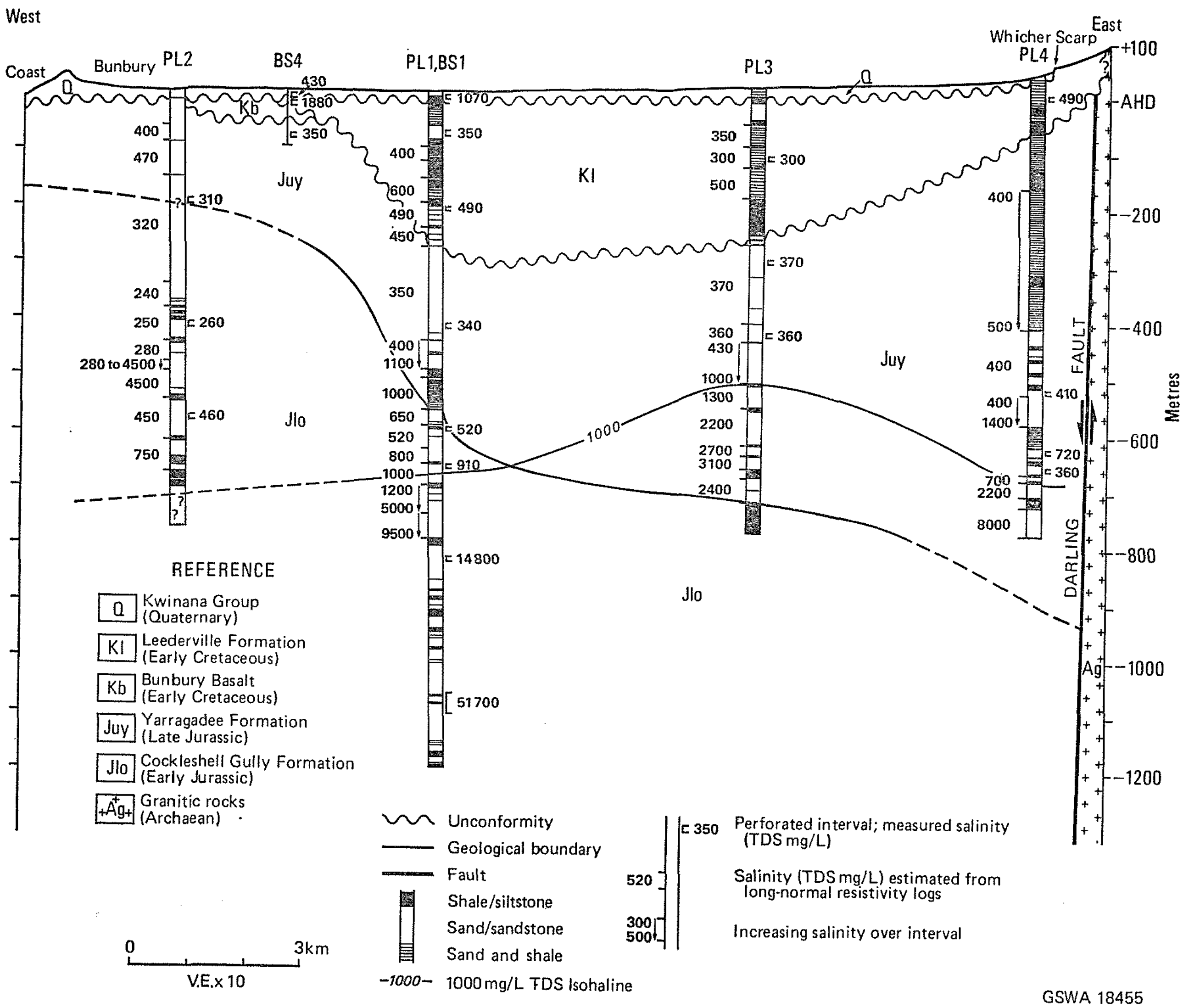

Figure 4 Variation in groundwater salinity.

Five samples of groundwater from the formation were analysed for iron, from bores PL2B, PL1 and PL4A, and ranged from 0·46 (PL4A) to 49 (PL2B) mg/L. Water from the Yarragadee Formation used for the Bunbury water supply also has a high iron content and requires treatment before use.

High manganese concentrations occur in the Bunbury Water Board Withers Bore (Commander, 1975), and may be present in other groundwater from the formation; however, samples analysed from the Picton Line bores had manganese concentrations of less than 0·5 mg/L.

Groundwater in the Yarragadee Formation is being exploited for town water supplies at Bunbury and Eaton, industrial usage at Australind and Bunbury, and the irrigation of parks and reserves in Bunbury. Commander (1975) estimates an average abstraction from the formation of about 30 000 m^3/day (11 x $10^6 m^3$/year).

The substantial thickness of sand containing fresh water, and its extent, make the Yarragadee Formation the most important aquifer in the region. It is capable of considerable further exploitation outside the area of influence of Bunbury water supply bores.

COCKLESHELL GULLY FORMATION

The Cockleshell Gully Formation is composed of weakly consolidated sandstone interbedded with some beds of silty shale and shale up to 12 m thick.

Groundwater in the Yarragadee Formation and the top of the Cockleshell Gully Formation forms a single flow system from PL4 westwards. Recharge to the Cockleshell Gully Formation takes place from the overlying Yarragadee Formation where head differentials are downward, and groundwater movement is not restricted by confining beds (Fig. 3). There is probably little groundwater movement in the formation east of PL1 and below a depth of about –700 m (AHD), where the formation contains saline to hypersaline groundwater. Discharge from the Cockleshell Gully Formation takes place west of PL1 where there are few shales and an upward head gradient (Fig. 3).

The measured heads of the two lower (saline) perforated intervals in PL1 were below sea level. Water from the interval 829 to 837 m had a salinity of 14 800 mg/L TDS and a head of –4·5 m AHD, and the 1 070 to 1 108 m interval had a salinity of 51 700 mg/L TDS and a head of –21·8 m AHD. To compare these heads with those of the fresh-water intervals, the environmental-water heads (vertical heads) were calculated using formulae given by Luscyzynski (1961). The calculation of environmental-water head corrects for the density distribution resulting from salinity variations, and allows the definition of the vertical hydraulic gradient. The environmental-water heads computed were 3·7 m AHD for the 829 to 837 m interval and 13 m AHD for the 1 070 to 1 108 m interval. These heads indicate a high hydraulic gradient and a very low vertical permeability of the confining beds.

The hypersaline groundwater in the Cockleshell Gully Formation at PL1 may have originated as connate water, with a concentration of salts by reverse osmosis (ultra-filtration). The main confining beds are probably the shales at depths of 797 to 808 m and 924 to 935 m.

The Cockleshell Gully Formation contains groundwater with salinities ranging from about 200 mg/L TDS to greater than 50 000 mg/L TDS. Groundwater with a salinity of less than 1 000 mg/L TDS occurs to a depth of about –700 m AHD in the Cockleshell Gully Formation, apart from a layer of more saline water (4 500 mg/L TDS) intersected in PL2A from 495 to 545 m (Fig. 4). Fresh water extends to a similar depth in the overlying Yarragadee Formation east of PL1. Below about –700 m AHD the Cockleshell Gully Formation contains water with salinities greater than 1 000 mg/L TDS.

This aquifer is undeveloped, but has the potential to provide large supplies of low-salinity groundwater in the western part of the basin.

GROUNDWATER TEMPERATURE

Differential temperature logs were run to the top of the packers in the deep bore at each site. The logs were run six months after the drilling had been completed to ensure that the groundwater temperature in the bores had readjusted to the ambient geothermal gradients. Temperature gradients range from 2·7 to 4·1°C/100 m to a depth of 250 to 420 m below surface, and about 1·7 to 1·8°C/100 m at greater depths. The high gradients were generally associated with shales of low thermal conductivity.

CONCLUSIONS

Drilling of the Picton Line bores has provided new geological and hydrogeological information on a section across the Perth Basin in the vicinity of Bunbury.

Sediments of the Cockleshell Gully and Yarragadee Formations dip gently to the east and are unconformably overlain by the Leederville Formation. The Leederville Formation occupies an asymmetric syncline, believed to have developed as a result of differential compaction of the Phanerozoic sediments over a faulted basement.

Two major groundwater flow systems are recognized, one in the Leederville Formation, and the other in the Yarragadee and Cockleshell Gully Formations. The Leederville Formation flow system occurs in a multi-layered aquifer up to 280 m thick. It is mainly confined and contains groundwater with a salinity generally less than 500 mg/L TDS. The flow system of the Yarragadee and Cockleshell Gully Formations is considerably larger. Groundwater with salinities mostly less than 500 mg/L TDS extends to a depth of about –700 m AHD. Below this depth the groundwater is saline and groundwater movement is probably negligible.

The two flow systems constitute a very large groundwater resource which is capable of substantial further development.

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GEOLOGY AND HYDROGEOLOGY OF THE ALLANOOKA AREA (GERALDTON WATER SUPPLY), NORTHERN PERTH BASIN, WESTERN AUSTRALIA

by A. D. Allen

ABSTRACT

The Allanooka area is about 50 km southeast of Geraldton, in the northern part of the Perth Basin. It is underlain by Permian to Quaternary sedimentary rocks overlying Pre-cambrian cyrstalline basement. The Permian to Cretaceous sediments are of marine and nonmarine origin, and range in thickness from 60 m in the north to 4 000 m in the extreme southeast. They dip gently to the southeast and have been dislocated by faulting into a series of rectangular fault blocks. The Tertiary to Quaternary sediments occur in a belt about 15 km wide along the coast. They are up to 150 m thick and consist of a flat-lying sequence of eolian, littoral and alluvial deposits.

Major groundwater flow systems occur in the Kwinana Group (?Tertiary-Quaternary), Yarragadee Formation (Late Jurassic-Early Cretaceous), and Cockleshell Gully Formation (Early Jurassic). They contain mainly brackish groundwater with the exception of large resources of potable groundwater (less than 1 000 mg/L TDS) in the upper part of the flow system in the Yarragadee Formation. Small localized resources of potable water also occur in the Kwinana Group and Cockleshell Gully Formation.

The Yarragadee Formation consists of sandstone, siltstone and shale of fluviatile origin. It ranges in thickness from about 20 to 1 000 m. The sandstones, which comprise about 60% of the formation, form a multilayer aquifer in which there is a regional groundwater flow system. This is recharged by rainfall on the upland in the eastern part of the Allanooka area, and flows southwestward, to be discharged from springs at the margins of the upland, and by subsurface discharge into the Kwinana Group. Potable groundwater is restricted to the upland area, and is underlain and in lateral continuity with brackish groundwater. The potable groundwater extends to an average depth of 90 m below the water table, and has a mean salinity of 700 mg/L TDS. In an area of 1 550 km² there is estimated to be about 20 000 x 10^6 m³ of potable groundwater in storage. From chlorinity data the average annual recharge is estimated to be about 3% of average annual rainfall (477 mm) or about 20 x 10^6 m³/year.

INTRODUCTION

LOCATION

Geraldton is about 500 km north of Perth, adjacent to Champion Bay (Fig. 1). It has a population of about 18 000, and is the fourth largest town in Western Australia. The town is an important port serving rock-lobster fisheries, and inland agricultural and mining districts. It is also important for market-gardening, light industry and tourism.

The Allanooka area is about 50 km southeast of Geraldton. It is about 2 500 km² in extent and is bounded by the Greenough River in the north, the Irwin River in the south, the Kockatea Creek and the Irwin River in the east, and by the coast in the west (Fig. 1).

PURPOSE AND SCOPE

Most of Geraldton's water supply is obtained from the Allanooka Scheme based on a borefield situated near Lake Allanooka, about 50 km southeast of Geraldton. Some water is also supplied from a borefield at Wicherina (Fig. 1), from which all of Geraldton's water supply was obtained prior to 1967. Dongara and Port Denison, about 25 km southwest of Lake Allanooka, are also supplied from the Allanooka Scheme.

Abstraction from the Allanooka Scheme commenced in 1967 and has steadily increased to 6·7 x 10^6 m³/year in 1977–1978. At present the scheme consists of 24 production bores

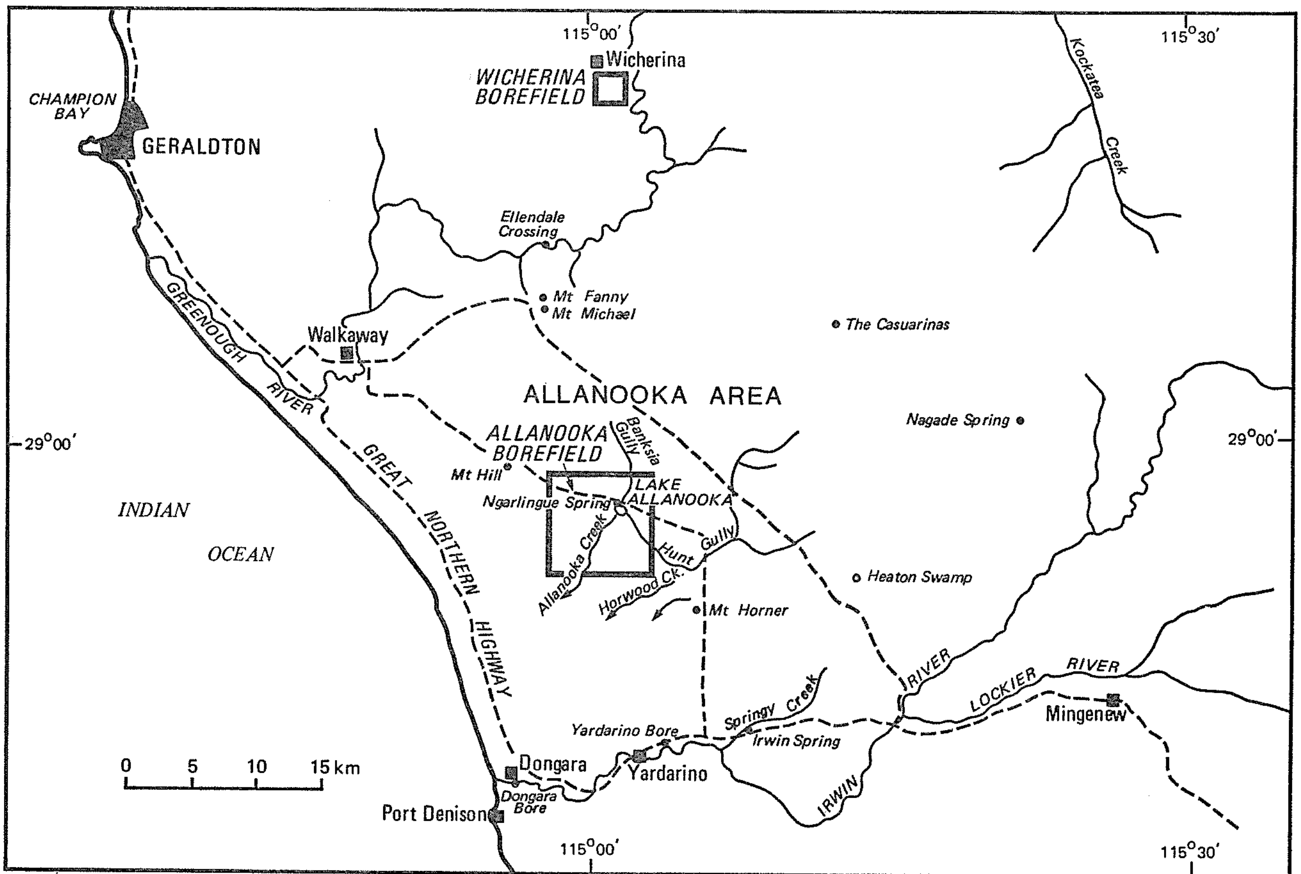

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Figure 1 Locality plan.

TABLE 1. AVERAGE RAINFALL, EVAPORATION AND TEMPERATURE DATA FOR GERALDTON (COMMONWEALTH DEPARTMENT OF METEOROLOGY)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total (year)
Rainfall (mm)	7	12	12	27	74	119	100	65	28	20	8	5	477
Potential evaporation (mm)	377	332	310	212	160	107	102	117	143	217	273	352	2 700
Mean max. (°C)	31·6	32·2	30·6	26·7	24·0	20·6	19·4	19·8	21·6	24·5	27·1	29·9	25·1
Mean min. (°C)	18·7	19·1	17·5	14·9	12·6	11·2	9·2	8·7	8·8	10·9	13·7	16·7	13·5

in an area of about 60 km² (Fig. 1). The first production bores were too close together and not located to best intercept throughflow. As a result local lowering of the water table by up to 12 m has occurred on the north side of Lake Allanooka. Production bores drilled since 1973, to the south of Lake Allanooka, are wider spaced, and observation bores have not detected any marked lowering of the water table.

The present abstraction exceeds the estimated local throughflow, and future demand is expected to continue to increase. The Public Works Department (PWD), therefore, carried out exploratory drilling and testing between 1974 and 1977 in order to plan an extension of the scheme. This paper summarizes the main results of this work.

CLIMATE AND LAND USE

The Allanooka area has a Mediterranean-type climate, with hot, dry summers and cool, wet winters.

The nearest available climatic data are for Geraldton (Table 1). These are expected to be similar to the coastal part of the Allanooka area, but inland, average rainfall and the mean minimum temperature are likely to be less, while potential evaporation and the mean maximum temperature are probably higher, than for Geraldton.

About 85% (413 mm) of the average annual rainfall (477 mm) falls during the winter months between April and September. The remainder falls during the summer, and is usually associated with local thunderstorms or the southward movement of a tropical cyclone. The annual rainfall shows wide variability between extremes of 220 mm and 843 mm, and sequences of years having low or high rainfall have occurred frequently. The potential evaporation is about 5·5 times the rainfall, and is only exceeded by rainfall in June or July.

The climate in the Allanooka area favours cereal growing. The arable land on the coastal plain has been cleared and developed for many years, but in the upland area large-scale clearing of the sandplain has only occurred during the last 15 to 20 years. Extensive areas of coastal dunes and limestone ridges remain uncleared on the coastal plain, and large tracts of low sclerophyll heath still remain in the upland sandplain.

PREVIOUS WORK

The first description of groundwater in the Allanooka area was by Maitland (1913) who discussed the groundwater encountered in deep bores drilled to explore for coal at Dongara and Yardarino. Later, a broad subdivision of the region into various groundwater provinces was made by Johnson and others (1954). They applied the name Irwin View groundwater province to the upland part of the Allanooka area and noted that the army had obtained water supplies in the area.

Prior to the construction of the Allanooka Scheme an extensive exploratory drilling programme was carried out by the Geological Survey Branch of the Mines Department (GSWA) and PWD, the results of which, together with a regional account of the hydrogeology, are given by Allen (1963, 1964, 1965). After the scheme had been in operation for 4 years, Forth (1971, 1972) made an assessment of the results of long-term pumping of the Allanooka Scheme, and noted a decline in the water table and possible hydraulic-barrier boundary effects caused by faults.

Later, after study of data from a bore census made by the GSWA, Forth (1973) recommended an exploratory drilling programme (Irwin View Project and Allanooka production bores) to extend information about the area to the southeast of the Allanooka borefield. Bores were drilled by the PWD, and the results were briefly examined by Davidson (1976) who recommended further drilling in the same general area (Irwin View Project).

Ventriss and Parsons (1978) made a brief study of the effects of abstraction from the Allanooka Scheme. They noted that water levels were continuing to fall in bores on the north side of Lake Allanooka but that there had been no apparent increase in groundwater salinity.

DRILLING PROGRAMMES

Data incorporated in this report are from the Allanooka Project (AP) drilled prior to the construction of the Allanooka Scheme; Allanooka production bores (A); the Irwin View Project (I); and the Dongara (D) and Mount Hill (MH) bores. General data for the bores are given in Table 2, except for the Allanooka Project bores for which reference should be made to Allen (1965).

Several of the drilling programmes have been carried out over a number of years. In these cases the bores are numbered in sequence followed by a suffix indicating the year (e.g. I1/73). Those bores which are designated by letters as well as numbers (Table 2) refer to sites recommended by Forth (1971, 1973) and Davidson (1976).

DRILLING, BORE CONSTRUCTION AND TESTING

The exploratory bores and production bores drilled prior to 1973 were drilled by cable-tool methods. Subsequently production and exploratory bores have been drilled using a PWD-owned and operated Walker-Neer mud-flush rotary rig, with the exception of D1–2/75 which were drilled with a rotary rig by a private contractor. Drilling conditions were found to give no problems for either cable-tool or rotary drilling techniques.

A variety of bore sizes and types of construction have been used. Production bores have been constructed using 260 mm casing, while the exploratory bores have 189 or 143 mm OD casing. Some bores prior to 1973 were constructed with gravel-packed slotted casing but subsequently all bores have had single or multiple, in-line, v-section wire-wound screens. Mild-steel screens were used in the exploratory bores, and stainless-steel screens in the production bores.

Sludge samples were collected during drilling at 3-m intervals for all bores. These have been geologically logged, and small samples are stored in the GSWA core library. Gamma ray, and long- and short-normal wireline logs have been run by the GSWA on all bores drilled since 1973.

Single borehole pumping tests using a shaft-driven turbine pump, and measuring water levels by airline, were carried out on all bores drilled since 1973 (Table 2). In most of the bores the results of the pumping tests could not be analysed.

Groundwater samples were taken at the end of the pumping tests, and partial analyses made by the Government Chemical Laboratories (GCL). Total dissolved solid and sodium chloride results, are given in Table 2. Standard analyses of groundwater from various formations were made by GCL for the Allanooka Project bores (Allen, 1965), and are given in Table 3.

The natural surface (ns) and top of casing (tc) of each bore is levelled to the Australian Height Datum (AHD), except for the Allanooka Project bores which had been levelled to Low Water Mark, Fremantle.

Groundwater levels are measured by the PWD. Observation and production bores in the Allanooka borefield are measured monthly while more distant Allanooka and Irwin View project bores are measured at 3-monthly intervals. The data are stored in the PWD computerized groundwater-levels recording system.

PHYSIOGRAPHY

GENERAL

The Allanooka area includes an upland having the form of a relatively flat plateau with a dissected margin, and a coastal plain which bounds it to the west.

The generalized topography and location of the major drainage divides are given in Figure 2. The physiographic subdivisions (inset Fig. 2) and the important drainage features are described below.

TABLE 2. SUMMARY OF RESULTS FROM ALLANOOKA, DONGARA, IRWIN VIEW AND MOUNT HILL BORES

Name	Drilling		RL ns AHD (m)	RL tc AHD (m)	Depth (m)	Test interval bns (m)	Water table btc (m)	Test yield (m³/d)	Draw-down (m)	TDS (mg/L)	NaCl (mg/L)
	Com-menced	Com-pleted									
Dongara No. 1	24/2/64	26/3/64	....	....	133·5	....	7·9	....	....	2 660 26 100	....
Pilot Bore No.—											
1	10/2/65	10/2/65	....	....	87·8	....	42·1	....	....	....	....
2	22/2/65	8/3/65	....	....	81·1	....	34·1	....	....	....	....
3	12/3/65	15/3/65	....	....	87·2	....	40·2	....	....	....	....
4	16/3/65	25/3/65	....	....	83·5	....	34·8	....	....	....	....
5	31/3/65	3/4/65	....	....	73·5	....	26·5	....	....	....	....
Allanooka Production No.—											
1	27/8/65	26/9/65	....	....	59·5	49·5 – 59·5	12·7	2 236	....	560	....
2	1/10/65	....	....	....	83·8	57·5 – 67·4	35·2	2 261	....	620	....
3	24/3/66	....	....	....	125·0	45·35– 55·2	28·2	2 182	....	430	....
4	....	11/2/66	....	....	46·9	37·19– 47·1	7·7	2 236	....	670	....
5	20/1/67	....	....	....	53·4	38·97– 48·87	12·3	2 199	....	....	....
5A*	18/10/66	4/12/66	....	....	56·4	46·73– 56·65	3·3	1 762	....	....	....
6	6/4/67	....	....	....	120·7	76·14– 86·05	57·3	975	....	1 150	....
7	27/6/67	....	....	....	64·6	54·72– 64·60	26·7	2 317	....	500	....
8	24/7/67	19/8/67	....	....	59·5	48·17– 58·07	20·5	2 306	....	570	....
9	25/11/68	....	....	....	64·3	53·37– 63·10	26·3	2 290	....	750	....
10	24/1/69	....	....	....	67·7	53·09– 62·80	28·6	2 191	....	520	....
11	2/9/69	....	....	....	103·7	92·76–102·40	48·8	2 313	....	380	....
12	29/10/69	....	....	....	100·6	87·27– 96·95	51·8	2 191	....	360	....
13*	5/12/69	20/12/69	....	....	94·5	....	....	....	....	....	....
14	27/1/70	16/2/70	....	....	100·6	82·03– 91·76	56·4	2 191	....	660	....
Allanooka—											
1/73	27/4/73	....	....	....	129·4	119·71–129·23	81·07	2 191	21·9	1 210	1 030
2/73	18/6/73	....	....	....	126·5	117·04–126·49	70·42	2 191	7·8	1 480	1 230
3/73	12/7/73	....	....	....	92·2	81·53– 90·98	36·89	2 191	11·2	2 080	1 680
1/74	7/9/74	19/9/74	82·06	....	286	120·4 –131·3	37·18	1 495	20·1	940	780
2/74	3/10/74	8/10/74	87·39	....	349	208·22–219·00	37·03	2 138	32·6	1 100	900
3/74	25/10/74	30/10/74	86·77	....	282	70·58– 80·0	37·18	2 793	11·6	740	585
4/74	–/11/74	12/11/74	88·94	....	197	96·25–110·14	39·3	2 793	18·9	790	635
Irwin View—											
1/74 (E)	28/11/74	4/12/74	169·58	169·94	240	193·88–200·00	77·46	No test	....	....	....
1/75 (F)	10/2/75	13/2/75	114·629	115·079	211	67·52– 75·33; 97·83–110·33	52·55	1 156	5·6	420	348
2/75 (A)	31/10/75	10/11/75	149·010	149·290	221	187·96–195·95	68·30	895	17·6	470	300
3/75 (A)*	16/11/75	?3/12/75	....	....	60	....	....	....	....	....	....
4/75 (B)	4/12/75	8/12/75	101·608	101·936	157	125·8 –132·0	57·91	1 626	16·1	550	280
Dongara—											
1/75 (V)	12/10/75	14/10/75	33·18	33·84	152·5	64·47– 73·7	20·47	1 636	9·1	1 050	760
2/75 (W)	27/10/75	30/10/75	33·49	....	137·5	51·07– 54·10; 84·65– 93·89	18·84	2 793	9·0	1 010	730
Allanooka—											
1/76 (A)	25/8/76	31/8/76	103·42	104·19	269	74·08– 80·30	61·80	1 636	4·2	760	561
2/76 (B)	9/9/76	14/9/76	86·33	86·94	208	139·94–149·30	43·20	1 636	38·0	1 080	900
3/76 (C)	29/9/76	30/9/76	85·38	85·98	220	124·88–134·00	40·50	1 636	20·5	not an-alysed	....
4/76 (D)	7/10/76	13/10/76	93·78	94·33	214	148·94–158·30	46·60	1 636	32·2	860	680
5/76 (E)	6/12/76	10/12/76	100·39	100·98	239	126·65–139·50	49·70	2 188	10·5	1 260	988
Irwin View—											
1/76 (J)	28/1/76	12/2/76	180·904	181·254	253	121·2 –129·0	69·4	1 156	6·2	410	353
2/76 (I)	23/2/76	27/2/76	145·713	146·014	207	50·3 – 55·0; 101·3 –106·0	57·9	1 156	5·1	480	407
3/76 (H)	11/3/76	18/3/76	112·326	112·651	306	115·06–119·73; 135·06–139·73	32·3	1 156	8·5	500	396
4/76 (C)	29/3/76	31/3/76	87·69	88·36	208	99·27–105·48; 131·99–138·18	45·7	1 156	2·8	....	....
5/76 (D)	8/4/76	13/4/76	85·487	85·779	222	117·3 –122·0; 141·3 –146·0	44·99	1 156	5·1	....	....
6/76 (G)	30/4/76	5/5/76	173·090	173·395	239·5	103·89–109·00	86·50	....	....	not an-alysed	....
Allanooka—											
1/77 (G)	26/1/77	1/3/77	79·16	....	221	109·1 –115·3; 136·18–142·4	36·8	2 032	40·9	990	790
2/77 (H)	14/2/77	18/2/77	88·67	....	233	100·07–106·30; 115·08–161·30	46·80	2 239	11·5	1 100	900
3/77 (J)	1/8/77	5/8/77	97·00	....	227	129·9 –142·3	54·00	2 190	....	990	780
4/77 (K)	16/8/77	22/8/77	100·69	....	207	118·74–125·00; 137·74–144·0	51·00	1 637	6·5	530	401
5/77 (L)	30/8/77	2/9/77	71·91	72·28	201	121·86–134·30	43·0	1 526	38·5	1 210	1 010
Irwin View—											
1/77 (K)	28/2/77	4/3/77	84·378	84·698	221	81·58– 87·78; 100·08–106·28	65·30	1 145	6·0	550	336
2/77 (M)	14/3/77	18/3/77	....	145·109	208	196·06–205·30	46·80	982	....	540	284
3/77 (S)	29/3/77	1/4/77	57·746	58·156	220	92·33–101·63	11·50	1 145	23·0	490	320
4/77 (R)	6/4/77	18/4/77	52·004	52·346	203	40·46– 50·70	21·30	1 625	5·0	1 370	1 040
5/77 (T)	22/4/77	28/4/77	....	88·004	214	57·06– 66·30	10·40	1 625	18·5	460	345
6/77 (W)	5/8/77	12/5/77	228·518	228·85	270	216·57–225·81	118·25	Bailed	....	630	402
7/77 (O)	20/5/77	25/5/77	140·241	140·538	195	138·51–147·75	92·48	245	15·9	470	272
8/77 (P)	1/6/77	3/6/77	147·223	147·584	229·9	85·12– 94·30	54·20	1 244	15·2	560	404
9/77 (L)	13/6/77	15/6/77	36·809	37·088	215	39·21– 48·30	20·75	1 625	....	1 330	979
10/77 (N)	21/6/77	23/6/77	47·679	48·009	208	45·18– 54·30	30·70	1 625	4·8	670	432
11/77 (Q)	29/6/77	30/6/77	....	110·567	212	80·97– 90·30	29·85	1 244	9·7	400	297
12/77 (U)	8/7/77	13/7/77	177·16	176·69	215	111·12–120·39	88·00	840	....	520	415
13/77 (V)	20/7/77	22/7/77	180·73	181·25	202·6	111·22–114·30; 135·22–138·33; 141·22–144·30	65·5	1 985	5·0	360	250
Mount Hill—											
1/77	14/9/77	21/9/77	31·51	31·77	201	38·16– 44·30	13·0	1 363	....	540	452
2/77	28/9/77	3/10/77	30·33	31·13	183	32·16– 38·30	15·5	130	....	1 310	979

* Abandoned   ns—Natural surface   bns—Below natural surface
AHD—Australian height datum   tc—Top of casing   btc—Below top of casing

LANDFORMS

Victoria Plateau

The Victoria Plateau (Playford and others, 1976) is a relatively flat sandplain, 200 to 300 m above sea level, bordered by steep escarpments (breakaways). The sandplain is composed of a gently undulating sand-sheet, about 6 m thick, overlying laterite. It is probably of Miocene age.

Arrowsmith Region

The Arrowsmith Region (Playford and others, 1976) is a deeply dissected part of the Victoria Plateau, 100 to 200 m above sea level, with remnants of the Victoria Plateau preserved as mesas and buttes. The present drainages are underfit and dissection must have occurred during more humid conditions, possibly during the Pleistocene. The boundary with the Victoria

TABLE 3. STANDARD CHEMICAL ANALYSES FROM ALLANOOKA PROJECT BORES (Milligrams per litre)

Name	Depth (m)	GCL No.	pH	Ca	Mg	Na	K	HCO_3	SO_4	Cl	NO_3	SiO_2	Fe	TDS Cond.	TDS Evap.	Formation
Allanooka No. 1	13·1– 60·9	5349/62	6·8	6	10	181	8	71	38	257	<1	....	<0·1	571	540	Yarragadee Fm
Allanooka No. 1	13·1– 93·9	10088/62	6·8	5	11	215	9	76	58	293	<1	....	0·1	....	600	Yarragadee Fm
Allanooka No. 2	96·0–115·9	10091/62	6·8	10	9	224	14	68	51	396	<1	....	0·2	....	690	Cockleshell Gully Fm
Allanooka No. 2	178·4–196·6	58/63	7·4	207	135	1 810	71	155	546	3 120	2	7	0·1	....	6 030	Proterozoic basement
Allanooka No. 3	24·4– 33·5	10090/62	7·6	117	133	655	39	305	159	1 300	80	....	0·1	....	2 650	Kwinana Group
Allanooka No. 4	275·3–282·9	6923/63	7·6	32	26	426	27	224	133	586	....	....	0·2	1 400	1 380	Cockleshell Gully Fm
Allanooka No. 5	50·3– 79·3	3234/63	6·6	11	27	208	9	46	50	363	<1	36	0·9	....	730	Yarragadee Fm
Allanooka No. 5	195·1	4875/63	7·0	34	54	608	24	136	171	971	<1	....	0·2	2 050	1 950	Yarragadee Fm
Allanooka No. 5	50·6–140·2	6327/63	6·3	14	26	206	9	54	45	362	....	....	<0·1	730	770	Yarragadee Fm
Allanooka No. 5	50·6–140·2	6329/63	6·8	16	33	301	14	73	82	499	....	....	0·1	1 010	1 040	Yarragadee Fm
Allanooka No. 6	36·9	7111/63	7·8	38	17	329	17	208	61	473	....	....	0·6	1 120	1 060	Yarragadee Fm
Allanooka No. 7	36·6	2644/64	7·3	36	26	194	13	131	55	333	....	....	0·4	830	740	Yarragadee Fm
Allanooka No. 8	128·7	9987/63	6·6	100	159	1 360	74	101	485	2 390	....	....	<0·1	4 690	4 690	Cockleshell Gully Fm
Allanooka No. 9	79·3	2645/64	7·4	16	13	92	2	58	16	164	<1	....	0·2	390	340	Yarragadee Fm
Allanooka No. 10	39·6	863/64	7·3	16	17	189	9	70	41	307	....	....	1·2	710	620	Yarragadee Fm
Allanooka No. 11	39·6	2647/64	7·0	3	5	180	7	49	19	262	<1	....	0·4	600	520	Yarragadee Fm
Allanooka No. 12	29·0– 39·3	2646/64	6·8	23	33	346	18	73	50	607	<1	....	0·3	1 270	1 100	Yarragadee Fm
Allanooka No. 13	41·5	897/64	6·6	54	54	286	15	55	56	634	....	....	<0·1	1 320	1 140	Yarragadee Fm
Allanooka No. 14	91·5	9988/63	6·8	10	17	207	8	82	40	317	....	....	0·1	760	670	Yarragadee Fm
Allanooka No. 15	152·4	2648/64	7·1	7	12	144	11	113	21	198	<1	....	0·1	520	440	Yarragadee Fm
Allanooka No. 16	85·3– 91·5	9986/63	7·5	7	12	203	7	113	36	274	....	....	<0·1	710	620	Yarragadee Fm
Allanooka No. 17	140·2–152·4	2649/64	7·0	8	14	259	12	128	35	296	120	....	0·6	860	780	Yarragadee Fm
Allanooka No. 18	76·2	3320/64	7·0	35	87	869	42	128	243	1 440	<1	....	<0·1	2 800	2 700	Yarragadee Fm
L. Allanooka	....	8426/63	7·2	10	10	157	12	131	21	208	....	....	....	560	550	Surface 21/8/63

Plateau is generally a steep breakaway up to 10 m high which, in some areas, may have weathered sedimentary rocks exposed beneath. Locally, as in Hunt Gully, some large laterite-capped areas that are detached from the Victoria Plateau may be landslips.

Lake Allanooka occurs at the boundary of the Arrowsmith Region and Swan Coastal Plain. It is a circular lake about 0·2 km^2 in area, occupying a shallow topographic depression about 95 m AHD. The lake is a discharge site for runoff from Banksia and Hunt Gullies, and was also the site for groundwater discharge from Ngarlingue Spring prior to discharge ceasing as a result of pumping from the Allanooka Scheme. The outlet from the lake is Allanooka Creek (Fig. 2) which flows for about 11 km before dissipating on the coastal plain (Allen, 1965).

The lake fills from direct rainfall and runoff during the winter, and when full is about 0·3 m deep and contains about 3 600 m^3 of water. It is underlain by about 2 m of kaolinitic clay which is presently being mined for brickmaking.

The lake is at the head of an extensive relatively flat topographic depression (Fig. 2), which extends onto the coastal plain. The depression appears to have been formed by runoff during and after the formation of the coastal plain, and the topography suggests that the depression may have been the site of a large temporary lake, of which Lake Allanooka is the remains.

Swan Coastal Plain

The Swan Coastal Plain (Playford and others, 1976) abuts against the western edge of the Arrowsmith Region. The boundary coincides with a fairly abrupt change in slope, marking the position of the Gingin Scarp, a former Quaternary or late Tertiary shoreline.

The coastal plain consists of a conspicuous belt of modern dunes along the coast abutting and overlying two older calcreted dune complexes which rise to an elevation of about 50 m. The calcreted dunes form a distinctive irregular topography, often with limestone exposed on the crests of the hills. Small fertile flood plains are associated with the major rivers, and small interdunal depressions are the sites of temporary lakes after flooding by the major rivers (Fig. 3). The plain is of ?Pliocene to Holocene age.

DRAINAGES

Greenough River

The Greenough River is a major river which reaches the sea, and which forms the northern boundary of the Allanooka area. It is intermittent, usually flowing during the winter and persisting during the summer as a series of partially interconnected pools upstream of Ellen Crossing. Flows are brackish and have an average salinity of 3 610 mg/L TDS (PWD data). This appears to be a natural condition of the river as its salinity was commented on by Grey (1841) prior to European settlement.

Irwin River

The Irwin River is a major river which reaches the sea, and which forms the southern boundary of the Allanooka area. It is an intermittent river with the major flows usually occurring during the winter months. The main catchment area is in salt-prone country to the east of the Allanooka area. Consequently, flows are brackish and have an average salinity of 3 480 mg/L TDS (PWD data).

Where the river traverses the Arrowsmith Region there is a small contribution of fresh groundwater from minor spring-fed tributaries, such as Springy Creek, and at the sites of some semi-permanent pools in the river bed.

GEOLOGY

SETTING

The Allanooka area (Fig. 3) is in the northern part of the Perth Basin. It is immediately south of the Northampton Block, within the Dandaragan Trough and Dongara Saddle structural subdivisions of the basin (Jones and Pearson, 1972; Playford and others, 1976).

STRATIGRAPHY

The stratigraphic succession consists of Phanerozoic sedimentary rocks resting on Precambrian crystalline basement rocks of the Northampton Block. Sedimentation has been controlled by the structurally high Northampton Block, and by subsidence in the Dandaragan Trough. Consequently, Mesozoic sediments on the Northampton Block form a thin shelf sequence, about 60 m thick (Playford, 1959), which thicken rapidly southeastward through the Allanooka area to about 4 000 m in the axis of the Dandaragan Trough.

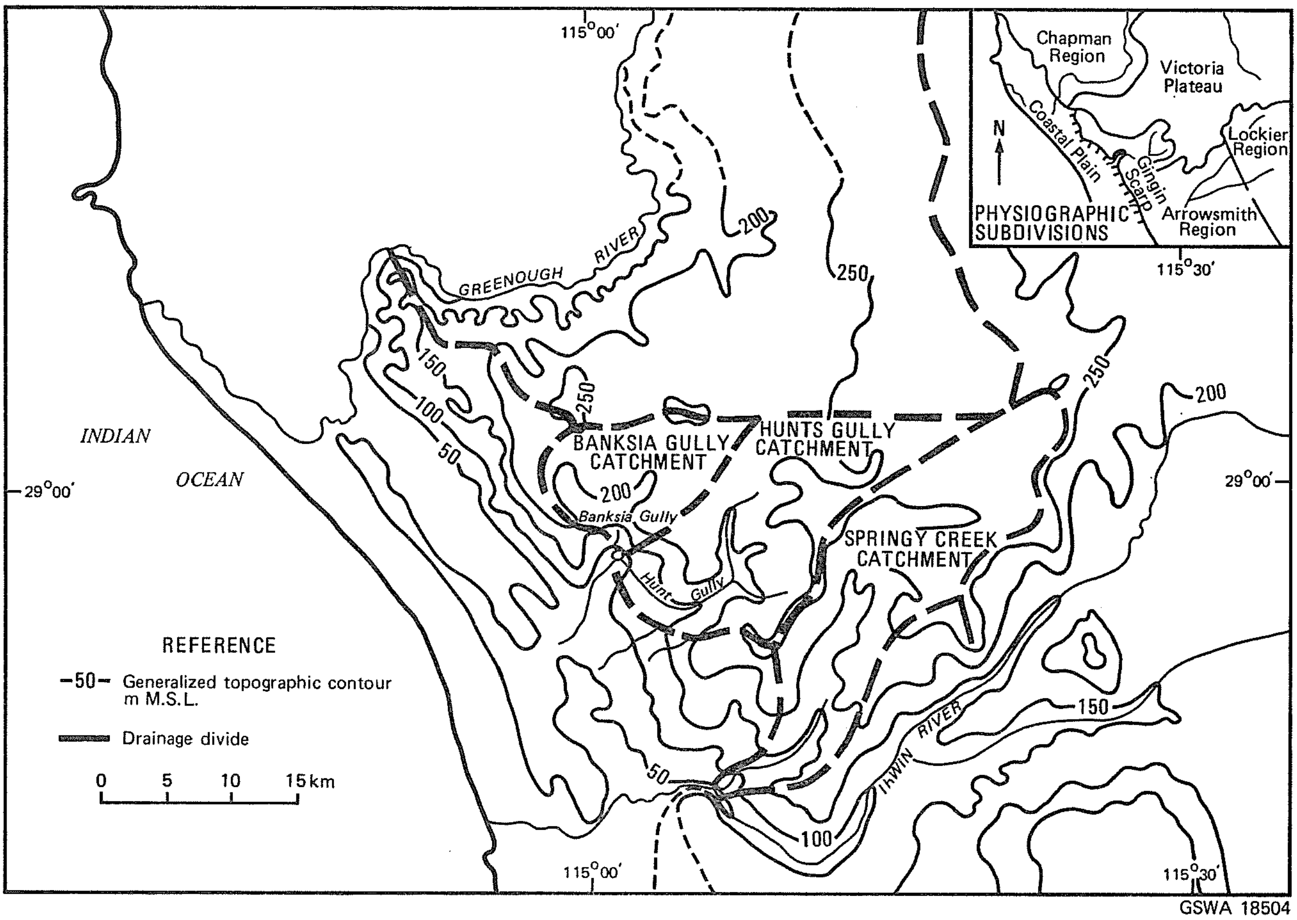

Figure 2 Generalized topography and drainage basins.

TABLE 4. MESOZOIC AND CAINOZOIC STRATIGRAPHIC SEQUENCE IN THE ALLANOOKA AREA

Age	Group/Formation	Maximum Thickness (m)	Lithology/Remarks
CAINOZOIC Quaternary	Kwinana Group	150	Calcarenite, alluvium, clay, calcareous sand, limestone, minor gravel. Major unconfined aquifer containing brackish water.
	UNCONFORMITY		
Tertiary	Laterite	20	?Eolian sand and pisolitic laterite.
	NONCONFORMITY		
MESOZOIC ?Cretaceous-Jurassic	Yarragadee Formation....	1 000	Interbedded sandstone, siltstone and shale. Major aquifer containing fresh and brackish water.
Jurassic	Cadda Formation	400	Shale, siltstone, minor limestone. Confining bed.
Jurassic	Cockleshell Gully Formation	1 200	Sandstone, siltstone, shale, minor coal. Aquifer containing brackish and minor fresh water.
	UNCONFORMITY		
Triassic	Kockatea Shale	?100	Shale, minor silstone, rare sandstone. Confining bed.
PALAEOZOIC Permian	Undifferentiated	2 500	Nonmarine, minor marine, and glacigene formations.
	UNCONFORMITY		
PROTEROZOIC	Undifferentiated	....	Granulite, granite, dolerite.

In the Allanooka area the formations containing or affecting the occurrence of potable groundwater resources are of Mesozoic to Holocene age. The formations, together with a brief description of their lithology, are given in Table 4. The lithology of the main aquifers is described in detail in the section on hydrogeology, but for detailed descriptions of the other formations reference should be made to Playford and others (1976).

STRUCTURE

The geological structure of the Allanooka area (Fig. 4) is relatively well known as a result of intensive seismic exploration following the 1963 discovery, and subsequent exploitation, of gas and a minor amount of oil from Yardarino, near Dongara.

In the Allanooka area the Mesozoic sedimentary rocks thicken and have a regional southeasterly dip toward the axis of the Dandaragan Trough. This general pattern is

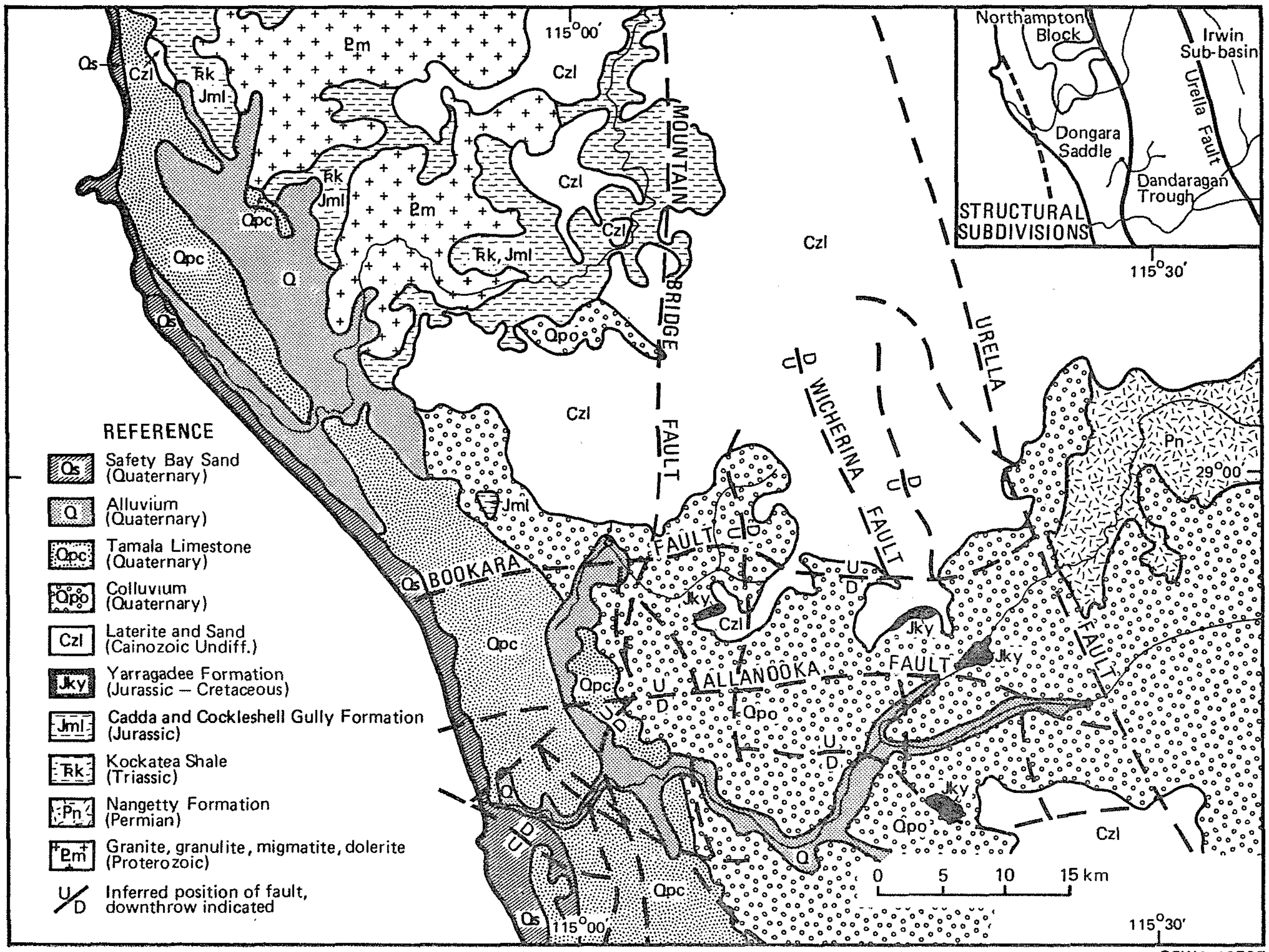

Figure 3 Generalized geology.

disrupted by a set of large north-trending normal faults parallel to the Urella Fault, and by a younger set of east-west normal faults. The result is that the Mesozoic rocks are faulted into a complex series of rectangular fault blocks.

The approximate position of the major faults, based on data supplied by West Australian Petroleum Pty Ltd, are given in Figure 3. In addition, there are numerous minor faults which are not shown. Allen (1965) inferred the location of several faults in the Allanooka borefield, and suggested that the roughly rectilinear drainage pattern may be fault controlled. However, the locations and trends of these and other minor faults cannot be established by drilling because of the difficulty of correlating sections of the Yarragadee Formation.

The Kwinana Group, which overlies the Yarragadee Formation on the coastal plain, is flat lying and not known to be faulted. The base of the group dips westward from about 90 m above sea level to 30 m below sea level. Some deep infilled channels incised into the Yarragadee Formation may occur near where the major drainages meet the coastal plain (Allen, 1965).

HYDROGEOLOGY

AQUIFERS

All of the Mesozoic and Cainozoic formations in the Allanooka area may locally contain groundwater, but major groundwater flow systems only occur in the Kwinana Group, and the Yarragadee and Cockleshell Gully Formations.

Kwinana Group

Lithology: The Kwinana Group (Playford and others, 1976) consists of the surficial deposits on the coastal plain, which rest unconformably on the Yarragadee Formation. The group is up to 150 m thick, and along the coast extends to a depth of about 30 m below sea level. The upper part of the group consists of eolian coastal dunes (calcarenite), calcreted dunes of sandy calcarenite, and red alluvial silt, clay and gravel associated with the major drainages. These overlie fossiliferous shallow-water marine deposits consisting of medium-to-coarse-grained calcareous sand, limestone and clay, which locally contain concentrations of heavy minerals. The sediments are Pliocene to Holocene in age.

Flow system: The Kwinana Group contains an unconfined groundwater flow system in lateral and vertical hydraulic continuity with the flow system in the Yarragadee Formation. The Greenough and Irwin Rivers (except in their tidal estuaries) form hydraulic recharge boundaries to the system, and the sea and tidal estuaries of the rivers form a discharge boundary.

The configuration of the water table is not well known, but water-table contours based on a few bore records, and elevation data interpolated from topographic maps, are given in Figure 5. The water table slopes downward to the southwest, except near Irwin River where a ridge in the water table is sustained by recharge from the river. There is a low groundwater gradient across the coastal plain, except along the eastern edge where there is a steep gradient near the contact with the Yarragadee Formation mainly resulting from the difference in transmissivity between the Kwinana Group and the Yarragadee Formation.

Recharge: Recharge to the Kwinana Group is by upward leakage from the Yarragadee Formation, and by flow losses from the Greenough and Irwin Rivers, and from streams draining the Arrowsmith Region. Some recharge by direct infiltration from rainfall also occurs, but this is believed to be small because the water table is about 50 m deep over large areas, and because of the extent of clayey alluvial plains where recharge is minimal. Data are insufficient to determine the amount of recharge from each source. However, from observed increases in salinity with depth (see section on quality), and the large upward head potential between the Yarragadee Formation and the Kwinana Group, leakage from the Yarragadee Formation is considered to be the major source of recharge.

Storage: The shallow-water marine sand comprises most of the water-bearing part of the Kwinana Group. Assuming that this has a specific yield of 0·30 and an average saturated

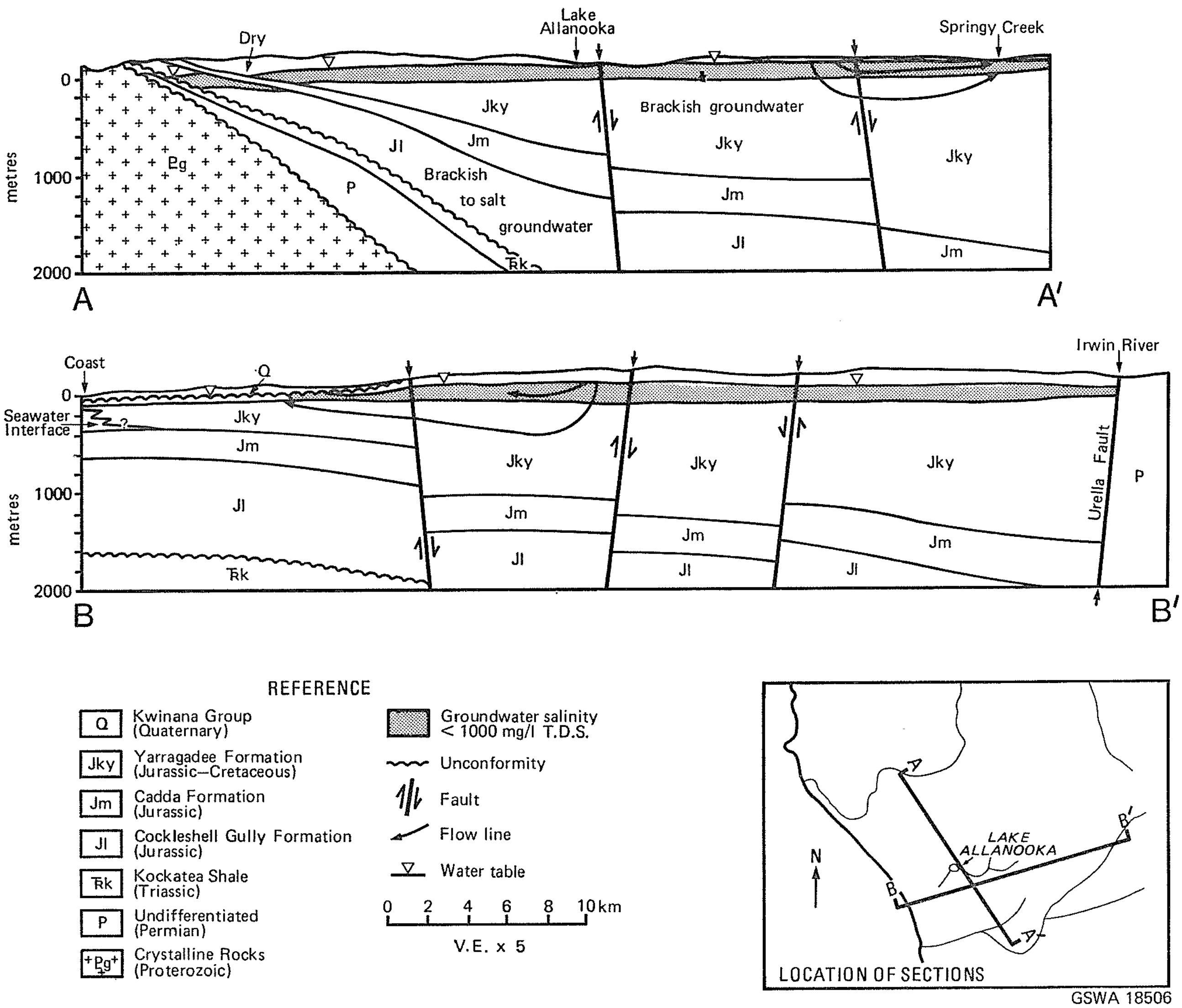

Figure 4 Diagrammatic hydrogeological cross sections.

thickness of 20 m, then the volume of groundwater in storage beneath the coastal plain between the Greenough and Irwin Rivers (375 km²) is:

$$0{\cdot}3 \times 20 \text{ m} \times 375 \text{ km}^2 = 2\,250 \times 10^6 \text{ m}^3.$$

Discharge: Discharge from the flow system takes place along the coastline and into the estuaries of the Greenough and Irwin Rivers. Outflow can be calculated from the form of the Darcy equation:

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

where Q = outflow (m³/day),
T = transmissivity (saturated aquifer thickness m x hydraulic conductivity, m/day),
I = hydraulic gradient (dimensionless),
and L = width of flow section (m)

Assuming a saturated aquifer thickness of 25 m, and a hydraulic conductivity of 30 m/day, and using a measured hydraulic gradient of 0·002, and a flow section of 35 km (C–D in Fig. 5), then the outflow from the Kwinana Group, between the Greenough River and Irwin River, is:

$$25 \times 30 \times 0{\cdot}002 \times 35\,000 = 52\,500 \text{ m}^3\text{/day},$$
$$\approx 20 \times 10^6 \text{ m}^3\text{/year}.$$

Quality: Groundwater in the Kwinana Group generally has a salinity of 2 000 to 3 000 mg/L TDS. In areas of local recharge such as interdunal swales and deep depressions in the limestones ridges, and where some of the small drainages from the Arrowsmith Region meet the coastal plain, groundwater with a salinity ranging from 250 to 1 000 mg/L TDS may be obtained in the upper part of the flow system. Groundwater with a salinity of between 6 500 and 19 000 mg/L is known from the base of the flow system, probably near the seawater interface, along the coast (Allen, 1963). In general the salinity of the groundwater increases with depth and with distance westward across the coastal plain.

Along the eastern edge of the coastal plain there is a relatively abrupt change in salinity from fresh groundwater in the contiguous Yarragadee Formation to brackish groundwater in the Kwinana Group. Evapotranspiration is not likely to cause the increase in salinity because of the depth to the water table. The increased salinity of groundwater in the Kwinana Group may result from flushing of seawater entrapped in shale and siltstone when the sea extended to the Gingin Scarp.

Local occurrences of fresh groundwater occur in the coastal dunes as a thin layer of fresh water resting on brackish water. However, only small supplies are available and the salinity may vary depending on the season and pumping rate. In addition, the groundwater is hard and may contain hydrogen sulphide.

Development: Several hundred bores and wells are used to abstract groundwater in the Kwinana Group for stock, and rarely for domestic supplies. Generally the salinity of the groundwater has prevented large-scale development of the groundwater resources. An exception to this was the former Port Denison water supply, where 16 000 m³/year of variable quality groundwater were abstracted by a series of spears in an interdunal depression (Allen, 1963). The supply was abandoned when water from the Allanooka Scheme became available.

Should large volumes of brackish groundwater be required in the future, the Kwinana Group in the Allanooka area contains a major, easily developed resource.

Yarragadee Formation

Lithology: The Yarragadee Formation consists of interbedded sandstone, siltstone, and shale. The beds of sandstone are discontinuous and range from 2 to 30 m in thickness, with an average of about 10 m. They are cross-bedded and consist of medium- to very coarse-grained, subangular, poorly sorted

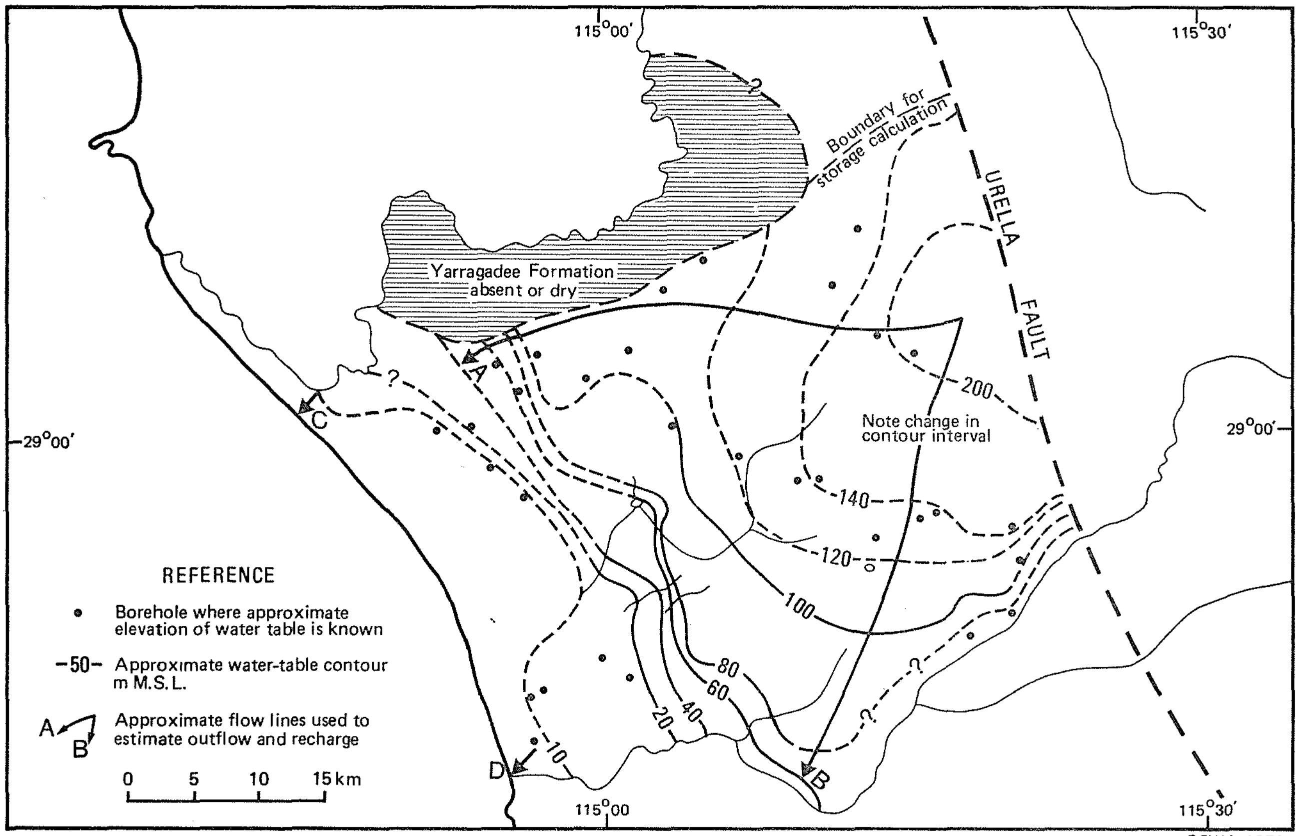

Figure 5 Approximate contours on regional water table.

to well-sorted sand. The sandstones are feldspathic, tending to arkose, and contain thin beds of conglomerate, and layers and nodules of pyrite. The siltstones and shales are usually laminated, and frequently contain mica, pyrite, and carbonaceous material. The upper part of the formation tends to be composed of alternating thin-bedded units, whereas at the base the beds are thicker.

The Yarragadee Formation is oxidized by weathering from the surface to some distance below the present water table. This zone is white, cream, red or yellow-brown; the feldspar is kaolinized, and the pyrite is altered to ferruginous layers or ferruginous nodules. Below the oxidized section the sandstones are grey and the siltstones and shales are dark grey or black. Allen (1965) has suggested that the oxidized zone extending below the water table may indicate that the water table has been lower in the past.

Beds of sandstone in the formation have porosities, measured from geophysical logs, ranging from 0·33% to 0·40%, with an average of 0·36%, from 14 determinations (WAPET, written communication, 5.4.65.) The specific yield for the sandstone has been estimated by Forth (1971) to be 0·26%, and the hydraulic conductivity to be 5 m/day (Forth, 1971) to 17 m/day (Forth, 1973). A value of 10 m/day is adopted for subsequent calculations.

The formation is between 20 and 1 000 m thick. It conformably overlies the Cadda Formation and is unconformably overlain by the Kwinana Group. On the Victoria Plateau and parts of the Arrowsmith Region a laterite profile is developed on the surface of the formation.

In the Allanooka area the Yarragadee Formation is of Middle Jurassic to ?Lower Cretaceous age. Further south in the Dandaragan Trough a tripartite division of the formation is possible into "upper" Yarragadee Formation, Otorowiri Siltstone Member, and "lower" Yarragadee Formation (Barnett, 1977; Commander, 1978). This subdivision has been recognized as far north as Mingenew, but the Otorowiri Siltstone Member was not identified in the Allanooka area and subdivision is not possible.

The formation was deposited mainly in a nonmarine fluviatile environment, hence the variable and discontinuous nature of its component beds.

Flow system: The Yarragadee Formation is a multilayer aquifer containing a regional groundwater flow system. Its boundaries are the Urella Fault in the east; the outcrop of the base of the formation south of the Greenough River; a groundwater divide (not shown) to the south of the Allanooka area (Commander, 1978); and the hydraulic discharge boundary formed by the sea. The flow system is isolated from the one in the Cockleshell Gully Formation by the Cadda Formation (confining bed), except where local interconnection may occur across faults. It is in lateral and vertical hydraulic connection with the Kwinana Group on the coastal plain (Fig. 4).

The upper part of the flow system forms a water table varying from about 15 to 120 m below the surface. At depth beneath the water table, the groundwater is confined to varying degrees because of the layered nature of the formation. Downward head gradients occur on the Victoria Plateau, as in AP4 (Allen, 1965), and upward head gradients occur along the edge of the Arrowsmith Region (AP1) and on the coastal plain, as in the Dongara and Yardarino bores (Maitland, 1913).

Faults may affect the flow system. Gouge or silicification along the fault planes may reduce hydraulic conductivity, and sandstones and siltstones may be brought into juxtaposition, impeding groundwater flow. The actual importance of faulting is uncertain. Allen (1965) considered that the configuration of the water table near Lake Allanooka was the result of faulting. Forth (1972) accepted this explanation, and Ventriss and Parsons (1978), studying hydrographs from the Allanooka Scheme, considered that faults forming boundary conditions were probably responsible for the limited area affected by the production bores. It now appears that the steep groundwater gradients at the edge of the Arrowsmith Region may result from upward flow, and the limited extent of drawdown caused by abstraction is mainly the result of close spacing between the pumping bores. Nevertheless, the fault blocks probably behave as groundwater compartments in which groundwater flow is affected at the fault boundaries.

A regional water-table map is given in Figure 5 and a more detailed water-table map for the area southeast of the Allanooka Scheme in Figure 6. Figure 5 is based on nonsynoptic water levels and bores for which the locations and elevations are approximate.

Figure 5 shows that the water table forms a regional mound reaching an elevation of over 200 m AHD beneath the highest part of the Victoria Plateau. The groundwater mound is relatively flat, with steeper gradients where upward groundwater discharge takes place on the eastern edge of the coastal plain and along the Irwin River.

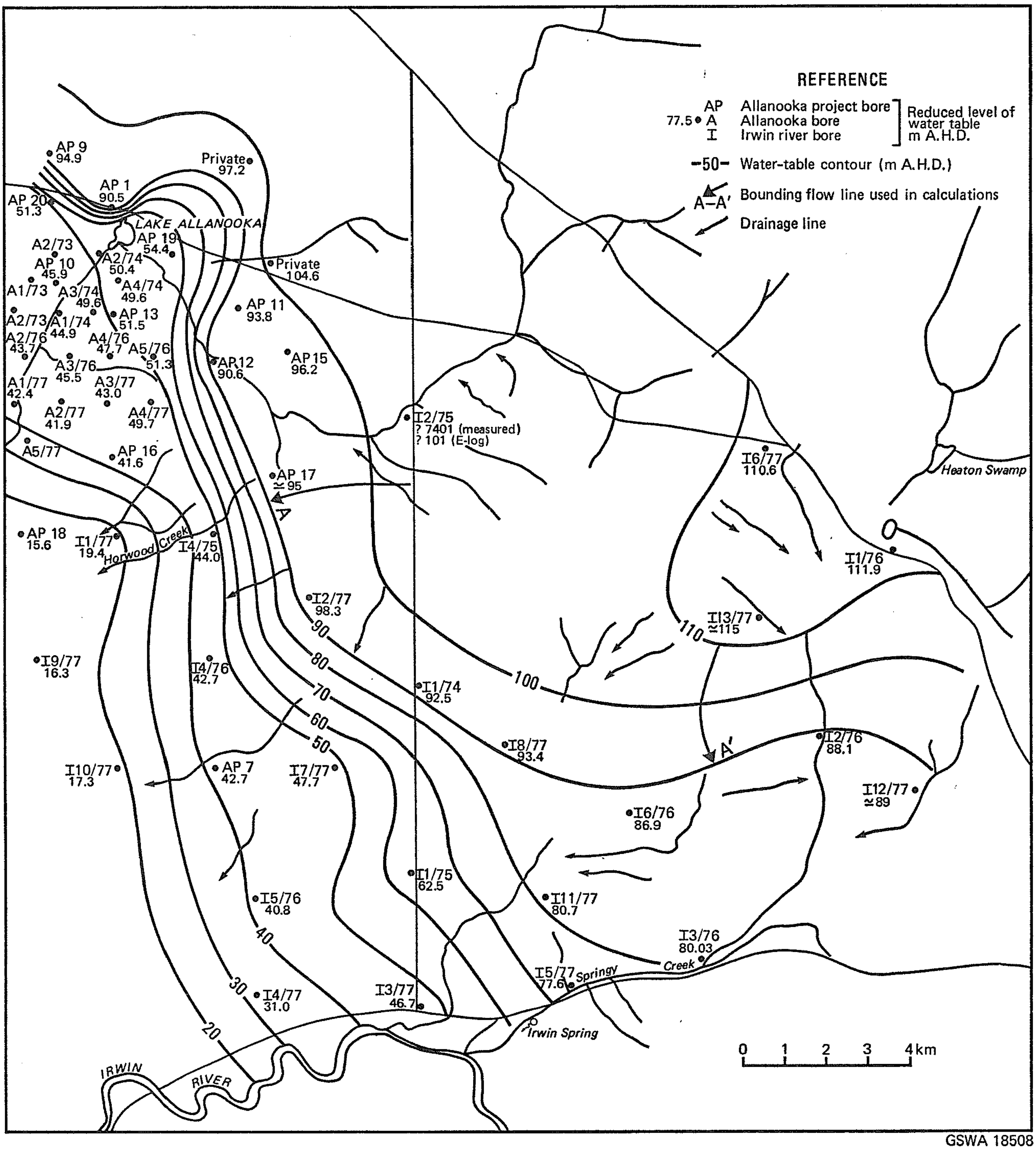

Figure 6 Water-table contours (nonsynoptic) in vicinity of Allanooka Scheme.

Recharge: Immediately south of the Greenough River the base of the Yarragadee Formation is at a higher elevation than the river bed, thus preventing recharge from that source. In the same area for about 2 km downdip it was observed in AP6, AP8 and Levetts bore (Allen, 1965) that the formation was unsaturated and a water table did not occur (Fig. 5).

The Victoria Plateau is overlain by a thick sand sheet which facilitates rainfall recharge. However, the water table is generally more than 100 m below the surface, and this, together with the impedence of recharge by interbedded siltstone and shale, results in the development of numerous perched water tables above the regional water table. The perched aquifers intercept much of the recharge which is discharged from springs and soaks around the edge of the Victoria Plateau, and only a small proportion eventually reaches the regional water table.

In the Arrowsmith Region the sand overlying the Yarragadee Formation is relatively thin, with the result that sufficient runoff occurs to sustain stream flow, as in Hunts Gully. An exception is Banksia Gully, where stream flow does not occur, possibly because it contains a thick valley-fill of sand.

Hydrographs of observation bores in the Allanooka borefield, redrawn from Ventriss and Parsons (1978), are given in Figure 7. Those bores on the northern side of Lake Allanooka show a gradual downward trend resulting from pumping, whereas those to the south show no effect. Bores PW1 and A1 show marked seasonal fluctuations. They are in sand, with the water table 15 to 20 m below surface. The other bores, due to depth to the water table or presence of interbedded siltstone or shale, do not show any seasonal fluctuations. It is probable that the water table beneath the Victoria Plateau and most of the Arrowsmith Region shows a similar lack of response.

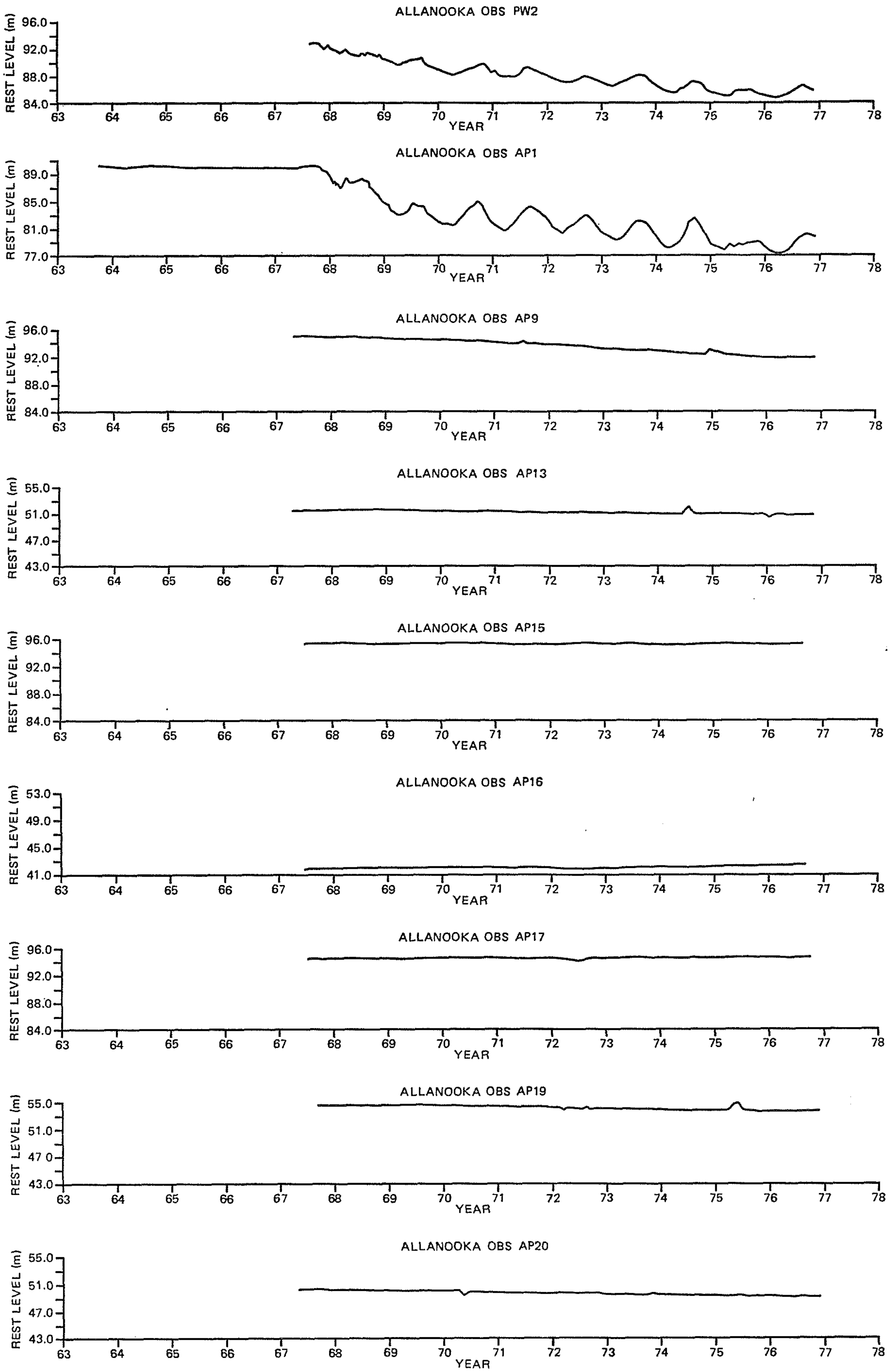

Figure 7 Selected hydrographs of observation bores in the Allanooka borefield (after Ventriss and Parsons, 1978).

Hence, it is inferred that recharge reaching the main flow system is relatively small and that it may only occur at a few favourable localities. It is possible that the present flow system is not in dynamic equilibrium with the prevailing climatic conditions.

Average throughflow normally equates to annual recharge, but in the Allanooka area reliable data on water-table contours, thickness of potable groundwater, and proportion of sand are only reliably known for the area to the southeast of the Allanooka Scheme (Fig. 6). In this area the throughflow past the 90 m water-table contour through the section A–A (14 km) may be derived from equation (1). The water table has an average gradient of 0·005 43, and the thickness of aquifer containing potable water is 100 m, of which 40% is sand with an assumed hydraulic conductivity of 10 m/day. Substituting derived and assumed values in equation (1) and solving:

$$Q = 10 \times 100 \times 0{\cdot}40 \times 0{\cdot}005\,43 \times 14\,000$$
$$= 30\,435 \text{ m}^3/\text{day}$$
$$= 11{\cdot}1 \times 10^6 \text{ m}^3/\text{year}$$
$$\approx 0{\cdot}8 \times 10^6 \text{ m}^3/\text{year/km}.$$

If the average annual outflow per kilometre is assumed to be $0{\cdot}8 \times 10^6$ m^3/year then the outflow from the whole Allanooka area past the 60-m contour (Fig. 5) between A-B (47 km) is:

$$47 \times 0{\cdot}8 \times 10^6 = 37{\cdot}6 \times 10^6 \text{ m}^3/\text{year}.$$

The area contributing the throughflow is about 735 km^2; therefore, the recharge expressed as a percentage of average annual rainfall (477 mm) is:

$$\frac{37{\cdot}6 \times 10^6}{735 \times 10^6} \times \frac{1}{0{\cdot}477} \times \frac{100}{1} = 10{\cdot}7\%$$

This estimate appears too large.

An alternative estimate of recharge may be made from the ratio of the chloride in rainfall to the chloride in the upper part of the flow system. The average chlorinity of all bores pump tested and found to produce potable groundwater was 268 mg/L from 26 samples (Table 2). The chlorinity of rainfall at Dongara during 1973–74 was 11·3 mg/L (Hingston and Gailitis, 1977). Assuming that the average chlorinity of rainfall in the Allanooka area is 10 mg/L, then the average recharge is:

$$\frac{10}{268} \times \frac{477}{1} = 17{\cdot}8 \text{ mm}$$
$$\approx 3{\cdot}7\% \text{ of average rainfall.}$$

This estimate of recharge may be of the correct magnitude. However, it does not take into account recharge which is intercepted and discharged from the perched aquifers; hence the average annual recharge to the main groundwater body may be 3% or less of the average annual rainfall.

The limited westward extent of potable water in the Yarragadee Formation and Kwinana Group beneath the coastal plain confirms that the recharge and resultant outflow of potable groundwater is relatively small.

Storage and movement: The aquifer system contains predominantly brackish groundwater, but potable groundwater is present in the upper part of the flow system beneath the Victoria Plateau and Arrowsmith Region. This zone of potable groundwater is known to range in thickness from 12 to 144 m below the water table, and to average 90 m. In general the zone is thinnest in the west near the edge of the coastal plain, and tends to be thicker toward the east. Apart from this trend there is no evident pattern to the thickness of the zone, or its relationship to the elevation of the water table, or to sea level.

The proportion of sandstone to siltstone and shale in the upper part of the flow system containing potable groundwater was estimated from geophysical logs. It ranged from 26% to 88%, and averaged 60%. The specific yield of these sandstones from the known abstraction and dewatering in the Allanooka Scheme was estimated by Forth (1971, 1973) to be 0·26.

Potable groundwater extends beneath about 1 550 km^2 of the Victoria Plateau and Arrowsmith Region (Fig. 5). If the zone of potable groundwater has the assumed specific yield, thickness, and proportion of sand, then the volume of potable groundwater in storage is:

$$1\,550 \times 10^6 \times 90 \times 60/100 \times 0{\cdot}26 = 21\,762 \times 10^6 \text{ m}^3$$
$$\approx 20\,000 \times 10^6 \text{ m}^3$$

The general direction of groundwater movement is towards the southwest (Fig. 5). Movement towards Irwin River in the south is also indicated, but it is considered that this probably only involves the upper part of the flow system.

Discharge: Subsurface groundwater discharge takes place from the Yarragadee Formation into the Kwinana Group. The low-salinity groundwater, from the upper part of the flow system, is discharged into the eastern part of the Kwinana Group, and progressively deeper, more saline, parts of the flow system are discharged westward beneath the coastal plain.

Surface discharge from the upper part of the flow system formerly occurred from Ngarlingue Spring near Lake Allanooka, and occurs along the Irwin River and especially its tributary, Springy Creek, where the largest spring (Irwin Spring) discharges about 400 m^3/day of groundwater with a salinity of 450 mg/L TDS.

Numerous springs and soaks which occur around the margin and occasionally on the top of the Victoria Plateau are discharge sites from the perched aquifers, and are not directly connected with the main flow system.

Brackish springs such as Nagadee Spring with a salinity of 8 650 mg/L TDS occur adjacent to the Urella Fault on the eastern side of the flow system. Whether or not they are related to the flow system in the Yarragadee Formation is uncertain.

Quality: The salinity of groundwater in the Yarragadee Formation increases with depth. This has been observed in various bores (Maitland, 1913; Allen, 1965), and from geophysical logs of exploratory bores drilled since 1973. The geophysical logs show a wide variation in salinity between, and occasionally within, aquifers, which is a common feature of a multilayer aquifer system. The groundwater salinity is rarely less than 400 mg/L TDS and is most commonly in the range of 650 to 750 mg/L TDS.

Analyses for TDS and sodium chloride in groundwater taken during pumping tests of bores drilled since 1973 are given in Table 2, and standard analyses from the Allanooka Project bores from Allen (1965) are given in Table 3. From the analyses, most of the water is of a sodium-chloride type, in which sodium chloride comprises 65 to 85% of the dissolved salts.

Ferrous iron and manganese occur in the groundwater from the Yarragadee Formation, but usually in low concentrations. Analyses indicate iron concentrations ranging from less than 0·05 mg/L to 6·0 mg/L with a wide variability, but generally sufficiently low in production bores of the Allanooka Scheme not to warrant treatment. Manganese concentrations are also variable but are generally 0·05 mg/L or less.

Some bores produce gas-charged groundwater. Two samples from AP5 (Allen, 1965) contained 4·3% and 3·3% of carbon dioxide, 12·5% and 11·9% of oxygen and 83·2% and 84·8% of nitrogen, respectively. The gas has the composition of air, except that there has been a large increase in the percentage of carbon dioxide, and the oxygen content has been reduced by half. Ventriss and Parsons (1978) noted that the levels of carbon dioxide have been responsible for the deterioration of some concrete-lined pipes and tanks in the Allanooka Scheme.

Gas is also present in some of the confined beds of sand above the water table. Bores "blowing" or "sucking" gas, depending on the atmospheric conditions, were noted during drilling of the Allanooka Project bores.

Nitrate levels in the groundwater are generally less than 1 mg/L. An exception is a sample from AP17 which contained 120 mg/L. The use of nitrogenous fertilizers for agriculture may ultimately lead to an increase in the nitrate content of the groundwater, but because of the depth to the water table and the low rate of recharge, this may take many years.

Thermal wire-line logs were run on I2/75, I4/75 and I4/76. They show a general increase of temperature with depth at rates ranging from 1·3 to 4·5°C/100 m, and groundwater temperatures ranging from 23·3 to 28·2°C. These temperatures are within the range of those measured during pumping tests for the Allanooka Project.

Development: On the Victoria Plateau and in the Arrowsmith Region about 250 private bores and wells abstract groundwater for domestic and stock use from the Yarragadee Formation. Some of these, as at "The Casuarinas", are probably obtaining supplies from perched aquifers. Those bores producing from the regional flow system are usually over 100 m deep and only small supplies are pumped by jack-pump or windmill. Assuming a daily abstraction of 5 m^3/day then the annual abstraction is only about $0{\cdot}5 \times 10^6$ m^3 year.

The largest abstraction from the Yarragadee Formation is by the Allanooka Scheme which has been in operation since 1967. Annual abstraction statistics since commencement of the scheme are given in Table 5.

The present borefield consists of 24 bores within an area of about 60 km^2. The bores produce about 18 000 m^3/day of groundwater, which is pumped into a 22 500 m^3 storage

TABLE 5. ALLANOOKA SCHEME ANNUAL PRODUCTION STATISTICS (JULY—JUNE), 1967 TO 1978

Year	67–68	68–69	69–70	70–71	71–72	72–73	73–74	74–75	75–76	76–77	77–78
Yield (m^3 x 10^6)....	2·37	3·02	3·30	3·08	3·75	4·42	4·87	5·81	5·81	6·46	6·74

tank about 127 m above sea level, and gravitated to service tanks at Geraldton and Dongara. The water is chlorinated and fluoridized before being reticulated.

In 1977–78 the borefield produced 6·7 x 10^6 m^3, and since commissioning has produced about 50 x 10^6 m^3. Forth (1971) estimated the throughflow to the Allanooka borefield to be about 5·5 x 10^6 m^3/year, which is exceeded by the abstraction and indicates that limited mining of the groundwater is occurring.

The Yarragadee Formation contains large potable groundwater resources, and very large brackish resources. In general, the depth to the water table on the Victoria Plateau and the Arrowsmith Region precludes large-scale private development, while on the coastal plain the salinity is suitable only for industrial use.

Cockleshell Gully Formation

Lithology: The Cockleshell Gully Formation consists of interbedded, silty, carbonaceous, pyritic, medium- to coarse-grained sandstone, with carbonaceous and micaceous siltstone and shale. It ranges in thickness from about 60 m on the Northampton Block to about 1 200 m in the southeast adjacent to the Urella Fault. The formation is conformably overlain by the Cadda Formation, and unconformably overlies the Kockatea Shale. It is of nonmarine, possibly fluviatile origin, and is of Early Jurassic age.

Flow system: The Cockleshell Gully Formation is a multilayer aquifer system confined above by the Cadda Formation, and below by the Kockatea Shale. The boundaries to the flow system are the Urella Fault in the east, a groundwater divide about 90 km to the south of the area (Commander, 1978), the Greenough River, and the sea. The flow system is isolated from that in the Yarragadee Formation, except where faults may have brought the two systems into partial juxtaposition.

Groundwater in the flow system is confined, except at the intake around the outcrop to the south of Greenough River. The configuration of the potentiometric surface is not known but is presumed to be similar to that in the Yarragadee Formation.

Recharge: Rainfall recharge is inferred to occur on the outcrop of the formation immediately south of Greenough River, between the eastern edge of the coastal plain and Ellendale Crossing. At the outcrop the formation is unsaturated so that bores drilled into it are dry, as in Levitts bore (Allen, 1965), but downdip it contains potable groundwater as in AP6 (Fig. 4).

East from Ellendale Crossing the groundwater in the formation is in hydraulic continuity with the Greenough River, and the aquifer is presumed to be recharged by the river. This is suggested from the geological structure and the similarity in head between the river and bores in the adjacent Cockleshell Gully Formation (e.g. AP8).

Storage, movement, and discharge: The volume of groundwater in storage is very large but most is brackish. Groundwater movement is presumed to be from the intake area towards Mount Hill and the southwest. Discharge is probably by upward leakage, or upward movement along faults, into overlying formations and ultimately into the sea.

Quality: Groundwater with a salinity less than 1 000 mg/L is restricted to the area where rainfall recharge is inferred to occur to the north of Mount Hill. The composition of the groundwater is indicated in analyses from AP2 (Table 3) and MH 2/77 (Table 2). Elsewhere groundwater in the formation is brackish.

Development: A limited amount of brackish groundwater for stock is abstracted 2 to 8 km to the south of the Greenough River, east of Ellendale Crossing, where the Yarragadee Formation is unsaturated or does not contain usable supplies. A few bores obtain groundwater of about 1 000 mg/L TDS in the Arrowsmith Region north of Mount Hill. The formation has been tested adjacent to the Allanooka Scheme pipeline by MH 1/77 and 2/77, which proved that small supplies of potable water are available. These may be developed in the future.

CONCLUSIONS

Large resources of potable groundwater have been proven in the Allanooka area, 50 to 80 km southeast of Geraldton. They are the nearest resources which can be developed for Geraldton's water supply, and are currently being exploited by the Allanooka Scheme.

The present abstraction from the Allanooka Scheme exceeds the estimated throughflow to the borefield, and gradual mining of the groundwater is presumed to be occurring. This is probably being accompanied by very gradual upward and lateral leakage of brackish water. Consideration should now be given to extending the borefield to meet increasing demands, so that abstraction does not exceed throughflow, and the salinity of the groundwater is not impaired.

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THE HYDROGEOLOGY OF LAKE JANDABUP, SWAN COASTAL PLAIN, W.A.

by A. D. Allen

ABSTRACT

Lake Jandabup is one of a chain of round or oval-shaped, shallow lakes on the Swan Coastal Plain. It is up to 1·5 m deep and is 3·95 km² in area. The lake is filled by reeds (*Cladium* spp.) except for a central area of open water 1·2 km² in extent. It contains lake deposits of diatomite up to 0·8 m thick extending over 55% of the lake bed while the remainder is sand. These deposits rest on sandy Pliocene-Holocene sediments which unconformably overlie Late Cretaceous sediments. A regional groundwater flow system (Gnangara Mound) occurs in the Pliocene-Holocene superficial formations. The system is in hydraulic continuity with the lake water so that variations in water table levels also affect lake levels. Groundwater flow into the lake occurs through the sandy sediments on its eastern side and outflow takes place through the lake deposits around the southwest margin. Rainfall adds a significant volume of water to the lake but losses by evapotranspiration are greater. Between April 1977 and March 1978 inflow was estimated to be 4·49 x 10⁶ m³; rainfall 2·04 x 10⁶ m³; outflow 1·10 x 10⁶ m³; and evapotranspiration 5·87 x 10⁶ m³. The groundwater inflow to the lake was from the upper part of the flow system while the lower part moved beneath the lake and into the underlying Cretaceous sediments. A plume of groundwater with a chlorinity five times that of the inflow was proved to extend downstream from the lake.

INTRODUCTION

LOCATION AND TENURE

Lake Jandabup is about 22 km north of Perth and 3 km east of Wanneroo (Fig. 1).

The lake is surrounded by freehold land except for a small area of Crown Land on its southeastern shore. The boundaries of the freehold land include part of the lake so that over a third of the lake is privately owned. The central part, including most of the open water, is a C class reserve for the conservation of flora and fauna, vested in the Department of Fisheries and Wildlife. There are also existing mineral claims for the extraction of diatomite.

CLIMATE AND VEGETATION

The climate in the vicinity of Lake Jandabup is Mediterranean with hot, dry summers and mild, wet winters. The annual rainfall is about 840 mm of which about 90% is received during the winter months between April and October. During the summer, temperatures and evaporation are high. The average maximum temperature ranges from 29·5°C in February to 17·0°C in July. Evaporation is highest in January (262 mm) when on extreme days it exceeds 12 mm, and is lowest in June (50 mm). The annual average evaporation is 1 707 mm, twice as much as the rainfall.

The vegetation in and around Lake Jandabup has been mapped by Marchant, in How (1978). It consists of algae and a few aquatic plants in the area of open water; a narrow zone of reeds (*Cladium junceum*) bordering the open water; a broad zone of reeds (*Cladium articulatum*) extending to the shores of the lake; and a narrow zone of sedges and grasses around the periphery of the zone subject to occasional inundation. Large trees are very sparse. Those which occur are restricted to a number of small groves amongst low scrub growing on the higher, old shorelines.

Around the northeastern part of the lake the marginal vegetation has been cleared up to 200 m from the present shoreline, toward the centre of the lake.

INVESTIGATION

An investigation programme for Lake Jandabup and other lakes on the coastal plain was proposed by Allen (1976b). The present study is a modification of the original proposals. Work commenced in 1976 and after construction of the observation bores, water samples were obtained for analysis and water levels monitored for a year prior to compilation and analysis of the results.

Observation bores

A trial bore (S9) was drilled near the southern shore of the lake in October 1976. Later, between January and August 1977, 31 bores at 16 sites (1 to 3 bores per site) were drilled around the lake (Fig. 1). A deep bore in the centre of the

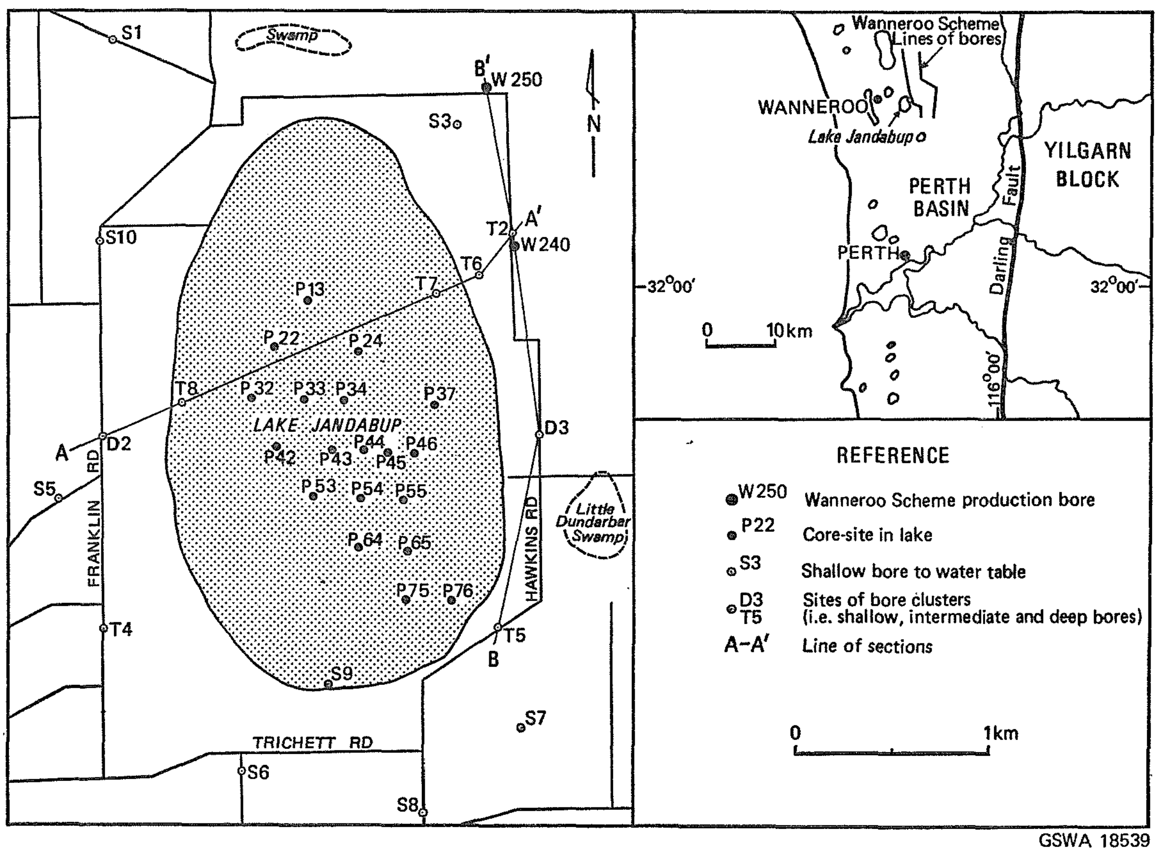

Figure 1 Locality plan.

TABLE 1. SUMMARY OF CABLE-TOOL DRILLING RESULTS

Name	Com-menced	Com-pleted	m A.H.D.		Depth (m)	Slotting (m bns)	Water level (A.H.D.) 28/3/78	Chlor-ide (mg/L) (May 1978)	Status	Base Super-ficial Form-ations (m bns)	Remarks
			Surface	Steel Casing							
S1	11/5/77	12/5/77	52·31	52·89	15	9–15	43·80	39	Shallow	....	
S3	11/7/77	12/7/77	57·20	57·92	22	10–20	n.a.	50	Shallow, not in use	....	
S5	1/7/77	7/7/77	63·87	64·20	22	10–22	42·76	201	Shallow	....	
S6	13/7/77	14/7/77	62·76	63·28	30	18–30	42·80	257	Shallow	....	
S7	18/7/77	18/7/77	49·44	49·97	12	6–10·7	45·67	35	Shallow	....	
S8	7/7/77	8/7/77	50·70	51·29	18	6–16	43·10	76	Shallow	....	
S9	26/10/77	26/10/77	n.a.	n.a.	6·2	0–6·2	n.a.	....	Shallow, not in use	....	
S10	9/7/77	11/7/77	57·06	57·63	22	10–22	43·38	102	Shallow	....	
D2A	15/3/77	23/3/77	55·85	55·83	70	62–64	43·22	267	Deep	65	
D2B	26/3/77	28/3/77	55·86	55·83	30	26–28	42·98	223	Intermediate	....	WM21 used as a shallow monitoring bore this site
D3A	9/3/77	14/3/77	52·91	53·38	62	50–52	45·98	73	Deep	54	?Poison Hill Greensand at base
D3B	2/3/77	4/3/77	52·99	53·45	22	18–20	46·53	73	Intermediate	....	
D3C	7/3/77	7/3/77	52·90	53·34	7	0–7	46·29	38	Shallow	....	
T2A	14/2/77	22/2/77	52·09	52·70	62	51–53	46·15	59	Deep	60·5	?Poison Hill Greensand at base
T2B	28/2/77	29/2/77	52·06	52·63	32	28–30	46·98	63	Intermediate	....	
T2C	1/3/77	1/3/77	52·07	52·61	7	0–7	48·56	62	Shallow	....	
T4A	29/3/77	6/4/77	63·02	63·04	77	62–64	42·56	197	Deep	74	
T4B	12/4/77	13/4/77	63·12	63·14	31	27–29	42·52	140	Intermediate	....	
T4C	14/4/77	15/4/77	63·18	63·22	20	18–20	42·70	....	Shallow	....	
T5A	24/1/77	2/2/77	50·50	50·53	60·3	50–52	45·46	102	Deep	58	
T5B	7/2/77	9/2/77	50·48	50·51	28	25–27	45·58	108	Intermediate	....	
T5C	10/2/77	10/2/77	50·38	50·41	7	0–7	45·43	25	Shallow	....	
T6A	8/6/77	22/6/77	47·74	48·24	62	50–52	45·88	51	Deep	54	
T6B	29/6/77	30/6/77	47·63	48·28	31	26–28	45·77	39	Intermediate	....	
T6C	29/6/77	30/6/77	47·64	48·20	9	0–8·2	45·84	63	Shallow	....	
T7A	17/5/77	1/6/77	46·79	47·20	58	51–53	44·98	63	Deep	54	?Poison Hill Greensand at base
T7B	19/5/77	2/6/77	46·68	47·07	29	24–26	45·17	49	Intermediate	....	
T7C	3/6/77	3/6/77	47·34	46·83	8	0–8	44·64	38	Shallow	....	
T8A	27/7/77	11/8/77	46·33	46·77	60·6	45–47	43·70	235	Deep	54	
T8B	17/8/77	19/8/77	46·33	46·72	26	21–23	43·62	252	Intermediate	....	
T8C	26/7/77	26/7/77	46·33	46·68	10	0–10	43·68	240	Shallow	....	

lake was also proposed but was not drilled because of the high cost. The bores were drilled by private contractors using cable-tool drilling rigs. They ranged in depth to 77 m and had an aggregate depth of 956·3 m (Table 1).

The sites were designated T (3 bores, deep, intermediate and shallow), D (2 bores, intermediate and shallow), and S (1 bore, shallow). The deep, intermediate and shallow bores were distinguished by the suffixes A, B, and C respectively. However, a deep bore was also drilled at all the D sites so that T and D sites were the same, with the exception of site D2 where a shallow bore (D2C) was not drilled because of the proximity of Wanneroo Monitoring No. 21 (WM21) shallow bore, which could be used.

At the T and D sites the deep bore was drilled first. Strata samples were taken at 2 m intervals and a bottom-hole sample was obtained for palaeontological examination after penetrating the underlying Cretaceous formation. On reaching total depth, or after casing the bore, a gamma ray log was run to assist correlation and to define bed boundaries.

An observation interval was selected near the bottom of each deep bore, at the base of the superficial formations. Then 80 mm class 9 PVC casing with bottom cap, sump, 2 m slotted interval and blank casing back to the surface was inserted. This was sand packed back to about 0·5 m above the slotted interval and the rest of the annulus was filled with cement slurry. For each intermediate bore an interval toward the middle of the Kwinana Group was selected and a bore drilled and constructed similar to the deep bore. The shallow bores were drilled to about 7 m below the water table and 80 mm class 9 PVC casing slotted over its entire length was inserted and stabilized with a sand pack. All the bores were fitted with protective steel sleeves fitted with hinged caps and set in a concrete block or, in some cases, fitted with flush magnetic caps set into the cement block. After construction the bores were developed by bailing, and later pumped, using a portable submersible pump to obtain water samples for chemical analysis.

Coring lake deposits

In January-March 1977 attempts were made to core the lake deposits at the sites shown in Figure 1. The coring was done using a pontoon-mounted "Vibroseis" rig designed and operated by the Harbours and Rivers Branch of the Public Works Department. Owing to the difficulty of moving through reeds, sites were limited to a 250 m grid in the area of open water. The rig vibrated a core barrel of 64 mm diameter PVC into the lake deposits. When no further penetration could be obtained the core barrel was removed from the hole. The core was retained by friction within the core barrel, which was cut lengthwise when the core was to be examined. However, the cores were usually partially or completely washed out and frequently were not retained in the core barrel. Roots and bog limestone also occasionally prevented penetration of the barrel. Coring was tried in 24 bores at 19 sites. Measured from the surface of the lake the aggregate depth of coring was about 115 m and the maximum depth cored was 7·9 m. Because of the generally unsatisfactory nature of the cores this programme was abandoned after considerable experimentation.

Augering and trenching

In March 1977 and February 1978 when the lake level was low, augering and trenching to examine sediments and groundwater movement was carried out in and around the lake.

Water sampling

On completion of some of the observation bores bailed samples were taken for partial analysis. Later, in May 1978, groundwater samples for standard analysis (Table 2) were obtained from the majority of the observation bores using a portable submersible pump. The bores were pumped at 0·3 L/sec (25·9 m^3/d) for 20, 30, or 60 minutes depending on whether the bore was shallow, intermediate or deep. Water samples from the surface of the lake (at the core sites) were taken on 25th March 1977 for partial analysis. All analyses were made by the Government Chemical Laboratories.

Levelling and monitoring

The natural surface and top of casing for all bores were levelled to the Australian Height Datum (AHD).

Groundwater levels were measured at synoptic, monthly intervals except at sites S3 and S9 which were omitted by mistake, and bore WM21 (to be used in lieu of D2C) which was damaged. The water levels are recorded in the MWB computerized groundwater levels record system.

PHYSIOGRAPHY

Lake Jandabup is situated in a depression which extends in a northwesterly direction, from where Bennet Brook enters the Swan River, to Lake Pinjar. The main part of the depression is near the junction of the Spearwood and Bassendean Dune Systems (McArthur and Bettenay, 1974). It appears the depression was a shallow, temporary arm of the Swan estuary during a period of high sea level, probably at the time of formation of the Spearwood Dunes. Subsequently the depression was modified and partly infilled with beach ridges, lunettes, and eolian dunes, which have produced the present system of isolated lakes and swamps.

Lake Jandabup occupies a shallow, north-south oval basin about 3 km long, 2 km wide and with an elevation of 50 m. The basin is closed by sand ridges except in the northwestern

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part where there is a low saddle marking the margin of an adjoining depression containing a series of small lakes and swamps.

The size of Lake Jandabup varies seasonally, and from year to year. The outer margin of the vegetation which marks the shoreline is at about 45·5 m A.H.D. Within this boundary the lake is about 2·8 km long and 1·7 km wide with an area of 3·95 km^2 and a circumference of about 6·5 km. Open water in the lake is restricted to a reed-bounded area of about 1·2 km^2 in the centre. Contours of the lake bed (Fig. 2), beneath the area of open water, show that this occupies a canoe-shaped depression with the deepest point at 43·8 m A.H.D. The rest of the lake bed is relatively flat except for a small depression in the southwest marked by an area of open water. The maximum water depth varies from 1·5 m in winter to about 0·5 m in summer and the corresponding volumes are about 3·0 x 10^6 m^3 and 1·5 x 10^6 m^3.

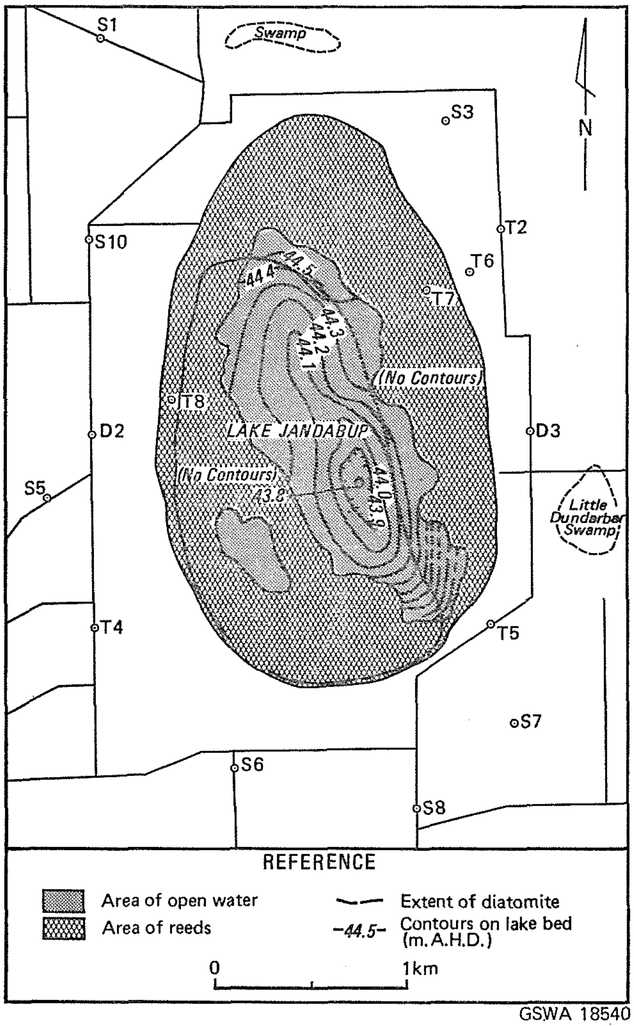

Figure 2 Contours of lake bed.

Fifty five per cent of the lake bed is covered with organic sediments, mainly diatomite, while the peripheral part is covered with carbonaceous sand (Fig. 3). The sand is most extensive in the northeastern part of the lake, possibly as a result of shoreline erosion, as this part faces the prevailing southwesterly wind. Near the edge of the diatomite the sand on the lake bed is strewn with rounded pebbles of diatomite 20 mm to 100 mm in diameter, which locally form pebble pavements grading laterally into diatomite which has an irregular but smoothed surface.

Around the northeastern shore of the lake, former shorelines can be recognized at about 46 m A.H.D. and 48 m A.H.D. These are distinguishable by changes in slope and vegetation cover. The 46 m A.H.D. shoreline around the northern and eastern edges of the lake is associated with beach ridges which locally support large trees, indicating that lake levels have been lower than 46 m A.H.D. for a considerable time. The pebble pavement of diatomite at about 44·2 m A.H.D. indicates that the diatomite has formerly been exposed to subaerial weathering or shallow wave action, indicating former low lake levels.

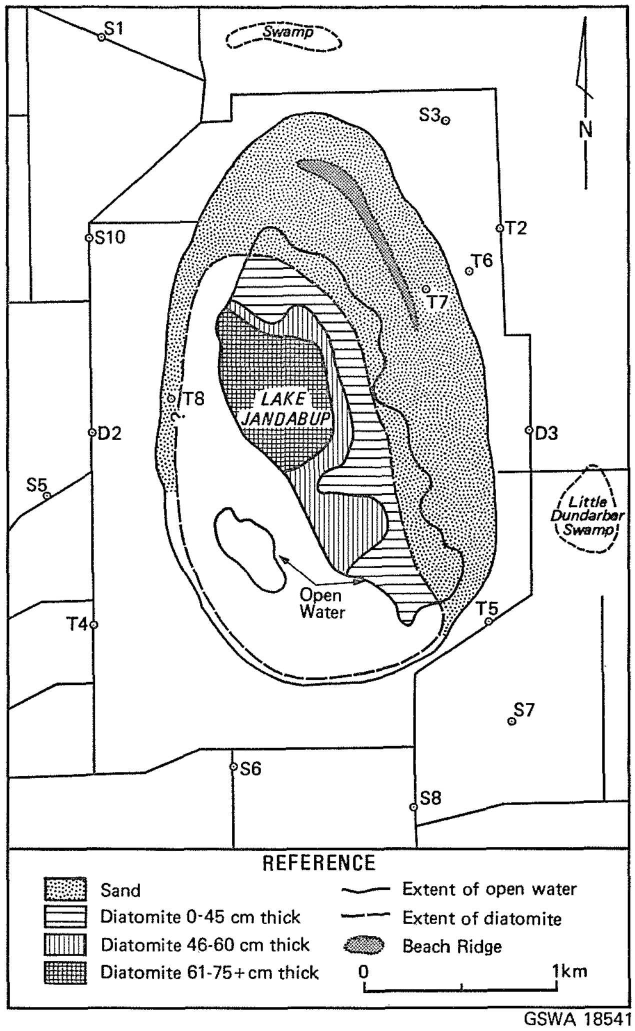

Figure 3 Lake deposits (diatomite and sand).

GEOLOGY

SETTING

Lake Jandabup is situated within the Perth Basin. It occupies a shallow depression, in Late Tertiary-Quaternary superficial formations which unconformably overlie Permian to Early Tertiary sedimentary rocks about 10 000 m thick. The lake contains a thin sequence of Quaternary lake deposits.

STRATIGRAPHY

The stratigraphic sequence at Lake Jandabup is given in Table 3.

Cretaceous

Poison Hill Greensand: The Poison Hill Greensand (Fairbridge, 1953) is believed to underlie the Lake Jandabup area. It has tentatively been identified on palaeontological evidence (Backhouse, 1977a, b, c). The formation was intersected in the base of all the deep bores and consists of dark-green to olive-green, glauconitic, sandy, slightly calcareous siltstone; and dark-green, clayey, poorly consolidated sandstone, which contains rare fossil fragments. The total thickness of the formation is not known, but it exceeds 8 m in D3A. It is unconformably overlain by the superficial formations.

Tertiary-Quaternary

Superficial formations: The superficial formations consist of an unconsolidated sequence of shallow-water marine and eolian deposits. The lower third of the sequence consists of a discontinuous sandy calcarenite lithologically similar, and possibly referable to the Ascot Beds (Playford and others, 1976). This section is principally a calcareous, slightly fossiliferous sand and a fine to coarse bimodal sand containing heavy minerals. Locally it contains quartz pebbles, pyrite, feldspar and carbonaceous fragments. These sediments are overlain by a uniform fine to coarse sand which tends to be feldspathic and contains occasional thin beds of clay and silt, which are, in turn, overlain by fine- to medium-grained

TABLE 2. STANDARD ANALYSES OF GROUNDWATER, SAMPLED MAY 1978

	GCL Lab. No.	pH	Turbidity, Colour (APHA units)		Odour	C mS/m at 25°C	milligrams per litre																									Remarks
							TDS (Evap.)	TDS (Cond.)	Free CO_2	Total Hard. (as $CaCO_3$)	Total Alk. (as $CaCO_3$)	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	NO_3	SiO_2	B	F	Fe	Mn	Cu	Pb	As	P	Nitrogen NH_4	Nitrogen NO_3	
S1	82491/78	6·1	60	220	nil	22	130	140	....	42	17	7	6	20	2	nil	21	39	15	....	8	0·07	<0·1	1·2	<0·02	<0·02	<0·01	<0·01	0·01	0·27	0·02	
S3	82702/78	5·2	14	18	nil	21	130	130	....	18	7	1	4	31	2	nil	9	50	11	....	7	0·05	<0·1	0·76	<0·02	0·07	0·01	<0·01	0·01	0·12	<0·02	
S5	82578/78	5·6	150	5	nil	79	440	510	50	85	10	6	17	119	3	nil	12	201	40	16	10	<0·05	<0·01	0·30	<0·02	0·07	0·01	<0·01	0·01	0·18	3·66	45 mins at 27m^3/day
S6	82579/78	5·7	700	120	H_2S	93	540	600	83	81	33	11	13	149	7	nil	40	257	17	<1	9	0·03	<0·1	0·46	<0·02	0·03	0·01	<0·01	0·05	0·40	0·03	Ditto
S7	82701/78	5·5	35	200	H_2S	16	140	100	....	14	10	1	3	23	1	nil	12	35	7	<1	6	0·19	<0·1	0·36	<0·02	0·03	0·01	<0·01	0·01	0·14	<0·02	45 mins at 27m^3/day
S8	82492/78	5·6	610	225	nil	31	190	200	....	35	20	4	6	46	2	nil	24	76	11	....	8	0·06	<0·1	1·1	<0·02	<0·02	<0·01	<0·01	0·05	0·25	0·02	
S10	82493/78	6·2	200	165	nil	49	280	310	....	86	35	13	13	57	2	nil	43	102	18	19	8	0·08	<0·1	0·4	<0·02	<0·02	0·02	<0·01	0·03	0·18	4·2	
D2A	82490/78	6·4	13	25	H_2S	114	630	730	....	166	135	32	21	160	8	nil	165	267	13	....	38	0·09	<0·1	<0·05	<0·02	<0·02	<0·01	<0·01	0·02	3·4	0·02	
D2B	82576/78	6·8	80	<5	nil	99	560	630	48	177	150	43	17	129	7	nil	183	223	3	<1	29	0·1	0·1	0·14	0·07	<0·02	0·02	<0·01	0·01	2·90	<0·02	30 mins at 27m^3/day
D2C	82577/78	5·6	4	120	nil	69	400	440	75	60	15	6	11	104	6	nil	18	188	11	1	9	0·16	<0·1	0·36	<0·02	0·04	0·01	<0·01	0·01	0·79	0·13	Ditto
D3A	82558/78	6·9	250	66	nil	52	290	330	38	160	150	46	11	42	4	nil	183	73	4	<1	12	0·06	0·1	3·2	0·04	<0·02	<0·01	<0·01	0·05	0·49	0·03	1 hour at 27m^3/day
D3B	82559/78	5·4	1 000	17	nil	27	150	170	80	37	10	5	6	37	2	nil	12	73	6	<1	9	0·01	0·1	0·08	<0·02	<0·02	<0·01	<0·01	0·01	0·09	<0·02	30 mins at 27m^3/day
D3C	82560/78	5·5	20	16	nil	19	90	120	44	26	7	4	4	27	1	nil	9	38	12	16	7	0·02	<0·1	<0·05	<0·02	0·05	<0·01	<0·01	0·01	0·08	3·65	20 mins at 27m^3/day
T2A	82555/78	6·0	300	78	H_2S	29	180	190	90	50	45	10	6	36	3	nil	55	59	4	<1	12	0·06	<0·1	<0·05	0·52	<0·02	0·01	<0·01	0·05	0·25	0·02	1 hour at 27m^3/day
T2B	82556/78	5·4	600	49	nil	25	140	160	80	23	10	3	4	36	2	nil	12	63	5	<1	10	0·06	<0·1	<0·05	0·16	<0·02	0·02	<0·01	0·01	0·23	0·03	30 mins at 27m^3/day
T2C	82557/78	5·4	5	210	H_2S	25	150	160	80	26	10	2	5	36	1	nil	12	62	8	<1	9	0·06	<0·1	0·5	<0·02	<0·02	<0·01	<0·01	0·01	0·21	0·05	20 mins at 27m^3/day
T4A	82580/78	6·7	10	22	musty	88	480	560	44	123	110	26	14	120	7	nil	134	197	5	<1	20	0·22	0·1	1·5	0·04	<0·02	0·05	<0·01	0·04	2·50	0·03	Max permitted Pb, 1 hour at 27m^3/day
T4B	82581/78	6·1	300	100	H_2S	95	540	610	60	107	43	15	17	143	7	nil	52	240	44	<1	6	0·29	<0·1	0·54	<0·02	<0·02	<0·01	<0·01	0·01	0·39	0·02	30 mins at 27m^3/day
T5A	82506/78	6·4	20 000	70	musty	51	260	330	....	79	76	12	12	65	4	nil	92	102	6	....	9	0·08	0·1	....	....	....	....	....	....	....	....	Too clayey to analyze metals and nutrients
T5B	82507/78	6·0	28	230	H_2S	42	250	270	....	53	17	5	10	54	2	nil	21	108	4	....	10	0·09	<0·1	0·28	<0·02	<0·02	<0·01	<0·01	0·01	0·30	0·02	
T5C	82508/78	5·8	1 000	69	nil	13	90	80	....	19	12	3	3	17	2	nil	15	25	12	....	7	0·06	<0·1	0·17	<0·02	<0·02	<0·01	<0·01	0·09	0·31	0·06	
T6A	82561/78	7·1	1 700	50	organic	52	300	330	30	171	186	57	7	38	4	nil	226	51	2	....	15	0·03	0·1	5·9	0·16	<0·02	<0·01	<0·01	0·04	0·27	0·05	1 hour at 27m^3/day
T6B	82562/78	5·7	7 000	15	nil	19	120	120	68	15	17	3	2	30	1	nil	21	39	10	<1	8	0·05	<0·1	0·54	<0·02	<0·02	<0·01	<0·01	0·06	0·10	0·06	30 mins at 27m^3/day
T6C	82563/78	5·1	50	240	nil	26	170	170	79	40	5	3	8	35	2	nil	6	63	24	<1	8	0·07	<0·1	0·86	<0·02	0·02	<0·01	<0·01	0·03	0·18	<0·02	20 mins at 27m^3/day
T7A	82564/78	7·4	19 000	48	organic	54	310	350	15	186	183	58	10	37	5	nil	223	63	2	<1	10	0·06	0·1	1·1	<0·02	<0·02	<0·01	<0·01	0·04	0·27	<0·02	1 hour at 27m^3/day
T7B	82565/78	5·3	300	25	nil	22	130	140	70	13	7	2	2	34	2	nil	9	49	13	<1	9	0·04	<0·1	0·06	<0·02	<0·02	<0·01	<0·01	0·03	0·15	<0·02	30 mins at 27m^3/day
T7C	82566/78	5·5	70	410	H_2S	18	160	120	63	9	10	2	1	32	1	nil	12	38	15	<1	9	0·13	<0·1	0·74	<0·02	0·02	<0·01	<0·01	0·03	0·52	<0·02	20 mins at 27m^3/day
T8A	82698/78	6·1	2	210	H_2S	85	510	540	....	63	40	9	10	142	7	nil	49	235	10	<1	8	0·05	<0·1	0·76	<0·02	0·02	0·01	<0·01	0·06	0·89	<0·02	1 hour at 27m^3/day
T8B	82699/78	7·7	310	88	H_2S	118	670	760	....	228	198	57	21	150	7	nil	241	252	11	<1	30	0·09	0·1	0·06	0·12	<0·02	<0·01	<0·01	0·08	3·4	<0·02	30 mins at 27m^3/day
T8C	82700/78	6·2	5	63	H_2S	87	470	560	....	81	45	11	13	138	6	nil	55	240	5	<1	13	0·05	<0·1	0·28	<0·02	<0·02	<0·01	<0·01	0·02	0·92	<0·02	20 mins at 27m^3/day
W250*	10249/74	6·0	25	60	H_2S	....	190	140	70	46	38	12	4	35	2	nil	46	5	58	....	11	0·05	0·1	0·37	<0·05	<0·05	<0·02	<0·02	0·03	0·25	<0·02	

* Sampled 22/5/74

TABLE 3. STRATIGRAPHIC SEQUENCE, LAKE JANDABUP AREA

Age	Formation	Max. thickness (m)	Lithology	Remarks
Quaternary	"Lake deposits"	2	Diatomite, peat, sand, minor limnic peat and bog limestone	
		?DISCONFORMITY		
Late Tertiary-Quaternary	Superficial formations	75	Fine-medium sand, calcareous sand, limestone, minor clay and ferruginous sand	Variable thickness and lithology
		UNCONFORMITY		
Late Cretaceous	?Poison Hill Greensand	8+	Glauconitic sand, glauconitic siltstone	Formation not definitely identified

sand of probable eolian origin. An irregular layer of limonite-cemented sand (coffee rock) occurs at the water table in the vicinity of the swampy depressions (Fig. 4).

The superficial formations rest unconformably on Cretaceous sediments, probably the Poison Hill Greensand, and are overlain by the lake deposits with probable disconformity. The unconformity with the Cretaceous is at a depth of about –1 m A.H.D. to –18 m A.H.D. and the thickness of the superficial formations ranges from about 45 m to 75 m depending on the topography.

No identifiable fossils were obtained from samples but the sediments probably range from Pliocene to Holocene age (Playford and others, 1976).

Lake deposits: The lake deposits (Fig. 3) consist of medium to coarse carbonaceous sand about 0·1 m thick which grades up into a carbonaceous diatomite towards the centre of the lake. This diatomite is as much as 0·8 m thick and locally contains layers of limnic peat and limestone up to ·05 m thick. These sediments are still in the process of deposition. The beach ridges, which mainly occur around the northeastern shore of the lake, are included with the lake deposits. They consist of medium sand with a thickness of up to 2 m.

Simpson (1903) gave a brief description of the diatomite occurring in Lake Jandabup and was of the opinion that the deposit may have been burned by bush fires during previous dry periods. The extent of the diatomite and approximate isopachs are given in Figure 3, which shows that the area of its greatest thickness does not coincide with the deepest part of the lake (Fig. 2). It is estimated that about 800 000 m^3 of diatomite occur within the lake. Samples of diatomite contained the following tentatively identified genera of diatoms, *Synedra*, *Surinella* and *Navicula* (Grey, 1977). Locally the diatomite also contained siliceous sponge spicules. The carbonaceous sand contains fragments of paperbark (*Melaleuca* sp.) not presently found growing around the lake. The age of the lake deposits is probably Late Pleistocene to Holocene.

STRUCTURE

Geological sections through the Lake Jandabup area illustrating the stratigraphy and geological structure are given in Figure 4.

The ?Poison Hill Greensand is believed to be flat-lying, but there is considerable relief on the unconformity between it and the superficial formations. There is a prominent east-west ridge in this unconformity which rises to an elevation of –2 m A.H.D. beneath the east-central part of the lake, and then falls to about –18 m A.H.D. beneath the southwestern side. The overlying superficial formations are flat-lying, but the apparent irregularity of some units suggests there are erosional breaks in the sequence. The overlying lake deposits form a thin saucer-shaped deposit slightly asymmetric toward the west, which probably disconformably overlies the superficial formations.

HYDROGEOLOGY

INTER-RELATIONSHIP OF LAKE AND GROUNDWATER

Lake Jandabup is in hydraulic connection with a regional groundwater flow system referred to as the Gnangara Mound (Allen, 1976a). This flow system is in dynamic balance between topography, geology, climatic factors, and vegetation. At present these factors combine so that the water table on

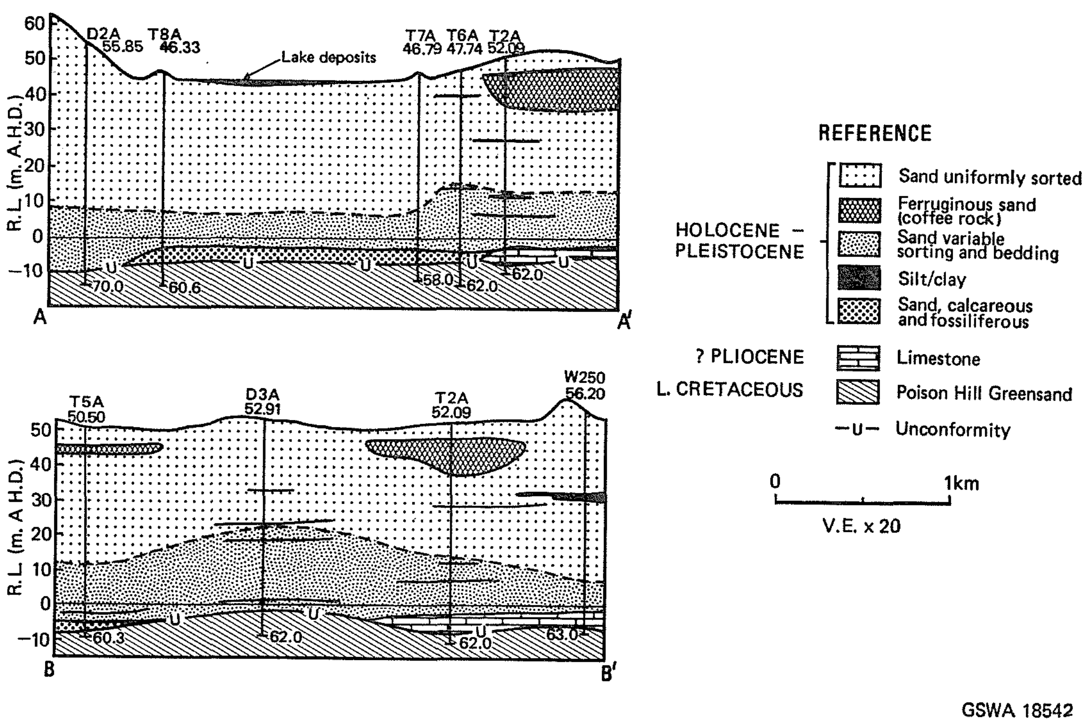

Figure 4 Geological sections.

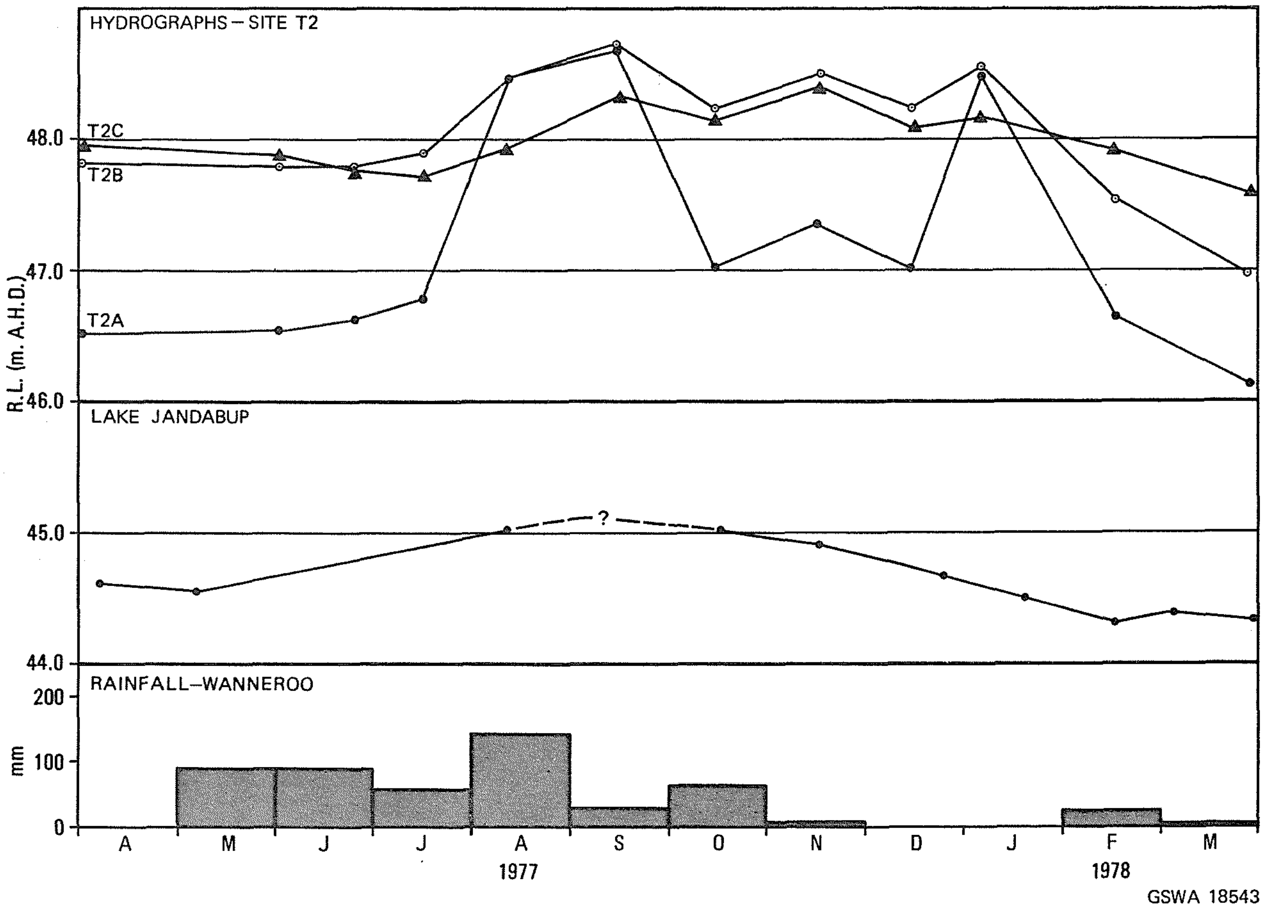

Figure 5 Hydrographs showing relationship to rainfall, lake level.

the eastern side of the lake is at a higher elevation than the lake bed, with the result that inflowing groundwater, together with rainfall, maintain water in the lake.

The lake level and the water table vary in phase, though it is probable that heavy rainfall events would affect the lake more rapidly than the groundwater. The water table and consequent lake level are usually highest in October after the winter rainfall and lowest in March at the end of summer (Fig. 5).

Maps of the water table around Lake Jandabup for October 1977 (winter) and March 1978 (summer) show that on the eastern side of the lake the groundwater has a relatively steep gradient with flow lines converging on the lake (Fig. 6). To the west the gradient is flatter and flow lines diverge. The pattern is essentially the same for winter and summer except that in winter the elevation of the water table is higher and the sections contributing inflow and accepting outflow are slightly longer. The water table decline between October 1977 and March 1978 ranged from 0·4 m to 0·8 m, with the greatest decline occurring along the southwestern margin of the lake where outflow is presumably greatest.

Sections approximately normal to the water table contours incorporating head measurements at different depths in the flow system for October 1977 and March 1978 are given in Figure 7. They show (in two dimensions) that groundwater inflow into the lake is from the upper half of the flow system and that as a result of evapotranspiration the outflow is considerably less than the inflow. The sections also show that during the winter there is flow into the underlying ?Poison Hill Greensand, whereas in the summer there is throughflow beneath the lake.

The groundwater inflow and outflow from the lake were confirmed by augering. On the northeastern side of the lake small artesian flows with head increasing with depth were observed from below a depth of 0·25 m, and runnels can be seen in the sandy lake deposits suggesting the sands form a broad seepage face. On the southwestern shore augering showed a slight decrease in head with depth, indicating the potential for downward flow. Presumably outflow takes place through part of the lake bed and around the sandy shoreline.

WATER BALANCE

A water balance is an accounting of all water entering and leaving a water system. For Lake Jandabup it can be expressed by the equation:

$$G_i + R + V_{77} = D + E_t + V_{78} \quad \text{.... ....} \quad (1)$$

where G_i = groundwater inflow
R = rainfall
D = outflow
E_t = evapotranspiration
V_{77} = volume of the lake in April 1977
V_{78} = volume of the lake in March 1978

The various components of the water balance are evaluated below for the period April 1977 to March 1978.

Groundwater inflow

The annual groundwater inflow into the eastern side of the lake was estimated by using the form of the Darcy equation:

$$Q = KbIL \quad \text{.... ....} \quad (2)$$

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

The hydraulic conductivity was taken as 30 m/d; the thickness of the upper part of the aquifer contributing to groundwater inflow was measured on the 46·5 m (winter) and 46 m isopotentials (summer) in Figure 7; the average hydraulic gradient in summer and winter and the width of the flow section A-A' were measured from Figure 6. The groundwater inflow in October 1977 was:

$$Q = 30 \times 25 \times 0{\cdot}005\,9 \times 2\,960$$
$$= 13\,098 \text{ m}^3\text{/d}$$

and in March 1978 was

$$Q = 30 \times 25 \times 0{\cdot}004\,8 \times 3\,200$$
$$= 11\,520 \text{ m}^3\text{/d}$$

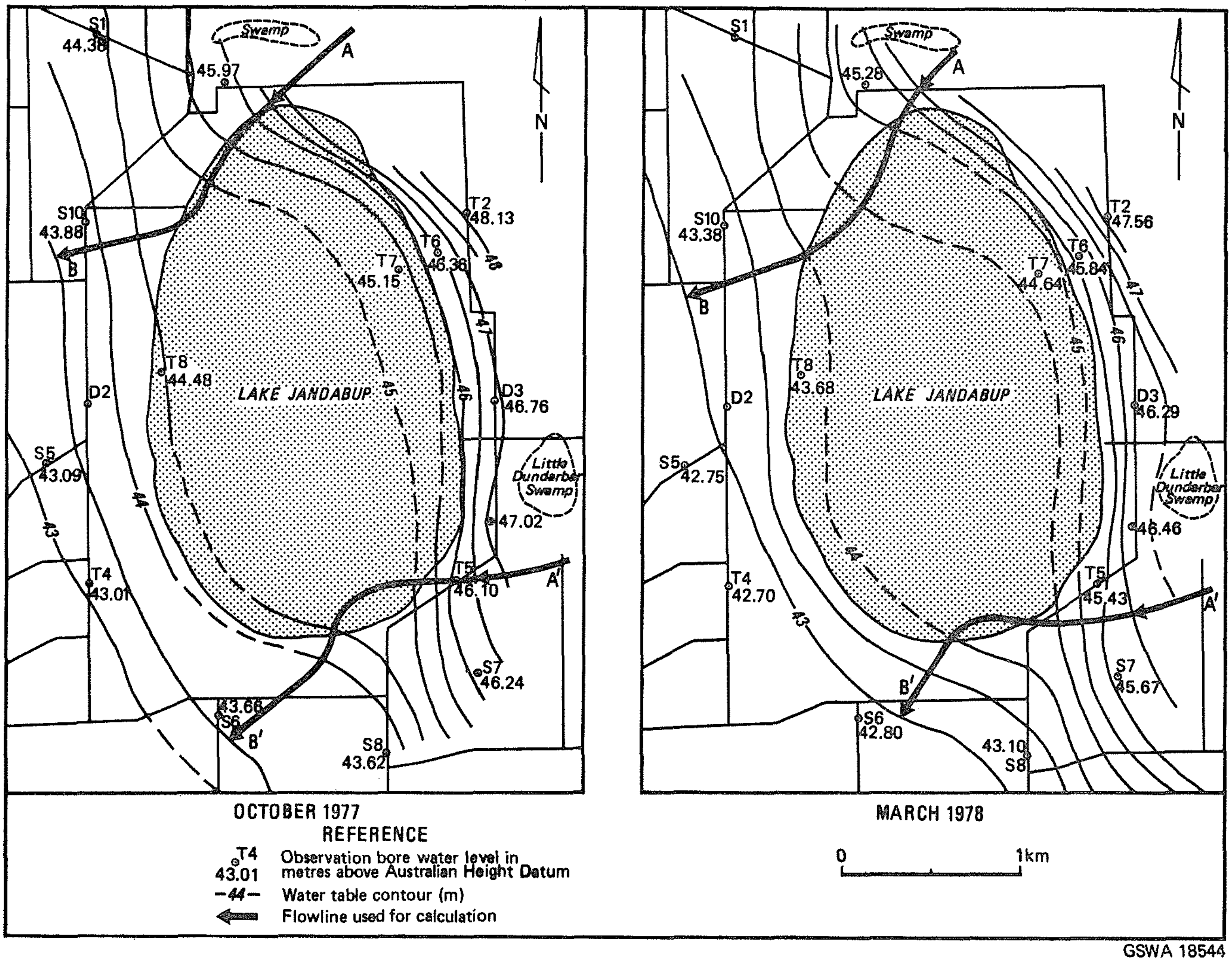

Figure 6 Water table contours.

The annual groundwater inflow from the average of the winter and summer groundwater inflow was $4{\cdot}49 \times 10^6$ m³.

The average annual groundwater throughflow passing beneath the eastern side of the lake for the same isopotentials, gradient and width of cross-section was $4{\cdot}54 \times 10^6$ m³.

Outflow

The average annual outflow from the lake contains a component of water received from direct rainfall. It is assumed to be the average of the winter and summer outflow using the measured aquifer thickness between flow lines on the 43 m isopotential (summer) and 43·5 m isopotential (winter) given in Figure 7, and the average gradient between the 43·0 and 43·5 m contours (summer) and 43·5 and 43·0 contours (winter) for the flow widths shown in Figure 6. The outflow in October was:

$$Q = 30 \times 39 \times 0{\cdot}001\,4 \times 2\,840$$
$$= 4\,652 \text{ m}^3/\text{d}$$

and in March was

$$Q = 30 \times 9 \times 0{\cdot}001\,9 \times 2\,720$$
$$= 1\,395 \text{ m}^3/\text{d}$$

The annual outflow from the average of the summer and winter outflows was $1{\cdot}10 \times 10^6$ m³.

Rainfall

The rainfall input to the lake will vary from year to year. In addition there may also be minor local run-off from around the shores of the lake, but for the present estimate this is disregarded. The area of the lake is 3·95 km² and for the period April 1977 to March 1978 the rainfall was 517 mm (Table 4).

The rainfall input to the lake was:

$$3{\cdot}95 \times 10^6 \times 0{\cdot}517 = 2{\cdot}04 \times 10^6 \text{ m}^3.$$

TABLE 4. RAINFALL AT WANNEROO JANUARY 1977 TO MARCH 1978, IN MILLIMETRES (DEPARTMENT OF METEOROLOGY)

1977												1978		
J	F	M	A	M	J	J	A	S	O	N	D	J	F	M
2	0	2	0	93	93	58	144	28	64	8	0	0	26	3

Evapotranspiration

Evaporation from the free water surface of the lake must be considerable considering the size, shallow depth and exposure, of the lake to wind. Similarly, the reeds extending over an area of about 2·8 km² with their root systems permanently beneath water or drawing from the water table must transpire large volumes of water. It is not possible to reliably estimate these components. They are considered together as evapotranspiration and are assumed to approximate 0·8 of the Class A pan evaporation figures applied to the area of the lake.

The Class A pan evaporation figures for Perth for the period of study are given in Table 5.

Between April 1977 and March 1978 the pan evaporation was 1 857·6 mm compared with an annual average of about 1 706·6 mm (Australian Standard Tank).

Knowing the area of the lake and applying the assumed coefficient to the pan evaporation figures the estimated evapotranspiration loss was:

$$3{\cdot}95 \times 10^6 \times 1{\cdot}857\,6 \times 0{\cdot}8 = 5{\cdot}87 \times 10^6 \text{ m}^3$$

TABLE 5. PAN EVAPORATION AT PERTH IN MILLIMETRES (DEPARTMENT OF METEOROLOGY)

1977												1978		
Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.
248·5	226·0	190·3	150·3	74·6	64·6	70·3	88·4	111·9	152·6	199·1	253·8	261·3	219·2	211·8

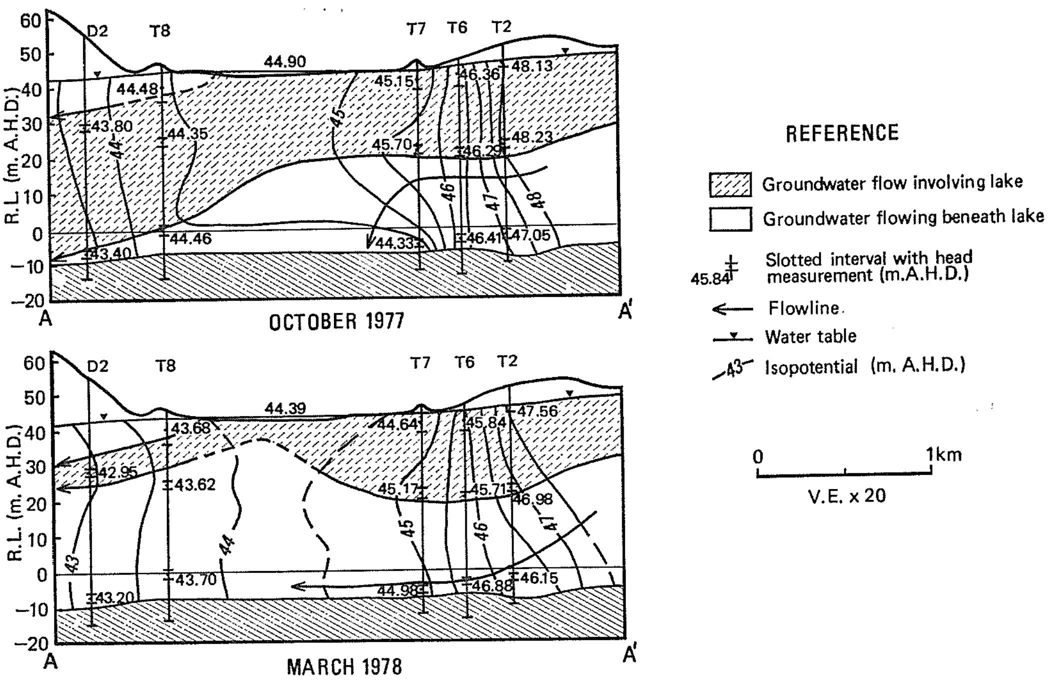

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Figure 7 Vertical head variation approximately parallel to direction of groundwater flow.

Change in lake storage

The volume of water in the lake varies between years depending on the seasonal conditions. On 4 April 1977 the level was 44·60 m A.H.D. whereas on 27 April 1978 it was 44·26 m A.H.D., showing a decline of 0·34 m in the lake level and a net reduction in lake storage.

In April 1977 water in the lake extended over an area of about 1·2 km² and from the bottom contours it is calculated that the lake contained about 0·31 x 10⁶ m³. In March 1978 the area of the lake was about 0·8 km² and the volume 0·19 x 10⁶ m³. The net loss in storage for the year was 0·12 x 10⁶ m³.

Balance

Substituting the estimates of the components of the water balance in equation (1) the water balance (millions of cubic metres) is:

$$4{\cdot}49 + 2{\cdot}04 + 0{\cdot}31 \approx 1{\cdot}10 + 5{\cdot}87 + 0{\cdot}19$$
$$6{\cdot}84 \approx 7{\cdot}16$$

The result is a fair balance considering the various assumptions and nature of the data used for calculation. The main features which the balance shows are that rainfall is significant in maintaining the lake and that evapotranspiration is a major source of water loss.

CHLORIDE BALANCE

The chloride in the lake and the groundwater flow system originates from rainfall. The total concentration of chloride is not known to be affected by the aquifer matrix or by vegetation. Consequently if the volumes and chloride concentrations of water entering the lake are known, it is possible to obtain a chloride balance which provides a check on the water balance.

Ignoring evapotranspiration which does not alter the mass of chloride in the system, the chloride balance can be expressed by the following equation:

$$G_i.C_{icl} + R.C_{rcl} + V_{77}.C_{L77c} = D.C_{ocl} + V_{78}.C_{L78cl} \quad .... \quad (3)$$

where G_i = groundwater inflow

C_{icl} = concentration of chloride in groundwater inflow

R = rainfall

C_{rcl} = concentration of chloride in rainfall

V_{77} = volume of lake in April 1977

C_{L77cl} = concentration of chloride in the lake in April 1977

D = outflow

C_{ocl} = concentration of chloride in outflow

V_{78} = volume of the lake in March 1978

C_{L78cl} = concentration of chloride in the lake in March 1978

The mass of chloride of the components in the balance is the product of the volume of water (m³) by the chlorinity (mg/L) which give the chloride content in grams.

Groundwater inflow

Isochlors for the upper part of the groundwater flow system (to 7 m below water table) are given in Figure 8. These show water of relatively uniform chlorinity on the eastern side of the lake and a plume of chloride-enriched groundwater extending from the southwestern side of the lake. The isochlors of the lake water also show an increase in concentration toward the southwest, confirming the direction of groundwater flow (Fig. 6).

Vertical variation in chlorinity in the flow system is shown in the section A-A′ in Figure 8. These data taken together with the vertical isopotentials (Fig. 7) show that groundwater in the upper part of the flow system which enters the lake has an average chlorinity of 43·5 mg/L (Site T7, average of shallow and intermediate bores). As the groundwater inflow for the period has been estimated to be 4·49 x 10⁶ m³, the associated chloride input becomes 4·49 x 10⁶ x 43·5 = 195·3 t.

Rainfall

The mean annual chloride concentration in rainfall decreases with increasing distance inland. In Perth the mean annual chloride concentration was 12·0 mg/L in 1973 and 10·7 mg/L in 1974 (Hingston and Gailitis, 1977). Lake Jandabup occurs at a similar distance inland and the average of these

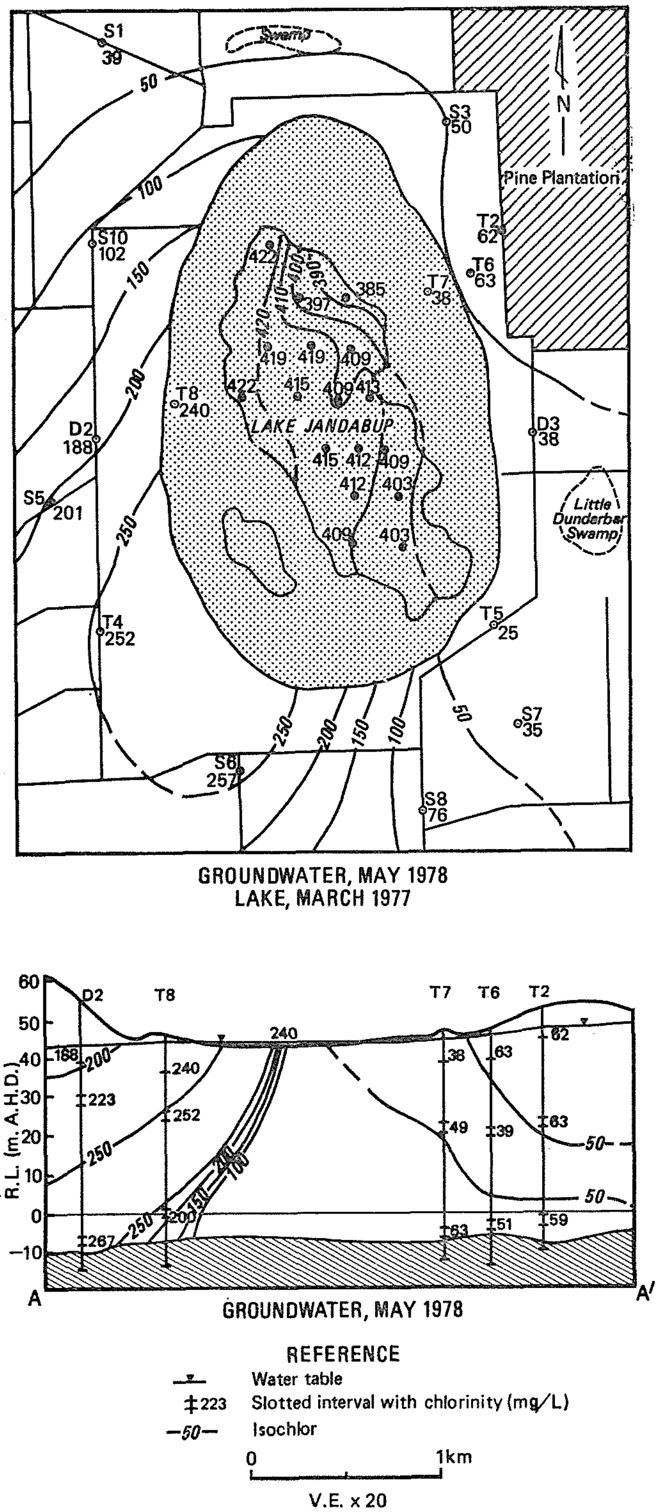

Figure 8 Variations in chlorinity at the water table and in a section approximately parallel to the direction of groundwater movement.

two values, 11·4 mg/L, is assumed to be the rainfall chlorinity for April 1977 to March 1978. As the rainfall input was 2·04 x 10^6 m^3, the mass of chloride added to the lake was 2·04 x 10^6 x 11·4 = 23·3 t.

Lake Water

The chloride content in Lake Jandabup varies throughout the year, being lowest at the end of winter and highest toward the end of summer. It also varies from year to year depending mainly on the amount of rainfall and rate of evaporation. Chloride analyses for the water from Lake Jandabup (Table 6) show the seasonal and annual variations which may occur.

TABLE 6. CHLORIDE ANALYSES FROM LAKE JANDABUP

Date	25/3/77	Early 5/1977*	Late 5/1977*	28/10/77*	23/5/78
Cl (mg/L)	410	373	355	185	240

*After How (1978)

In April 1977 the lake extended over about 1·2 km^2 and from the lake-bottom contours and known water levels it is estimated to have contained about 0·31 x 10^6 m^3 of water, with an average chlorinity of about 410 mg/L; the chloride storage was then 127·1 t.

In March 1978 the lake was about 0·8 km^2 in extent and contained 0·19 x 10^6 m^3 of water with a chlorinity of about 230 mg/L (by interpolation from data in Table 6). This gave a chloride storage of 43·7 t.

Outflow

Figure 8 shows that the outflow from Lake Jandabup is associated with a plume of groundwater with a chloride concentration about five times that of the inflow. The pattern of chlorinity variation agrees well with the flow pattern inferred from the vertical isopotentials (Fig. 7) except that the plume of chloride-enriched water extends to the base of the superficial formations. This may result from downward groundwater movement in the winter (Fig. 7) when some of the groundwater flow beneath the lake goes into the ?Poison Hill Greensand. The distribution of chloride in the outflow is also probably affected by dispersion and diffusion. From Figure 8 the chlorinity of the outflow can be seen to exceed 250 mg/L and the highest measured value to be 267 mg/L at the base of the superficial formations in bore D2A. The chlorinity of water in the lake (Table 6) is generally higher than these values except after rainfall. It is possible that the chlorinity of outflow varies seasonally; however, for the purpose of the chloride balance it is assumed to be 265 mg/L. The annual groundwater outflow is calculated to be 1·10 x 10^6 m^3 so that the estimated mass of the chloride discharged is 1·10 x 10^6 x 265 = 291·5 t.

Balance

The computed values for the various components of the chloride balance in tonnes may be substituted in equation (3):

$$195{\cdot}3 + 23{\cdot}3 + 127{\cdot}1 \approx 291{\cdot}5 + 43{\cdot}7$$

$$345{\cdot}7 \approx 335{\cdot}2$$

This is a reasonable balance considering the quality of the data and it tends to confirm that the water balance is of the correct order.

CONCLUSION

Lake Jandabup is a surface expression of part of the Gnangara Mound flow system. It is maintained by groundwater inflow from the upper half of the flow system and by rainfall. The lake behaves as an evaporative basin from which outflow is impeded by organic lake deposits. As a result about 90% of the groundwater inflow and rainfall is lost by evapotranspiration. Consequently a plume of relatively more saline groundwater extends downstream from the lake.

Other circular lakes on the coastal plain are probably maintained in a similar way. However, there are likely to be some differences from one lake to another as a result of variations in size, topography and subsurface geology.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1979

by K. A. Crank

ABSTRACT

The level of petroleum exploration in Western Australia continued its upward trend during 1979. Activity has increased steadily each year since 1975, when exploration was at its lowest level for many years.

In 1979, 17 exploration wells were completed compared with 15 in 1978, and four were drilling ahead at the end of the year, for a total penetration of 66 428 m, an increase of 18 318 m, or 38 per cent, compared with the previous year. Expressed in rig months, the increase was 84 per cent compared with 1978. Drilling was mainly offshore, in the Carnarvon, Canning, Browse, and Bonaparte Gulf Basins, but the most significant activity of the year was the drilling of seven wells in the deeper waters of the Exmouth Plateau area. Forty development wells were completed in the Barrow Island Oil Field during 1979.

No major discoveries were made, although significant non-commercial gas discoveries were reported in Brecknock 1 in the Browse Basin and in Scarborough 1 in the Exmouth Plateau area, and hydrocarbon shows were encountered in several other wells.

The only notable decrease in activity was in marine seismic surveys, which declined by 32 per cent compared with 1978, and totalled 26 312 line kilometres.

INTRODUCTION

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

Type of well	Wells completed		Wells drilling on 31 December	
	1978	1979	1978	1979
New-Field Wildcats	13	15	0	4
New-Pool Wildcats	2	1	0	0
Extension Tests	0	1	1	0
Total	15	17	1	4

Total effective drilling: 1978—48 110 m
1979—66 428 m

Two non-commercial gas discoveries were made in 1979, at Brecknock 1 in the Browse Basin, and at Scarborough 1 in the Exmouth Plateau area.

Figure 1 summarizes seismic activity since 1967. Geophysical survey activity in 1979 is shown below:

Type of survey	Line kilometres		Party months or geologist months	
	1978	1979	1978	1979
Land seismic	1 143	909	....	....
Marine seismic	38 996	26 312	....	....
Land gravity	459	0	....	....
Marine gravity	1 023	9 626	....	....
Aeromagnetic	1 847	0	....	....
Marine magnetic	2 336	4 903	....	....
Oceanographic	....	....	3·5	0
Geological	....	....	2	0
Geochemical	....	....	2	0

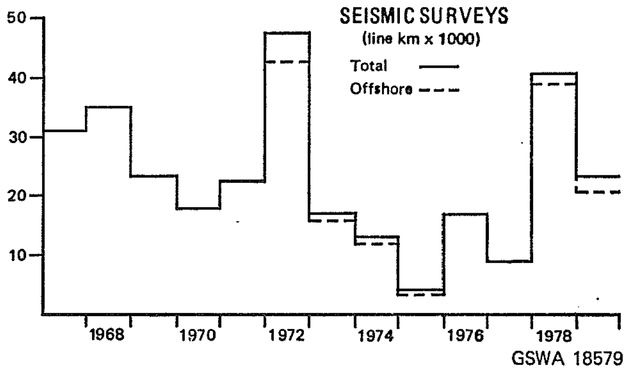

Figure 1 Seismic surveys since 1967.

DRILLING

DRILLING OPERATIONS

Expressed in rig months, overall exploration operations increased by 84 per cent to 44·8 rig months in 1979 compared to 24·3 rig months in 1978. Offshore operations increased by 89 per cent compared with 1978 (40·0 compared with 21·2 rig months), and onshore operations increased by 55 per cent (4·8 compared with 3·1 rig months). In addition, 11·0 rig months were spent on a 40-well development program on Barrow Island in 1979. This compared with 4·7 rig months spent on seven wells in 1978.

A total of nine rigs, seven offshore and two onshore, operated in Western Australia. Early in the year the drill-ship Penrod 74 drilled one well for Getty Oil, Tamar 1, and then left Western Australian waters. The semi-submersible Southern Cross was not utilized further after drilling Bruce 1 in August; and, after completing Pueblo 1 for Woodside, the Ocean Digger (semi-submersible) drilled one more well in Northern Territory waters before being laid up. Other details of rig deployment are shown in Figure 2.

Only one tropical cyclone ("Hazel"), which occurred in March, affected operations during the year, when four days were lost while drilling Sultan 1, as well as 3 days on Zeewulf 1, and one day on Pueblo 1.

Figure 3 is a summary comparison of drilling operations for the 13-year period 1967–1979.

WELLS COMPLETED IN 1979

The locations of wells drilled for petroleum exploration in Western Australia during 1979 are shown in Figure 4. Details relating to wells drilled during the year are given in Table 1. All petroleum exploration wells drilled in Western Australia up to the end of 1979 are listed in the Geological Survey Record 1980/1 (Crank, 1980). A summary of the principal results of drilling in each basin during the year is as follows:

TABLE 1. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1979

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	Com-menced	Reached TD	Rig released			
Bonaparte Gulf	Tamar 1	WA-70-P	Getty	NFW	11°52′15″	126°12′40″	....	31	64	15/2/79	11/4/79	23/4/79	2 863	Triassic	Dry, P & A
Browse	Brecknock 1	WA-33-P	Woodside	NFW	14°26′13″	121°40′21″	....	11	544	31/7/79	9/11/79	12/12/79	4 300	Triassic	Gas shows, P & A
	Barcoo 1	WA-32-P	Woodside	NFW	15°20′38″	120°38′12″	....	11	720	14/12/79	....	....	2 174	....	Drilling
Canning	Bruce 1	WA-58-P	W. Energy	NFW	19°22′32″	117°55′41″	....	21	77	19/7/79	3/8/79	11/8/79	2 168	L/M Triassic	Dry, P & A
	Ellendale 1	EP101	Amax	NFW	17°54′18″	124°42′15″	95	100	....	24/7/79	1/10/79	15/10/79	3 190	?U. Devonian	Gas shows, P & A
	Puratte 1	EP104	Esso	NFW	17°05′16″	123°14′18″	27	33	....	3/11/79	31/12/79	....	3 750	....	Logging
Carnarvon	Goodwyn 5	WA-28-P	Woodside	EXT	19°40′42″	115°53′45″	....	8	129	5/12/78	27/1/79	27/2/79	3 664	U. Triassic	Gas well
	Sultan 1	WA-25-P	WAPET	NFW	20°02′39″	115°11′21″	....	21	146	18/1/79	7/3/79	20/3/79	3 620	U. Triassic	Dry, P & A
	Pueblo 1	WA-28-P	Woodside	NFW	19°46′32″	115°51′43″	....	30	112	8/3/79	20/4/79	26/4/79	3 485	U. Triassic	Gas shows, P & A
	Campbell 1	WA-23-P	WAPET	NFW	20°24′42″	115°43′00″	....	22	145	20/3/79	27/4/79	30/4/79	2 750	U. Jurassic	Dry, P & A
	Walcott 1	WA-28-P	Woodside	NFW	19°37′05″	116°22′17″	....	8	81	13/7/79	16/11/79	23/11/79	4 383	M. Jurassic	Gas shows, P & A
	Barrow F72	PL1H	WAPET	NPW	20°51′12″	115°22′40″	9	12	....	18/8/79	22/8/79	24/8/79	796	L. Cretac.	Oil well
	Parker 1	WA-28-P	Woodside	NFW	20°00′08″	115°40′08″	....	8	80	26/11/79	....	....	3 078	....	Drilling
"Exmouth Plateau"	Zeewulf 1	WA-96-P	Esso	NFW	21°06′33″	113°37′01″	....	10	1 194	5/3/79	28/4/79	5/5/79	3 500	U. Triassic	Gas shows, P & A
	Gandara 1	WA-93-P	Hudbay	NFW	19°16′31″	115°49′15″	....	21	308	9/5/79	8/7/79	15/7/79	4 361	U. Triassic	Dry, P & A
	Investigator 1	WA-96-P	Esso	NFW	20°21′07″	112°58′01″	....	10	841	7/5/79	11/7/79	17/7/79	3 746	U. Triassic	Gas shows, P & A
	Jupiter 1	WA-84-P	Phillips	NFW	19°34′54″	113°31′58″	....	10	960	16/5/79	14/10/79	17/10/79	4 946	? Triassic	Gas shows, P & A
	Resolution 1	WA-97-P	Esso	NFW	21°17′58″	113°41′24″	....	10	1 086	23/7/79	1/11/79	10/11/79	3 884	U. Triassic	Gas shows, P & A
	Mercury 1	WA-84-P	Phillips	NFW	19°33′54″	113°52′42″	....	10	1 142	29/10/79	19/12/79	31/12/79	3 812	U. Triassic	Dry, P & A
	Scarborough 1	WA-96-P	Esso	NFW	19°53′06″	113°08′45″	....	10	912	11/11/79	9/12/79	19/12/79	2 360	U. Jurassic	Gas shows, P & A
	Vinck 1	WA-97-P	Esso	NFW	20°35′04″	112°11′34″	....	10	1 383	20/12/79	....	....	2 515	....	Drilling

Getty: Getty Oil Development Co. Ltd
Woodside: Woodside Petroleum Development Pty Ltd
W. Energy: Western Energy Pty Ltd
Amax: Amax Iron Ore Corporation
Esso: Esso Exploration & Production Aust. Inc.
WAPET: West Australian Petroleum Pty Ltd
Hudbay: Hudbay Oil (Aust.) Ltd
Phillips: Phillips Australian Oil Co.

NFW: New-field-wildcat well
NPW: New-pool-wildcat well
EXT: Extension test well
P & A: Plugged and abandoned

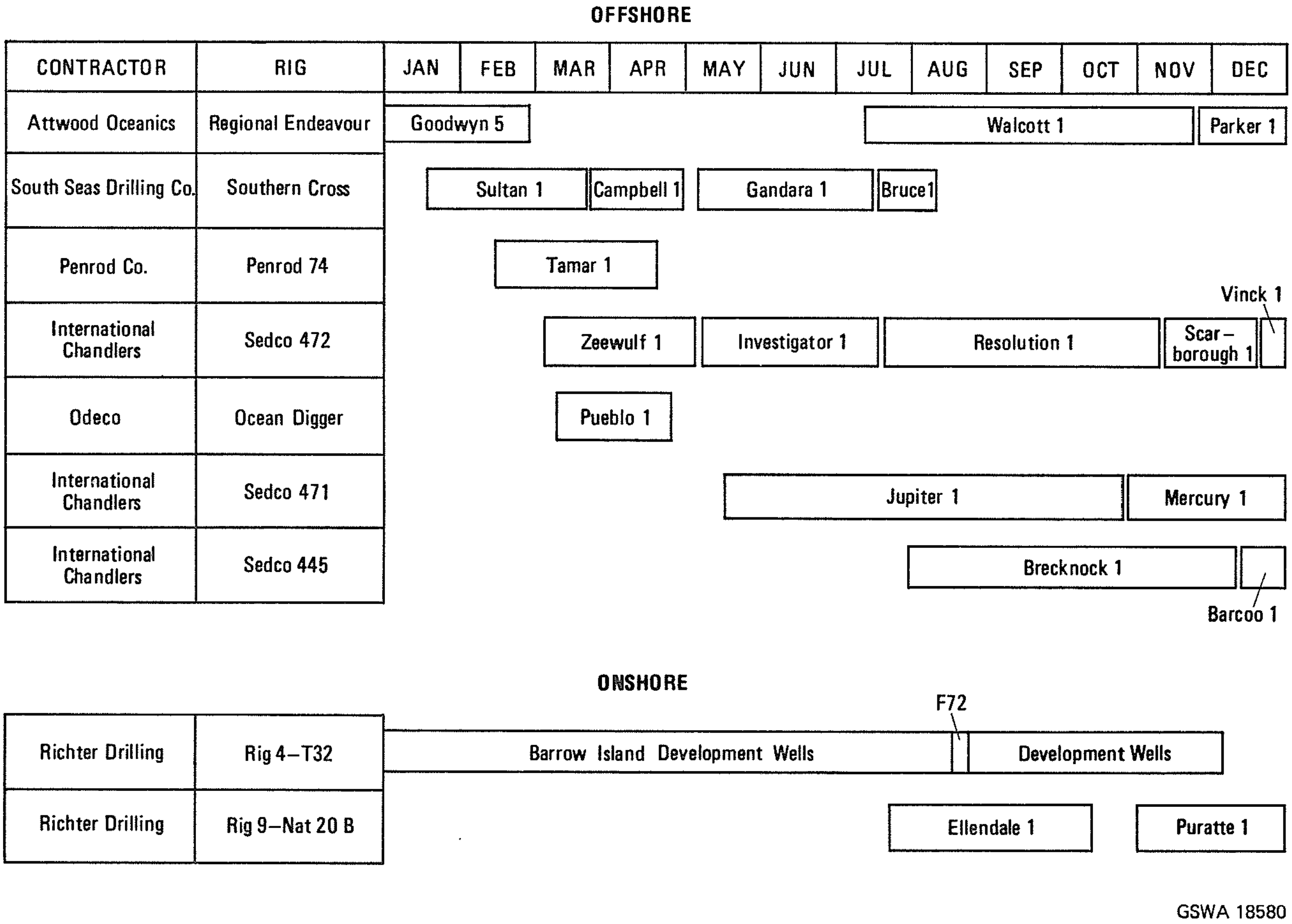

Figure 2 Rig utilization, 1979.

Bonaparte Gulf Basin

Getty Oil Development Co. Ltd completed one well, Tamar 1, in the Bonaparte Gulf Basin in 1979. This was drilled in Exploration Permit WA–70–P on an anticlinal structure, 76 km southwest of Eider 1 and 100 km south-southwest of Flamingo 1. The main objectives were Middle to Lower Jurassic sands and, although porous sands were encountered in all target horizons, there were no significant hydrocarbon shows. The well was plugged and abandoned at a total depth of 2 863 m in Upper Triassic rocks.

Browse Basin

Woodside Petroleum Development Pty Ltd completed one well in the Browse Basin (Brecknock 1) and was drilling a second (Barcoo 1) at the end of the year. Brecknock 1 was drilled in WA–33–P in 544 m of water on a horst block on the Scott Reef trend, located about 32 km south-southwest of Scott Reef 2. Gas-bearing sandstones were encountered in the section between 3 843 and 3 934 m. A production test was attempted on this zone but it failed for mechanical reasons. It is believed that this is the deepest water in which such a production test has been attempted anywhere in the world. The well was abandoned at a total depth of 4 300 m. Although this discovery cannot be considered economic at current prices and with current production technology because of the water depth, the well was encouraging in confirming the Browse Basin as a hydrocarbon-bearing province.

Canning Basin

In the Canning Basin one offshore well and one onshore well were completed, and a second onshore well, Puratte 1, drilled by Esso, reached its total depth on December 31st.

The offshore well, Bruce 1, was drilled by Western Energy Pty Ltd on the southern edge of the Beagle Sub-basin, in WA–58–P, on a large fault-induced anticlinal feature, about 22 km west-southwest of Poissonnier 1. The well was drilled to a depth of 2 168 m in the Triassic, penetrating a total of 1 121 m of Triassic sediments. No significant hydrocarbon shows were reported, and the well was plugged and abandoned.

In the onshore Canning Basin, Amax Iron Ore Corporation completed Ellendale 1 in EP101, about 26 km northwest of Mt Hardman 1. The objectives of this well were Lower Carboniferous sands and possible carbonate build-ups in the Late Devonian. At the total depth of 3 190 m, the well was probably in the Upper Devonian. Three drillstem tests were conducted, the first of which, over the interval 2 366 to 2 373 m, was mechanically unsuccessful. DST 2, over the interval 2 155 to 2 173 m, yielded some low-pressure gas and a trace of low-gravity oil. DST 3, over the interval 1 649 to 1 701 m, also recovered a small amount of gas and a trace of condensate. It was abandoned as a dry hole.

Carnarvon Basin

Four new-field-wildcat wells were drilled in the offshore Carnarvon Basin, as well as one new-pool-wildcat on Barrow Island. One extension test, Goodwyn 5, commenced in 1978, and was completed as a suspended gas well, and one exploratory well, Parker 1, was drilling at the end of the year.

Woodside completed three wells: Goodwyn 5, Pueblo 1, and Walcott 1. Pueblo 1 was drilled in WA–28–P, in 112 m of water, to investigate Upper Triassic sandstones on a fault block downdip from Goodwyn 3. Only very thin gas sands were penetrated in this well, and it was abandoned as a dry hole at 3 485 m.

Walcott 1 was drilled in 81 m of water in WA–28–P, approximately 3·8 km north-northeast of Madeleine 1, to test sandstone below the Jurassic unconformity, in an upthrown position relative to the Madeleine structure. This well bottomed in Middle Jurassic shales. Some gas was encountered, but permeability was low, and the well was plugged and abandoned.

Two wells were drilled by West Australian Petroleum Pty Ltd (WAPET) in the offshore Carnarvon Basin: Sultan 1 and Campbell 1. Sultan 1 was completed in WA–25–P, on a structural closure on the Rankin Trend, between the West Tryal Rocks discovery and North Tryal Rocks 1. No significant hydrocarbon shows were encountered, and the well was abandoned at 3 620 m in Upper Triassic rocks.

Campbell 1 was drilled on a simple anticlinal feature in WA–23–P, on a trend with the Barrow Anticline, 25 km to the southwest, and the Rosemary-Legendre feature to the northeast. No significant shows of gas and oil were encountered, and the well was plugged and abandoned at 2 750 m in the Upper Jurassic Dupuy Formation.

Barrow F72 was drilled by WAPET on Barrow Island, and was classified as a new-pool wildcat. The well found oil in the "Windalia sand" (Lower Cretaceous) in a separate small fault block to the south of the main Barrow Island Oil Field.

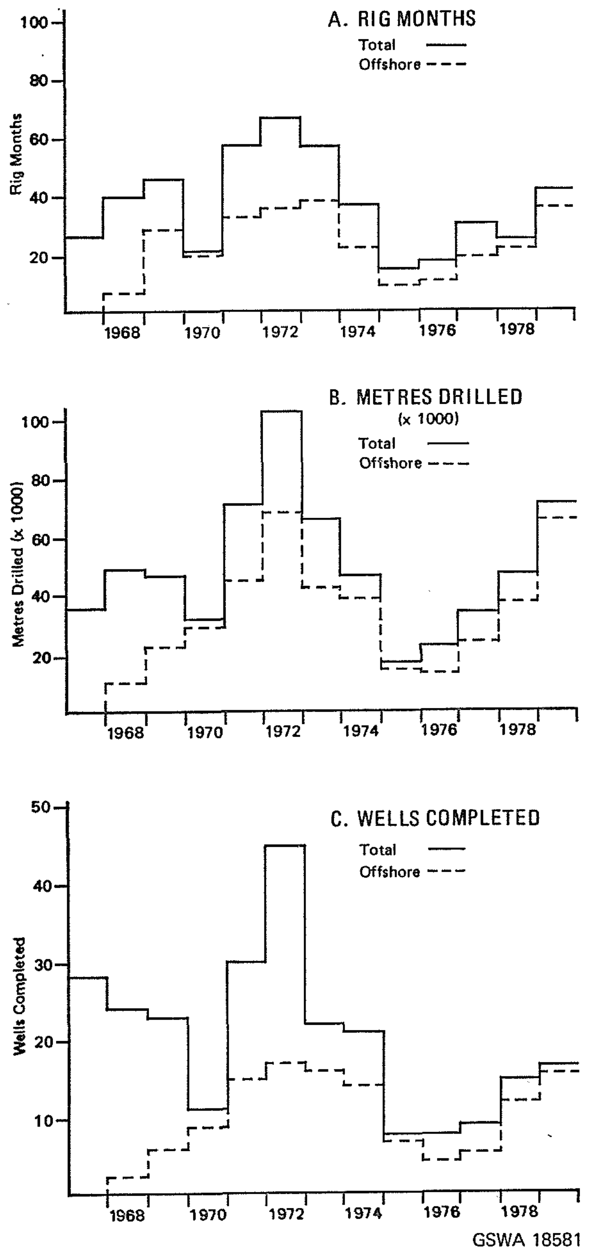

Figure 3 Drilling operations since 1967.

Barrow Island development wells

During 1979 40 development wells were drilled by WAPET within the Barrow Island Oil Field. Ten of these were classed as development wells, 26 as infill wells, two as water-injection wells, one as a water-source well, and one was a dry hole.

The status of these wells at the end of the year is shown in Table 2. A total of 28 433 m of development drilling was carried out in the year. Twenty-seven of the wells were completed as "Windalia sand" oil producers, one as a Muderong Shale oil producer, one as a Gearle Siltstone oil producer, and one as a Gearle Siltstone gas producer. Three were completed as water-injection wells, three were awaiting stimulation, one was testing, and three were shut in.

Exmouth Plateau area

The most significant feature of Western Australian petroleum exploration in 1979 was the drilling of seven wells in the deep-water areas of the Exmouth Plateau, in water depths between 841 m and 1 194 m. At the end of the year, Esso was drilling Vinck 1 in 1 383 m of water, which is very close to the maximum water depth in which a conventional oil-well drilling programme has been carried out anywhere.

Esso completed four wells in this area: Zeewulf 1, Investigator 1, Resolution 1 and Scarborough 1. Zeewulf 1 was drilled in WA–96–P, in 1 194 m of water, 82 km northwest of Muiron 1, on a northeast-trending horst feature. Only minor hydrocarbon shows were recorded after encountering porous sands, and the well was abandoned at a total depth of 3 500 m, in Upper Triassic rocks.

Esso's second well, Investigator 1, also in WA–96–P, in the central part of the Exmouth Plateau, was located about 200 km north-northwest of North West Cape, and was drilled in 841 m of water to a total depth of 3 746 m, in rocks of Late Triassic age. Although some minor gas was encountered, the well was plugged and abandoned.

Following this well, Esso drilled Resolution 1 in WA–97–P, 22 km south-southeast of Zeewulf 1, in 1 086 m of water. Although some minor gas was recorded the well was plugged and abandoned in Upper Triassic rocks, after having been sidetracked from 3 758 to a total depth of 3 884 m.

Esso's fourth well, Scarborough 1 was drilled on a broad domal structure located 55 km north-northeast of Investigator 1, and 145 km north-northwest of Zeewulf 1, in 912 m of water. The well encountered gas-bearing Lower Cretaceous sandstone, but because of the water depth this discovery is not considered to be commercial, and the well was abandoned.

Phillips Australian Oil Company drilled two wells, Jupiter 1 and Mercury 1, in its Exmouth Plateau permit, WA–84–P. Jupiter 1 was located near the crest of the plateau in 960 m of water on one of the largest and highest of a series of tilted fault blocks. Only minor gas shows were recorded and the well was abandoned at 4 946 m in the Triassic.

Mercury 1 was drilled, about 40 km east-northeast of Jupiter 1, in a water depth of 1 142 m. It is on the eastern side of the Exmouth Plateau Arch on the first major closed structure west of the Kangaroo Syncline. No significant hydrocarbon shows were encountered, and the well was plugged and abandoned.

Hudbay Oil (Aust.) Ltd drilled one well (Gandara 1) in its permit WA–93–P, in relatively shallow water (308 m) on a horst block on the Brigadier Trend, which, although in the general Exmouth Plateau area, is considered to be in the

TABLE 2. STATUS OF BARROW ISLAND DEVELOPMENT WELLS

Well Name	TD	Status	Well Name	TD	Status
L28	762	Oil producer—Windalia	L41G	626	Shut in
L18	762	Oil producer—Windalia	L32G	643	Oil producer—Gearle
G87A	707	Oil producer—Windalia	F72	796	Oil producer—Windalia
B15A	741	Oil producer—Windalia	F81A	721	Oil producer—Windalia
G85A	744	Oil producer—Windalia	G88A	686	Oil producer—Windalia
B13A	753	Oil producer—Windalia	B18A	683	Oil producer—Windalia
G84A	760	Oil producer—Windalia	B26A	709	Oil producer—Windalia
B14A	724	Oil producer—Windalia	B25A	706	Oil producer—Windalia
G86A	716	Oil producer—Windalia	B21A	770	Oil producer—Windalia
B24A	732	Oil producer—Windalia	B22A	753	Oil producer—Windalia
B17R	677	Water injection	B11A	777	Oil producer—Windalia
B16M	926	Oil producer—Muderong	B12A	762	Oil producer—Windalia
Q87	774	Oil producer—Windalia	G81A	771	Oil producer—Windalia
Q85	778	Oil producer—Windalia	G82A	786	Oil producer—Windalia
L15	777	Oil producer—Windalia	G83A	757	Oil producer—Windalia
L17	753	Water injection	B32A	750	Oil producer—Windalia
Q86	762	Water injection	B33A	737	Awaiting stimulation
E21G	504	Shut in	B34A	716	Awaiting stimulation
L78G	455	Gas producer—Gearle	B35A	707	Awaiting stimulation
L58G	436	Shut in	R88G	433	Testing

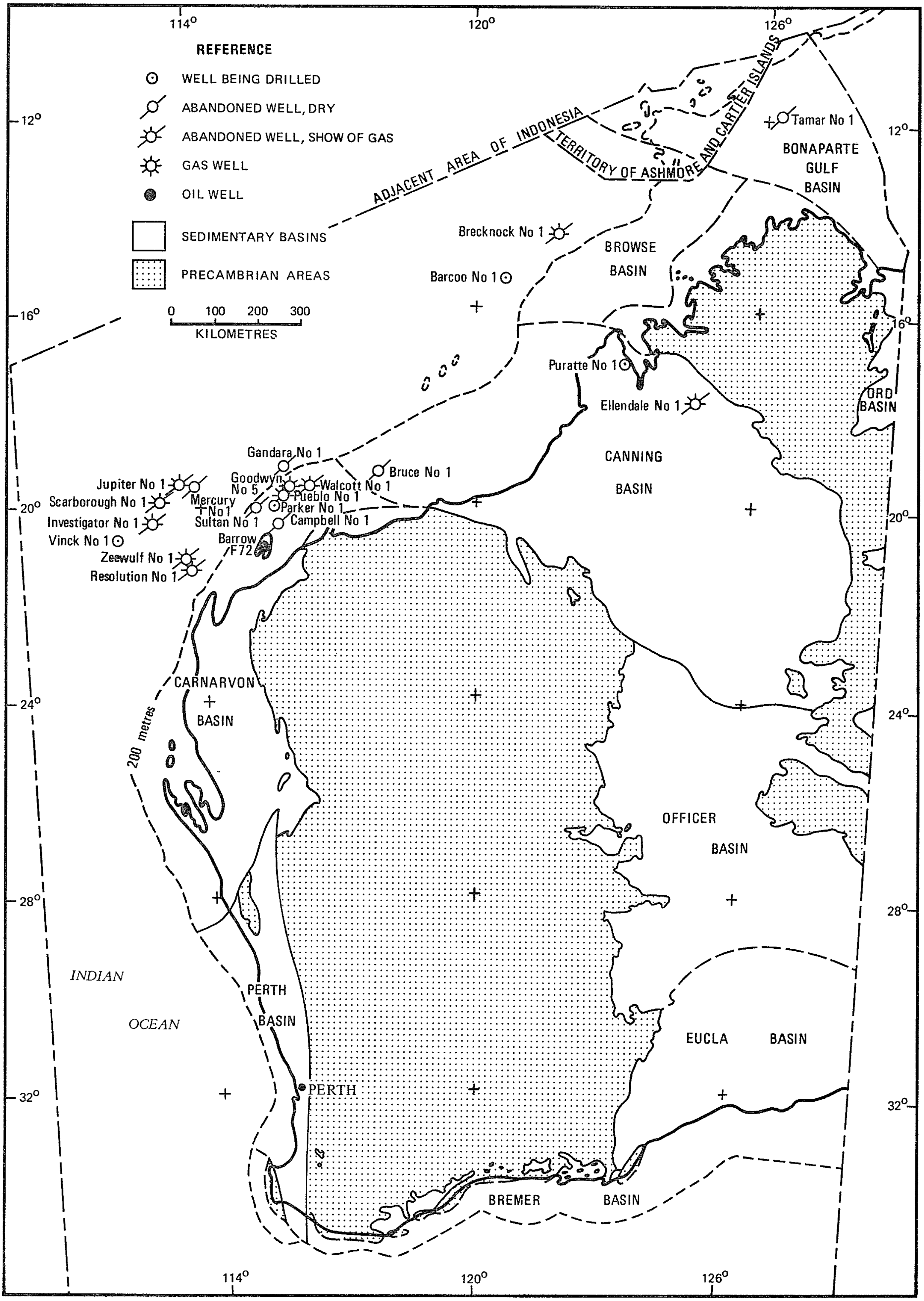

Figure 4 Map showing wells drilled for petroleum in W.A. during 1979.

northern part of the Carnarvon Basin. No significant shows of oil or gas were recorded, and the well was abandoned as a dry hole.

GEOPHYSICAL SURVEYS

Geophysical surveys consisted mainly of seismic surveys. These decreased in line kilometres by about 32 per cent compared to 1978. This decrease was to be expected because 1978 had been the year when the exploration companies conducted their initial large regional surveys on the newly awarded Exmouth Plateau permits. In the second stage of exploration in this deep-water area there was more emphasis on drilling.

Other geophysical activities were marine gravity and magnetic surveys, largely in conjunction with seismic surveys.

SEISMIC

During 1979, offshore seismic surveys were conducted in the Eucla Basin (3 151 km), Carnarvon Basin (4 642 km), Canning Basin (1 789 km), Browse Basin (1 994 km), Bonaparte Gulf Basin (1 906 km), and in the Exmouth Plateau area (12 830 km). Onshore seismic surveys were conducted in the Perth Basin (257 km), the Carnarvon Basin (2 km), and the Canning Basin (650 km). Details are as follows:

SEISMIC SURVEYS—ONSHORE

Basin	Tenement	Company	Line km
Perth	EP96	XLX N.L.	60
	EP100	N.W. Mining	187
	EP111	Jervois Sulphates (NT) Ltd	10
Carnarvon	EP137	J. O. Clough & Son Pty. Ltd	2
Canning	EP104	Esso Exploration & Production Aust. Inc.	182
	EP102	Amax Iron Ore Corporation	137
	EP129	Home Oil Aust. Ltd	331
Total			909

SEISMIC SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Eucla	WA-125-P WA-126-P	Esso Exploration & Production Aust. Inc.	3 151
Carnarvon	WA-28-P	Woodside Petroleum Development Pty Ltd	333
	WA-58-P	Western Energy Pty Ltd	459
	WA-64-P	Offshore Oil N.L.	360
	WA-81-P	Continental Oil Co. of Aust. Ltd	1 389
	WA-102-P	Canada North West Land Ltd	1 789
	WA-110-P	CNW Oil (Aust.) Pty Ltd	161
	WA-116-P	Geometals N.L.	151
Canning	WA-62-P	Oxoco International Inc.	402
	WA-79-P	Getty Oil Development Co. Ltd	725
	WA-109-P	Esso Exploration & Production Aust. Inc.	662

SEISMIC SURVEYS—OFFSHORE—*continued*

Basin	Tenement	Company	Line km
Browse	WA-32-P	Woodside Petroleum Development Pty Ltd	70
	WA-33-P	Woodside Petroleum Development Pty Ltd	389
	WA-34-P	Woodside Petroleum Development Pty Ltd	115
	WA-37-P	Woodside Petroleum Development Pty Ltd	73
	WA-68-P	Oxoco International Inc.	262
	WA-104-P	Oberon Oil Pty Ltd	1 085
Bonaparte Gulf	WA-74-P	Pelsart Oil N.L.	1 021
	WA-77-P	Magnet Metals Ltd	487
	WA-103-P	Lennard Oil N.L.	398
Exmouth Plateau Area	WA-84-P	Phillips Aust. Oil Co.	3 716
	WA-90-P	Woodside Petroleum Development Pty Ltd	1 072
	WA-93-P	Hudbay Oil (Aust.) Ltd	1 382
	WA-96-P	Esso Exploration & Production Aust. Inc.	4 164
	WA-97-P	Esso Exploration & Production Aust. Inc.	2 496
Total			26 312

GRAVITY

One marine gravity survey was conducted, mainly over Exploration Permits WA-1-P and WA-28-P, and other gravity surveys were carried out in conjunction with marine seismic surveys, as follows:

GRAVITY SURVEYS—OFFSHORE

Basin	Tenement	Company	Line km
Carnarvon	WA-1-P	Woodside Petroleum Development Pty Ltd	1 924
	WA-28-P	Woodside Petroleum Development Pty Ltd	2 746
	WA-102-P	Canada North West Land Ltd	130
Exmouth Plateau Area	WA-84-P	Phillips Aust. Oil Co.	3 700
	WA-90-P	Woodside Petroleum Development Pty Ltd	53
	WA-93-P	Hudbay Oil (Aust.) Ltd	1 073
Total			9 626

MAGNETIC

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

MAGNETIC SURVEYS

Basin	Tenement	Company	Line km
Carnarvon	WA-102-P	Canada North West Land Ltd	130
Exmouth Plateau Area	WA-84-P	Phillips Aust. Oil Co.	3 700
	WA-93-P	Hudbay Oil (Aust.) Ltd	1 073
Total			4 903

REFERENCE

Crank, K. A., 1980, Wells drilled for petroleum exploration in W.A. to the end of 1979: West. Australia Geol. Survey Rec. 1980/1.

A FORMATION TEMPERATURE STUDY OF THE CARNARVON BASIN

by H. T. Moors

ABSTRACT

From borehole temperature measurements in 120 oil exploration wells in the Carnarvon Basin, approximately 350 formation temperatures were determined. The temperature gradient in each well was calculated using the difference between the surface temperature and the deepest measured formation temperature. These range from 2·08 to 14·9°C/100 m, with a median value of 3·3°C/100 m. Heat input from ancient crystalline basement is well expressed by low temperature gradients where the sedimentary section is thick (Barrow Sub-basin), and increased gradients where the section thins (at the base margin). High temperature anomalies are associated with faults; the excess heat could be due to residual mechanical energy from Miocene and younger movement, or hot deeper formation fluids migrating up the fault planes. Up-dip migration of hot basinal waters is suggested to explain high anomalies in the Robe River area. A thick Tertiary carbonate wedge in the offshore northwestern part of the basin lowers the geothermal gradient, because of its rapid rate of deposition, and also because its porous nature allows dissipation of heat by convective processes in formation fluids, with concurrent heat conduction.

INTRODUCTION

Estimates of the formation temperatures to be encountered in a sedimentary basin are essential for the prediction of the porosity of potential reservoir rocks, the maturity of potential source rocks, and hence the time of migration and generation of oil and gas. To this end, all the temperature data available from oil-exploration wells in the Carnarvon Basin were examined, and as many formation temperatures as possible were calculated. The present-day overall geothermal gradient (from the surface to the deepest formation temperature determined) for each well was plotted and contoured to provide coverage for the whole basin (Fig. 1). The calculated formation temperatures for each well are presented in Table 1, as well as sectional and overall gradients between data points. The average surface temperature is taken as 25°C both on land and on the sea bottom. Investigation of sea-water temperatures has revealed that a high degree of mixing results in a uniform water temperature at all depths, at least on the continental shelf. A plot of temperature/depth relationships of all the wells, extrapolated to the surface, gives a broad range of surface temperatures, but suggests that 25°C is a valid assumption. The extrapolated surface temperatures of the land wells appear to be somewhat higher, but with the sparse data available no adjustment is justified.

CALCULATION OF FORMATION TEMPERATURE

It is standard practice to include a mercury, maximum-reading thermometer with the sondes for each suite of electric logs run in exploration wells. However, it is obvious that the bore-hole temperature (BHT) measured cannot be the true formation temperature. Circulation fluids, used whilst drilling, cool the surrounding formation to below its natural temperature and, therefore, the BHT requires adjustment to true formation temperature.

Numerous methods of correction are available, but that adopted here is the time-ratio method, simply described by Fertl and Wickmann (1977). It utilises the ratio between the time (T_1) of formation cooling whilst drilling and the times (T_2) of temperature build-up in the form $T_1 + T_2/T_2$. Cooling takes place during drilling and circulating before logging, while temperature build-up commences at the end of mud circulation and continues while the suite of logs is run. The true formation temperature is not regained until the time of thermal build-up is much larger than the time of cooling. This is achieved when the time ratio $T_1 + T_2/T_2$ approaches one. Therefore, the BHT for each log run is plotted against its time ratio (for simplicity on a logarithmic axis) and a line through these points is extended to a time ratio of one. The associated temperature is recorded as the true formation temperature (Fig. 2). A more mathematical treatment with additional references can be found in Evans and Coleman (1974), and Dowdle and Cobb (1975).

Unless the daily drilling log for the well under study is available, it is usually necessary to estimate the time of cooling, T_1. As the temperature is recorded some distance above the bottom of the drilled hole, cooling takes place while the drill is penetrating beyond the point at which the reading is subsequently made. It is also frequently necessary to circulate for a period after drilling stops, to bring up samples or to condition the mud and hole before logging. At shallower depths, the rate of drilling is usually faster and mud circulation takes less time, so a lower value of T_1 is selected. At depths less than 1 000 m, 2 hours is used for T_1; between 1 000 and 2 000 m, 3 hours; between 2 000 and 3 000 m, 4 hours; between 3 000 and 4 000 m, 5 hours; and below 4 000 m, 6 hours. Complications such as reconditioning of the hole and/or mud have not been taken into account. Some examples are given in Figure 2.

The largest maximum difference recorded between a bore-hole temperature and the calculated formation temperature is approximately 30°C, but the difference is usually less. Not only is the formation temperature significant in the rate of temperature readjustment, but the lithology (depth of invasion of circulation fluid), and perhaps the drilling conditions (bore diameter, etc.), have an effect. This may explain why in some wells the rate of temperature readjustment appears to be above, or below, the norm, throughout the whole temperature range of the well (Fig. 2b). In some cases, a marked divergence in rate of change from the norm for a given temperature can be attributed to a variation in lithology.

Only one temperature was recorded for the whole logging suite in early wells and to utilize these data a nomogram was constructed. The temperature build-up-trends from all wells with a good fit of three or more points (e.g. Fig. 2a, Anchor 1, 2 143 m, 3 051 m, but not 1 217 m) were plotted on one set of axes (Fig. 2b). Two or more apparently independent families occur, presumably due to differing drilling techniques or formation lithology, and only the more common family (solid lines) was adopted in this study. For a single value well, a time ratio of 1·5 is chosen (as a general value assuming the temperature was taken on the middle log run), and the measured temperature was corrected by moving parallel to the nearest build-up trend line. In the example in Figure 2b, a measured temperature of 133°C is thus corrected to 141°C as the formation temperature.

SOURCES OF HEAT

Sources of heat in a sedimentary basin fall into two basic categories:

(1) sources from outside the sediments, which include
  - (i) heat flow from deep within the earth via basement,
  - (ii) heat from igneous intrusives, and
  - (iii) heat introduced by migrating fluids; and

(2) sources within the sediments
  - (i) radiogenic content,
  - (ii) clay-mineral diagenesis,
  - (iii) compactional friction, and
  - (iv) deformational energy.

No obvious evidence exists for the presence of igneous intrusives, but proximity to basement is well expressed in the temperature-gradient pattern, and an anomalously high geothermal gradient in the Robe River area could be attributed to migration of hot fluids. The intra-sedimentary sources would have greatest expression on vertical temperature profiles, but because of the limited vertical control (usually only three temperature values per well), if they are present, they have not been detected in this study. However, anomalous high temperatures in the North West Cape region could possibly be due in part to recent activity of adjacent faults providing deformational energy.

GEOTHERMAL GRADIENT DISTRIBUTION

Over 120 wells were found to contain sufficient information for an estimate of the formation temperature to be made, providing nearly 350 separate values. Many of the shallower wells have only one temperature reading, taken at the completion of the well. The deeper oil exploration wells usually have three temperature values, taken progressively as the well is drilled, but two or four values are common.

Unfortunately, the distribution of the data points is very uneven, with a concentration of 100 wells in the northern Mesozoic portion of the basin, but only 20 wells in the south. The northern area thus shows much more detail than the south, is more reliable, and can be sensibly contoured with a finer contour-interval spacing. A lot of gradient data are available in the south from water-bore temperatures. Unfortunately, most of these come from shallow depths and the geothermal gradient is thus very susceptible to inaccuracy of formation-temperature measurements or surface-temperature estimation. The water-bore gradients have been used very generally as form lines in areas of little data, but at best only reflect the near-surface gradients and are disregarded if in conflict with deeper data. As a rule, it has been possible to contour the data points without conflict. Discrepancies occur, but apart from Locker 1 and Onslow 1 they are fairly minor, or are shown to be spurious by adjacent data, for example North Rankin 3 or Goodwyn 4.

The maximum overall present-day geothermal gradient is 14·9°C/100 m at Mulyery 1, and the minimum is 2·08°C/100 m at Kalbarri 1. The 3·3°C/100 m contour divides the study area into almost equal portions and can be regarded as the basin average. A world-wide average geothermal gradient is considered to be 3·0°C/100 m (Tissot and Welte, 1978), making the Carnarvon Basin a slightly hot area.

The most obvious trend on the geothermal-gradient map is an increase in the gradient from west to east. This trend in the eastern portion of the basin is probably controlled by the depth to basement. The basement can be assumed to be in thermal equilibrium and conducts heat at a fixed rate. The younger, overlying sediments, on the other hand, are still in disequilibrium because of their more recent deposition and thermal insulative properties. Thus, where the sedimentary section is thin, the sediments more rapidly reach thermal equilibrium, and a higher temperature gradient results, than in other areas where the sedimentary blanket is thicker. The thick sedimentary piles of the Lewis, Barrow and Merlinleigh Sub-basins are thus well expressed by trends of low geothermal gradient.

The continued decrease in geothermal gradient in the north-western portion of the basin is a function of the thick pile of Tertiary sediments in this area. During rapid sedimentation the thermal front cannot keep pace with the rapidity of burial, and the geothermal gradient drops. As well, the Tertiary

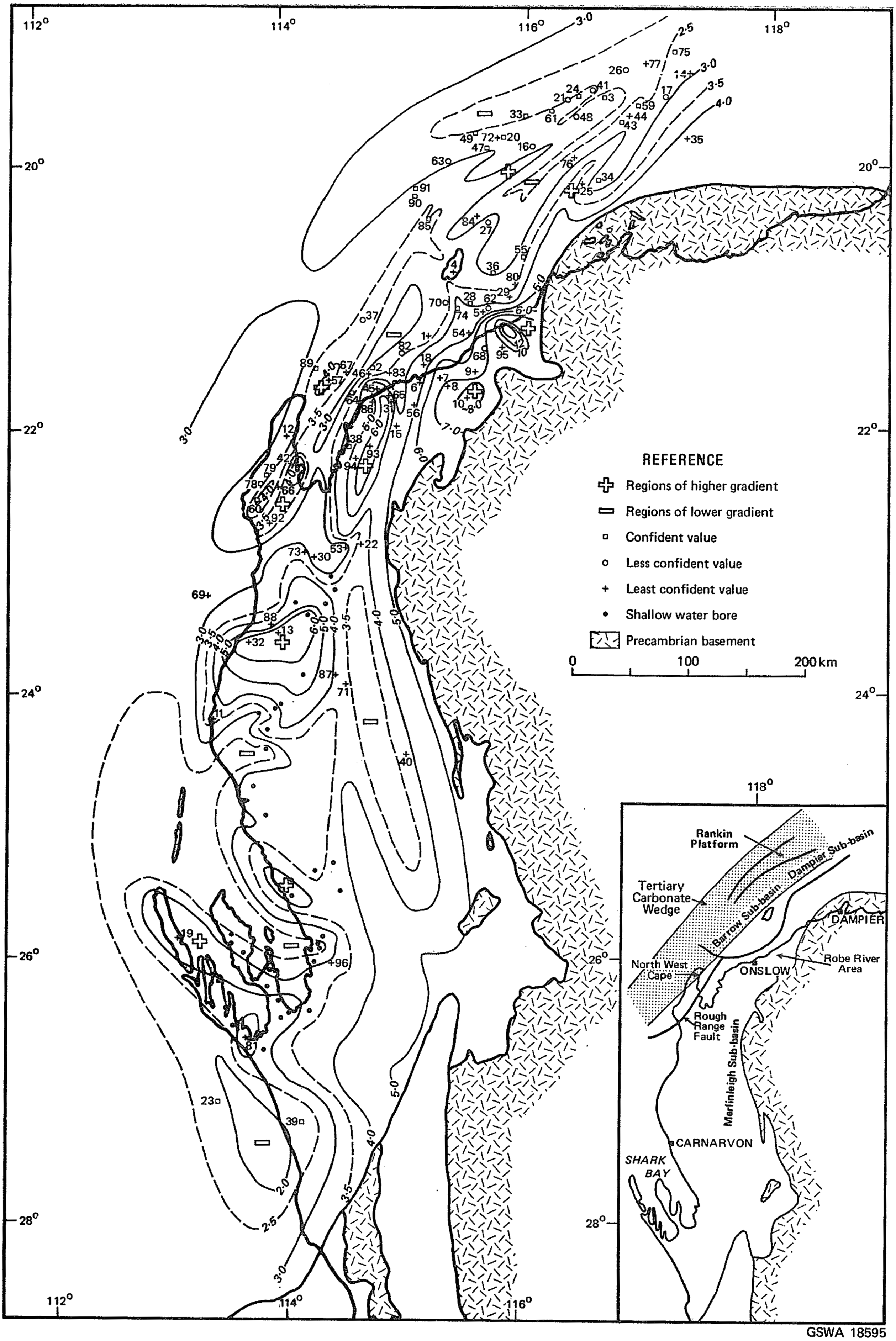

Figure 1 Contour map of present-day overall geothermal gradients, in °C/100 m, Carnarvon Basin. Simplified in the Robe River area due to congestion of data. Wells used are keyed to Table 1.

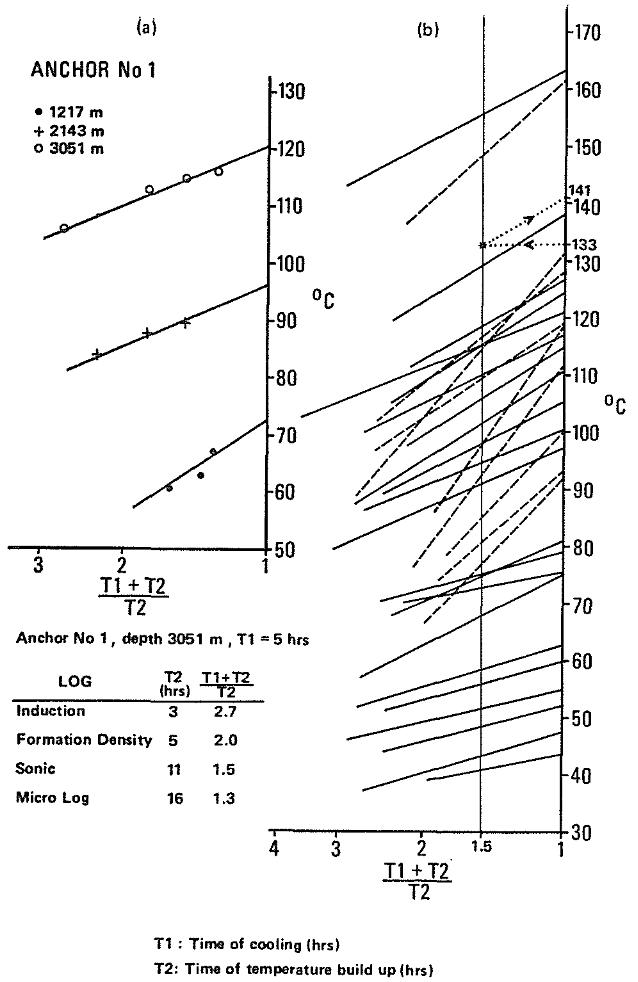

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Figure 2 Time-ratio graphical solution of true formation temperature from bore-hole temperature.
(a) Example well, Anchor No. 1.
(b) Nomogram developed for formation temperature estimation for 36 wells, with only one bore-hole temperature reading in each. Measured temperature entered at time-ratio 1·5, moved parallel to trend lines to true formation temperature at time ratio 1. Solid lines are favoured trend, dashed lines probably reflect variations in lithology or drilling operations.

section consists predominantly of coarse, porous and permeable carbonates through which formation water is able to circulate freely. Thus, a convection process of heat transfer occurs in tandem with the conductive process, making heat transfer more efficient. This lowers the formation temperature, resulting in a lower geothermal gradient. As the carbonate wedge thins beyond the Rankin Platform, the geothermal gradient can be expected to rise again.

Conversely, in the case where there is no permeability, the geothermal gradient is usually increased. The high gradient trends to the south of the Rankin Platform, and the Dampier trend, could be manifestations of this process. In these areas overpressured shales are prevalent. These shales are very porous, but lack permeability, making the convective process of heat transfer inoperable, thus increasing the formation temperature and hence the gradient. A compounding feature is that the overpressured shales contain large volumes of water, which has a thermal conductivity four to five times less than the constituent minerals, making the conductive transfer of heat even less efficient than in a normal shale.

Another obvious feature of the contour map is the presence of linear zones of high geothermal gradient in the North West Cape region. Their linear nature suggests that they are probably associated with the underlying Rough Range and Paterson Faults. The Cape Range and Rough Range Anticlines are generally believed to be due to late Miocene to Quaternary reactivation along these faults. The high geothermal gradients may be due to insufficient time having elapsed for dissipation of the deformational energy. A more likely reason, however, could be the presence of high-temperature formation fluids, from deep within the basin, migrating up the fault planes. The location of a small oil accumulation at Rough Range 1 also suggests that the faults may have acted as conduits for deeper expelled fluids.

The hot anomaly in the Gnaraloo 1—Chargoo 1 area may also be due to fluids migrating up faults associated with the anticlines in this area.

The anomaly with greatest amplitude occurs in the Robe River area. Gradients above 10°C/100 m exist with a maximum of 14·9°C/100 m recorded in Mulyery 1. Unfortunately, temperature data in many of the wells are unreliable, and as the sedimentary section here is very thin (100–200 m) even small temperature errors lead to large variations in the calculated geothermal gradient. Nonetheless, the presence of anomalously high values cannot be denied.

A possible explanation is that fluids from deeper in the basin are channelled through this region. Thomas (1978) has shown that the so-called "Robe River Embayment" acted as a migration path for hydrocarbons from the Barrow Sub-basin; presumably even more formation water has passed the same way. The Barrow Island structure drains a large portion of the Barrow Sub-basin, and has a spill point offshore from the Robe River. Fluids gathered by the structure are channelled through the spill point. The path taken by these fluids can be traced by an inflection in the gradient contours all the way to Barrow Island, though the magnitude diminishes as the sediment pile thickens. Thomas (1978, Fig. 12) produced salinity data suggesting the flow of surface water into the basin. He also pointed out that he believed this inflow ceased towards the end of the Tertiary (Thomas, 1978, p. 16), and that the present flow may again be out of the basin, but flushing is still incomplete. This would still be compatible with the hypothesis presented here.

The reason for the region of high geothermal gradients in the Shark Bay area is not clear. The data available are poor and widely spaced so that the contouring shown in this area on Figure 1 may be inaccurate. It would be expected that this area should be a geothermal low as it is basically in a position of thick sediments and is underlain by the evaporitic sequence of the Dirk Hartog Formation. Evaporites are very efficient conductors of heat, which should result in a low geothermal gradient. This is clearly shown in Yaringa 1, where the temperature change of only 4°C between 868 m and 2 288 m can be attributed to the evaporitic section over this interval.

CONCLUSIONS

The present-day geothermal gradient of the Carnarvon Basin is higher than the world-wide average. Control of the geothermal gradient by varying thermal transmissibility properties is clearly shown by the part played by the Tertiary carbonates east of the Rankin Platform, and over-pressured shales in parts of the Dampier Sub-basin. The influence of external energy sources such as, proximity to basement, deformational energy, or migration upwards of deeper fluids, can also be detected, for example in the Cape Range and Robe River areas.

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TABLE 1. FORMATION TEMPERATURE AND GEOTHERMAL GRADIENTS, SECTIONAL AND PROGRESSIVE OVERALL; OIL EXPLORATION WELLS, CARNARVON BASIN. WELL NUMBERS ARE KEYED TO FIGURE 1.

Well Name	Fig. 1 No.	Derrick Floor Elevation (m)	Depth (m)	Temperature (°C)	Sect. Grad. (°C/100 m)	Overall Grad. (°C/100 m)
Airlie 1	1	5	1 050	(65)	3·81	3·81
			2 220	(100)	2·99	3·38
Anchor 1	2	42	1 217	73	4·09	4·09
			2 143	97	2·59	3·43
			3 051	121	2·64	3·19
Angel 1	3	89	1 490	(59)	2·43	2·43
			2 463	(90)	3·19	2·74
			3 027	(104)	2·48	2·69
			3 177	(109)	3·33	2·72
			3 408	115	2·60	2·71
Barrow Deep 1	4	27	888	63	4·41	4·41
			1 795	79	1·76	3·05
			2 589	100	2·64	2·93
			3 054	(118)	3·87	3·07
			3 215	(124)	3·73	3·11
			3 254	(122)	–5·13	3·01
			3 267	(125)	23·08	3·09
			3 572	(133)	2·62	3·05
			3 616	(133)	0	3·01
			3 622	(132)	–16·67	2·98
			3 654	(133)	3·13	2·98
			3 868	(149)	7·48	3·23
			3 938	(145)	–5·71	3·07
			4 151	163	8·45	3·35
			4 535	(172)	2·34	3·26
Beagle 1	5	1	561	(50)	4·46	4·46
Bidgemia 1		....	....	N.A.	....	....
Cane River 1	6	8	696	(57)	4·65	4·65
Cane River 2	7	8	413	(53)	6·86	6·86
Cane River 3	8	2	255	(44)	7·51	7·51
Cane River 4	9	2	173	(36)	6·43	6·43
Cane River 5	10	2	202	(41)	8·00	8·00
Cape Cuvier 1	11	0	557	(45)	3·59	3·59
Cape Range 1	....	3	2 472	(105)	3·24	3·24
Cape Range 2	12	3	1 154	(60)	3·04	3·04
			3 078	(115)	2·86	2·93
			3 360	(130)	5·32	3·13
Chargoo 1	13	2	428	(52)	6·34	6·34
Coonga 1	....	....	....	N.A.	....	....
Cossigny 1	14	125	1 291	(55)	2·57	2·57
			3 198	(79)	1·26	1·76
Cunaloo 1	15	3	795	(61)	4·55	4·55
Dampier 1	16	85	1 083	48	2·30	2·30
			2 618	75	1·76	1·97
			3 162	116	7·54	2·96
			3 804	(118)	0·31	2·50
			4 137	138	6·00	2·79
De Grey 1	17	124	1 116	49	2·15	2·15
			2 003	83	3·83	2·90
Direction Island 1	18	1	671	(58)	4·92	4·92
Dirk Hartog 17B	19	3	366	(35)	2·75	2·75
			974	(56)	3·44	3·19
			1 290	(64)	2·55	3·03
			1 410	(66)	0·83	2·91
			1 523	(82)	14·16	3·75
Dockrell 1	20	140	1 413	55	2·36	2·36
			3 144	(95)	2·31	2·33
			3 500	112	4·78	2·59
			3 890	124	3·08	2·64
Eaglehawk 1	21	132	1 304	(52)	2·30	2·30
			3 067	(96)	2·50	2·42
			3 475	100	0·98	2·24
East Marilla 1	22	1	637	(48)	3·61	3·61
Edel 1	23	123	1 002	44	2·16	2·16
			1 411	56	2·93	2·41
			2 749	80	1·79	2·09
Egret 1	24	130	1 254	(48)	2·05	2·05
			3 251	106	2·90	2·60
			3 651	118	3·00	2·64
Enderby 1	25	63	881	(52)	3·30	3·30
			2 139	(95)	4·53	3·37
Finucane 1	26	147	1 715	59	2·17	2·17
			2 968	95	2·87	2·48
Flag 1	27	60	1 256	(62)	3·09	3·09
			2 357	(95)	3·00	3·05
			2 769	(105)	2·43	2·95
			3 231	(109)	0·87	2·65
			3 525	(135)	8·84	3·17
			3 802	145	3·61	3·21
Flinders Shoal 1	28	41	1 203	75	4·30	4·30
			2 134	95	2·15	3·34
			3 032	115	2·23	3·01
			3 353	143	8·72	3·56
			3 505	150	4·61	3·61
			3 616	153	2·70	3·58
Fortescue 1	29	1	610	(48)	3·78	3·78
Giralia 1	30	2	1 237	(60)	2·83	2·83
Glenroy 1	31	5	648	(62)	5·75	5·75
Gnaraloo 1	32	2	502	(59)	6·80	6·80
Goodwyn 1	33	156	1 290	45	1·76	1·76
			2 744	76	2·13	1·97
			3 520	112	4·64	2·59
Grierson 1	....	....	....	N.A.	....	....
Grierson 2	....	....	....	N.A.	....	....
Grierson 3	....	....	....	N.A.	....	....
Hampton 1	34	83	1 196	60	3·14	3·14
			2 560	93	2·42	2·75
Hauy 1	35	95	393	(42)	4·33	4·33
Hermite 1	36	43	2 232	(93)	3·11	3·11
			2 495	(97)	1·52	2·94
			3 304	122	3·09	2·97
Hilda 1A	37	157	2 058	(88)	3·32	3·32
			2 555	(91)	0·60	2·75
			3 205	126	5·38	3·31
			3 454	140	5·62	3·48
Hope Island 1	38	9	1 426	81	3·95	3·95
Kalbarri 1	39	1	456	49	5·31	5·31
			1 539	57	0·74	2·08
Kennedy Range 1	40	4	615	(58)	5·40	5·40
			1 193	(69)	1·90	3·70
			2 215	(111)	4·11	3·89

TABLE 1. FORMATION TEMPERATURE AND GEOTHERMAL GRADIENTS, SECTIONAL AND PROGRESSIVE OVERALL; OIL EXPLORATION WELLS, CARNARVON BASIN. WELL NUMBERS ARE KEYED TO FIGURE 1—*continued*

Well Name	Fig. 1 No.	Derrick Floor Elevation (m)	Depth (m)	Temperature (°C)	Sect. Grad. (°C/100 m)	Overall Grad. (°C/100 m)
Lambert 1	41	135	1 280	(52)	2·36	2·36
			3 186	101	2·57	2·49
			3 701	116	2·91	2·55
Learmonth 2	42	3	1 501	(82)	3·81	3·81
			1 732	(95)	5·63	4·05
Legendre 1	43	64	1 036	57	3·29	3·29
			2 162	83	2·84	3·05
			2 488	93	1·23	2·81
			3 238	110	2·27	2·68
Legendre 2	44	57	1 130	(54)	2·70	2·70
			1 940	(79)	3·09	2·87
			2 054	(80)	0·88	2·75
			2 588	(88)	1·50	2·49
			3 617	(127)	3·79	2·87
Locker 1	45	1	767	(65)	5·22	5·22
Long Island 1	46	9	814	(61)	4·47	4·47
			1 389	(78)	2·96	3·84
			2 159	(98)	2·60	3·40
Lowendal 1	47	115	1 197	52	2·50	2·50
			3 630	123	2·92	2·79
Madeleine 1	48	78	1 188	(57)	2·70	2·70
			2 764	(92)	2·22	2·42
			3 154	(114)	5·64	2·82
			3 686	125	2·07	2·71
			4 212	(138)	2·47	2·68
Malus 1	49	96	1 446	63	2·81	2·81
			3 652	112	2·22	2·45
Mangrove 1	50	1	284	(63)	13·38	13·38
Mardie 1	51	1	222	(40)	6·76	6·76
Mardie 2	52	8	165	(41)	10·19	10·19
Marilla 1	53	3	305	(35)	3·28	3·28
			456	(38)	1·99	2·85
Mary Anne 1	54	1	533	51	4·89	4·89
Merlinleigh 1	....	1	304	(43)	5·92	5·92
Merlinleigh 2	....	1	304	(43)	5·92	5·92
Merlinleigh 3	....	....	....	N.A.	....	....
Merlinleigh 4	....	....	....	N.A.	....	....
Merlinleigh 5	....	....	....	N.A.	....	....
Mermaid 1	55	55	465	(47)	5·37	5·37
			1 268	66	2·37	3·38
Minderoo 1	56	12	344	(33)	2·41	2·41
			500	(37)	2·56	2·46
			696	(38)	0·51	1·90
Moogooree 1	....	....	....	N.A.	....	....
Moogooree 2	....	....	....	N.A.	....	....
Muiron 1	57	9	1 012	(97)	7·18	7·18
			1 781	(110)	1·69	4·80
Mulyery 1	58	6	140	(45)	14·9	14·9
Nelson Rocks 1	59	85	1 153	47	2·06	2·06
			2 049	(77)	3·35	2·65
			2 186	80	2·19	2·62
Ningaloo 1	60	4	668	48	3·46	3·46
			1 229	75	4·81	4·08
North Rankin 1	61	152	1 704	(60)	2·26	2·26
			2 958	84	2·08	2·18
			3 431	115	5·41	2·74
			3 530	(118)	3·03	2·75
North Sandy 1	62	1	607	50	4·13	4·13
North Tryal Rocks 1	63	118	1 820	(63)	2·23	2·23
			3 060	(98)	2·82	2·48
			3 652	125	4·57	2·83
Observation 1	64	4	986	62	3·77	3·77
			2 157	93	2·65	3·16
Onslow 1	65	5	535	(47)	4·15	4·15
			917	(59)	3·14	3·73
			1 791	(85)	3·89	3·36
			2 999	(119)	2·81	3·14
Paterson 1	66	4	1 269	(69)	3·47	3·47
			1 408	(81)	8·63	3·99
			1 855	(96)	3·36	3·85
			2 282	(103)	1·64	3·42
Peak 1	67	4	698	(43)	2·59	2·59
			1 513	(73)	3·68	3·18
			2 141	(102)	4·62	3·60
Peedamulla 1	68	2	328	47	6·75	6·75
Pendock 1	69	1	1 048	(44)	2·10	2·10
			1 854	(77)	4·09	3·04
			2 498	(92)	2·33	2·85
Pepper 1	70	35	462	(48)	5·39	5·39
			1 327	79	3·58	4·18
			2 539	(108)	2·39	3·31
			2 606	117	13·43	3·58
			2 745	117	0	3·39
Quail 1	71	3	882	(77)	5·92	5·92
			1 373	(91)	2·85	4·82
			2 795	(112)	1·48	3·12
			3 261	(137)	5·36	3·44
			3 580	(152)	4·70	3·55
Rankin 1	72	102	1 610	(58)	2·19	2·19
			2 919	(99)	3·13	2·63
			3 494	(118)	3·30	2·74
			4 109	(135)	2·76	2·75
Remarkable Hill 1	73	11	153	(47)	15·49	15·49
			933	(70)	2·95	4·88
			2 214	96	2·03	3·22
			3 206	(132)	3·63	3·35
Ripple Shoal 1	74	32	1 101	(44)	1·78	1·78
			2 278	115	6·03	4·01
Ronsard 1	75	170	1 300	(45)	1·79	1·79
			2 837	93	3·10	2·55
Rosemary 1	76	74	1 802	67	2·43	2·43
			1 864	(71)	6·45	2·56
			2 915	(105)	3·24	2·82
			3 265	(115)	2·86	2·82
Sable 1	77	163	1 386	48	1·88	1·88
			2 745	85	2·72	2·32
			3 806	(113)	2·64	2·42
			3 969	(116)	1·84	2·39
Sandy Point 1	78	4	1 222	66	3·37	3·37
			1 994	(104)	4·92	3·97

TABLE 1. FORMATION TEMPERATURE AND GEOTHERMAL GRADIENTS, SECTIONAL AND PROGRESSIVE OVERALL; OIL EXPLORATION WELLS, CARNARVON BASIN. WELL NUMBERS ARE KEYED TO FIGURE 1—*continued*

Well Name	Fig. 1 No.	Derrick Floor Elevation (m)	Depth (m)	Temperature (°C)	Sect. Grad. (°C/100 m)	Overall Grad. (°C/100 m)
Sandy Point 1—*continued*			2 466	(108)	0·85	3·37
			2 514	(108)	0	3·31
			3 045	**120**	1·51	3·12
Sandy Point 2	79	4	647	(42)	2·64	2·64
			1 680	87	4·36	3·70
Sholl Island 1	80	5	734	(52)	3·70	3·70
			1 269	(67)	2·80	3·32
Surprise 1	....	....	....	N.A.	....	....
Tamala 1	81	4	527	56	5·88	5·88
			1 225	(74)	2·58	4·00
Thevenard 1	82	4	969	79	5·60	5·60
			1 994	102	2·24	3·87
Tortoise 1	83	4	787	(56)	3·96	3·96
			1 563	(90)	4·38	4·17
			2 133	(100)	1·75	3·52
Trimouille 1	84	4	685	(45)	2·94	2·94
			1 175	(59)	2·86	2·90
			2 400	(89)	2·45	2·67
Tryal Rocks 1	85	74	1 220	55	2·62	2·62
			1 923	(82)	3·84	3·08
			3 033	**123**	3·69	3·31
			3 696	**152**	4·37	3·51
Urala 1	86	2	763	(61)	4·73	4·73
Wandagee 1	87	3	807	(64)	4·85	4·85
			1 071	(72)	3·03	4·40
Warroora 1	88	1	1 824	(110)	4·66	4·66
West Muiron 2	89	92	965	63	4·35	4·35
			1 816	82	2·23	3·31
			2 163	91	2·59	3·19
			3 306	**134**	3·76	3·39
West Tryal Rocks 1	90	150	3 432	**126**	3·08	3·08
			3 864	**145**	4·40	3·23
West Tryal Rocks 2	91	138	1 495	54	2·14	2·14
			3 206	**118**	3·74	3·03
			3 815	**144**	4·27	3·24
Whaleback 1	92	3	1 048	58	3·16	3·16
			1 116	(61)	4·41	3·23
			1 168	(66)	9·61	3·51
			1 366	(77)	5·56	3·82
			1 527	(80)	1·86	3·61
Windoo 1	....	....	....	N.A.	....	....
Wonangara 1	93	2	571	(63)	6·68	6·68
Woorawa 1	....	....	....	N.A.	....	....
Yanrey 1	94	3	428	(49)	5·61	5·61
Yarraloola 1	95	2	163	(54)	17·90	17·90
			269	(50)	−3·77	9·33
Yaringa 1	96	6	742	(68)	5·84	5·84
			868	76	6·35	5·91
			2 288	(80)	0·28	2·41

NOTES: **83** Confident formation temperature with good extrapolation of 3 or more points.
83 Temperature with poor fit of 3 or more points or only 2 points.
(83) Poor temperature—only one point or no temperature range.
N.A. Not Available.

MODIFIED STRATIGRAPHIC NOMENCLATURE AND CONCEPTS IN THE PALAEOZOIC SEQUENCE OF THE CARNARVON BASIN, W.A.

by R. M. Hocking, P. S. Moore and H. T. Moors

ABSTRACT

The following amended names applicable to the Palaeozoic sequence of the Carnarvon Basin, are proposed: Nannyarra Sandstone, Cordalia Sandstone, Mallens Sandstone, Nalbia Sandstone, Coolkilya Sandstone and Jimba Jimba Calcarenite Member (of the Billidee Formation). The following names, formerly applicable to the Permian Byro Group, are deleted: "Newman Subgroup", "Minilya Subgroup", "Madeline Formation", "Bogadi Greywacke", and "Warra Warringa Formation". These changes result from (a) the deletion of the term "greywacke" from the Carnarvon Basin nomenclature and (b) a better understanding of the stratigraphy of the Byro and Wooramel Groups.

INTRODUCTION

Various parts of the stratigraphy of the Carnarvon Basin have been revised since publication by the Bureau of Mineral Resources of a bulletin on the Carnarvon Basin (Condon, 1965a, 1967, 1968), although this bulletin is still a standard reference. The present paper proposes more changes to Palaeozoic formation and group names and ranks in the basin, and summarizes the revisions made in the Permian stratigraphy since 1967.

"GREYWACKE" AND SANDSTONE NOMENCLATURE

History and rationale

In erecting formal stratigraphic nomenclature for the Carnarvon Basin, the term "greywacke" was commonly used in Palaeozoic formation names by Condon (1954, 1962) and Konecki, Condon, Dickins and Quinlan (1958). Of these, the Nannyarra "Greywacke" (Devonian), Cordalia "Greywacke", Mallens "Greywacke", Nalbia "Greywacke" and Coolkilya "Greywacke" (Permian) remain valid formations, but we here suggest that the lithological term "greywacke" is inappropriate for these units and should be deleted from the names of valid formations. The "Coyango" and "Koomberan Greywackes" were relegated to member status by van de Graaff and others (1977), the name "Norton Greywacke" was abandoned in favour of Nalbia "Greywacke" by Playford and others (1975), and the name "Bogadi Greywacke" is abandoned in this paper.

Condon (1965a, p. 14) defined greywacke as "Arenite consisting of angular and/or subrounded quartz and/or rock fragments with or without feldspar and with a fine-grained matrix which is generally micaceous and/or chloritic". This is a purely qualitative definition, although he made reference to his earlier article which has quantitative limits for a much

TABLE 1. ROCK-TYPE COMPOSITION OF RELEVANT PALAEOZOIC FORMATIONS AND MEMBERS. USE OF "WACKE" AND "ARENITE" AS BY DOTT (1964)

Formation	Age	Dominant rock-type	Subsidiary rock-types
Nannyarra Sandstone	Early-Middle	Coarse- to fine-grained quartz and feldspathic wacke and arenite.	Siltstone, sandy siltstone
Cordalia Sandstone	Early Permian (Artinskian)	Medium- to very fine-grained silty quartz wacke and arenite.	Siltstone, sandy siltstone, minor claystone
Mallens Sandstone	Early Permian (Artinskian)	Medium- to very fine-grained quartz wacke and arenite	Minor siltstone
Nalbia Sandstone	Early Permian (Artinskian)	Medium- to very fine-grained quartz wacke and arenite	Sandy siltstone
Coolkilya Sandstone	Early Permian (Kungurian)	Fine- to very fine-grained quartz wacke and arenite	Siltstone, sandy siltstone
Coyango Member, Lyons Formation	Early Permian (Sakmarian)	Feldspathic and quartz arenite and wacke	Diamictite, siltstone, conglomerate
Koomberan Member, Lyons Formation	Early Permian (Sakmarian)	Feldspathic wacke and arenite	Diamictite, siltstone, limestone, quartz wacke

broader "Greywacke Group". In the earlier definition, he stated: ". . . the only essential component of this group is the matrix . . ." (Condon, 1952, p. 54), which he defined as ranging between 30% and 50%.

By using the terms "sandstone" and "greywacke" in formation names, Condon differentiated between sand-sized siliclastic sediments with negligible matrix (termed sandstones), which are potential aquifers and hydrocarbon reservoirs, and those with significant matrix (termed greywackes), which lack economic reservoir properties.

Current usage and definitions

Greywacke is a term which has been used in many different senses and has been much abused in the past (cf. Dott, 1964; Pettijohn, Potter and Siever, 1972; Sanders, *in* Fairbridge and Bourgeois, 1978). The *Glossary of Geology* (Gary and others, 1972, p. 312) lists eight modern definitions and concludes ". . . the term 'greywacke' should not be used formally without either a specific definition or a reference to a readily available published definition." Condon's (1965a) definition is neither widely known nor accepted. Folk (1968) recommended that the term be used only in non-quantitative field descriptions. Pettijohn (1975) restricted the term to the "classical" usage, two of the essential requirements being a dark, fine-grained matrix, and a lithic clastic component in the framework. In addition, he considered that greywackes generally occur in deformed, marine, flysch-type, miogeosynclinal or eugeosynclinal environments.

Applicability

Carnarvon Basin "greywackes" are not dark grey and are not highly indurated. They do not contain an appreciable amount of lithic material within their framework (Table 1), which is an essential feature of all common definitions (Gary and others, 1972). Moreover, none that we have examined contain as much as 30% matrix, the minimum amount required by Condon's (1952) definition.

Furthermore, Carnarvon Basin "greywackes" certainly were not deposited in Flysch-type, geosynclinal environments. All were deposited in shallow-marine environments in an intracratonic basin, or (for the Nannyarra, "Coyango" and "Koomberan Greywackes") in partly fluviatile environments. Further details on the depositional environments of the Mallens, Nalbia and Coolkilya "Greywackes" are presented by Moore, Denman and Hocking (1980) and Moore, Hocking and Denman (1980) in this volume.

Thus, the "greywackes" of the Carnarvon Basin are not greywackes by common definition, common usage, or Condon's (1952, 1965a) definition.

Modified stratigraphic nomenclature

We propose to modify the names "Nannyarra Greywacke", "Cordalia Greywacke", "Mallens Greywacke", "Nalbia Greywacke" and "Coolkilya Greywacke", amending them to Nannyarra Sandstone, Cordalia Sandstone, Mallens Sandstone, Nalbia Sandstone, and Coolkilya Sandstone. The last three were originally named "sandstone" by Teichert (1950). Sandstone is the predominant lithology in all these units (Table 1) and "sandstone" is thus the preferred term to "formation".

Sandstone classification

Although it is considered that "greywacke" is an inappropriate term for the Carnarvon Basin sandstones, we appreciate the need to discriminate between those sandstones with negligible matrix, and those with a significant matrix. There are many schemes of sandstone classification (such as those proposed by Folk (1968), Dott (1964), Pettijohn (1957, 1975), Packham (1954) and Crook (1960)), of which we prefer the scheme by Dott (1964) (Fig. 1), because it discriminates between impure sandstones (wackes) and clean sandstones (arenites) in a logical, gradational manner. The scheme also avoids the term "greywacke" and has the advantage of wide acceptance and usage.

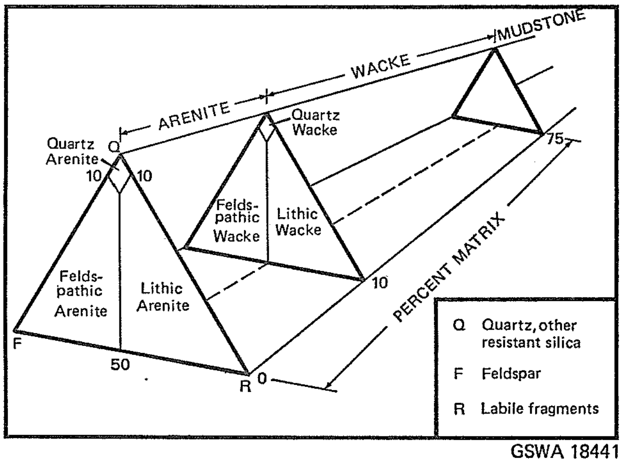

Figure 1 Nomenclature of sandstones as proposed by Dott (1964).

LYONS FORMATION

Members

Van de Graaff and others (1977) reduced the "Lyons Group" to formation status, and relegated the constituent formations, proposed by Condon (1962), to member status. However, of these seven members only a basal sandstone, the Austin Member, has been consistently recognized throughout the Carnarvon Basin. More detailed work is needed to clarify the validity and extent of the remaining six units, which cannot be distinguished beyond their immediate type areas at 1:250 000 scale, and thus are not shown in Table 2.

Age

Condon (1967) and Playford and others (1975) considered the Lyons Formation to be wholly Permian (Sakmarian) in age, but Kemp and others (1977), on palynological grounds, place the lower part of the formation in the Late Carboniferous. Also, 850 m of unnamed glacigene sediments in the Remarkable Hill 1 well (22°57′36″S, 114°09′27″E, Fig. 2) is of apparent Carboniferous age (Berven, 1969) and in our opinion should be included within the conformably overlying Lyons Formation. Lastly, lithological correlatives of the Lyons Formation in the Canning Basin (Grant Formation) and the Perth Basin (Nangetty Formation) have been shown to extend into the Carboniferous (Balme, *in* Johnson, 1968; Kemp and others, 1977), on more evidence than is available for the Lyons Formation.

Carrandibby Formation

We consider that the Carrandibby Formation is a lateral variant of the uppermost Lyons Formation, transitional into the overlying Callytharra Formation. Although it is too

TABLE 2. MODIFICATIONS IN LATE CARBONIFEROUS AND LOWER PERMIAN STRATIGRAPHY SINCE 1967

AGE		CONDON (1965, 1967)			PLAYFORD AND OTHERS (1975)			REVISIONS 1975-1980		
		MERLINLEIGH SUB-BASIN		BYRO SUB-BASIN	MERLINLEIGH SUB-BASIN		BYRO SUB-BASIN	MERLINLEIGH SUB-BASIN		BYRO SUB-BASIN
PERMIAN	KUNGURIAN	KENNEDY GROUP	BINTHALYA FM		KENNEDY GROUP	BINTHALYA FM		KENNEDY GROUP	BINTHALYA FM	Age uncertain, no diagnostic fossils
			MUNGADAN SST			MUNGADAN SST			MUNGADAN SST	
			COOLKILYA GWKE			COOLKILYA GWKE	3		COOLKILYA SST$_2$	? ?
	? ARTINSKIAN	BYRO GROUP, MINILYA SUB-GROUP	BAKER FM		BYRO GROUP, MINILYA SUB-GROUP	? BAKER FM		BYRO GROUP$_2$	BAKER FM	4
			NORTON GWKE			NALBIA GWKE			NALBIA SST$_2$	
			WANDAGEE FM			WANDAGEE FM			WANDAGEE FM	
			QUINNANIE SH			QUINNANIE SH			QUINNANIE SH	
			CUNDLEGO FM			CUNDLEGO FM ?			CUNDLEGO FM	
		BYRO GROUP, NEWMAN SUB-GROUP	BULGADOO SH	WARRA WARRINGA FM	BYRO GROUP, NEWMAN SUB-GROUP	BULGADOO SH	WARRA WARRINGA FM		BULGADOO SH	
			MALLENS GWKE	BOGADI GWKE		MALLENS GWKE	BOGADI GWKE		MALLENS SST$_2$	
			COYRIE FM	MADELINE FM		COYRIE FM	MADELINE FM		COYRIE FM	
		WOORAMEL GROUP	BILLIDEE FM	KEOGH FM, ONE GUM FM, BILLIDEE FM	WOORAMEL GROUP	BILLIDEE FM	KEOGH FM, ONE GUM FM, BILLIDEE FM	WOORAMEL GROUP	BILLIDEE FM	KEOGH FM, BILLIDEE FM$_1$
			JIMBA JIMBA CA			JIMBA JIMBA CA			JIMBA JIMBA CA MBR 2	
			MOOGOOLOO SST	MOOGOOLOO SST, CURBUR FM, CONGO FM, MONUMENT FM, NUNNERY SST		MOOGOOLOO SST	NUNNERY SST, MOOGOOLOO SST		MOOGOOLOO SST	
			CORDALIA GWKE			CORDALIA GWKE			CORDALIA SST$_2$	
			CALLYTHARRA FM							
	SAKMARIAN			CARRANDIBBY FM		CALLYTHARRA FM			CALLYTHARRA FM	
		LYONS GROUP	WEEDARRA SH		LYONS GROUP	WEEDARRA SH	CARRANDIBBY FM		CARRANDIBBY FM	
			THAMBRONG SLT			THAMBRONG SLT	LYONS GP		LYONS FM$_1$	
			MUNDARIE SLT			MUNDARIE SLT				
			KOOMBERAN GWKE			KOOMBERAN GWKE				
			DUMBARDO SLT			DUMBARDO SLT				
			COYANGO GWKE			COYANGO GWKE				
			HARRIS SST	AUSTIN FM		AUSTIN FM				
LATE CARBONIFEROUS						HARRIS SST			AUSTIN MBR$_1$	
									HARRIS SST	

GSWA 18443

Zig-zag boundary indicates formation is discontinuous. Modifications by (1) Van de Graaff and others (1977); (2) this paper; (3) Cockbain (1980); (4) Moore, Hocking and Denman (1980).

small to be mapped at 1:250 000 scale, it is present in the Merlinleigh Sub-basin as well as in the Byro Sub-basin, and is therefore shown as such in Table 2.

Harris Sandstone

The validity and stratigraphic relationships of the Harris Sandstone are uncertain. It has only been recognized near Moogooree homestead and in its type area near Williambury homestead (Fig. 2). Condon (1967) considered that the outcrops near Moogooree homestead belonged to the basal Lyons Formation (Austin Member), but we (in agreement with Read and others (1973)) consider that they should be assigned to the Harris Sandstone. Condon (1967) correlated the Harris Sandstone (which he only recognized in the Williambury area) with the Austin Member of the Lyons Formation, but we are not certain whether this correlation is valid or, alternatively, whether the Harris Sandstone is older than the Austin Member. The lithology and outcrop pattern of the two units are very similar, but the relationship of one to the other has not been established at any locality. No evidence of glacial influence has been found in any outcrops mapped as Harris Sandstone; in contrast, the Austin Member locally contains glacigene boulder beds at its base and exhibits soft-sediment ice-drag striae near the Weedarra Inlier (Fig. 2).

Read and others (1973) postulated an angular unconformity between the Lyons Formation and Harris Sandstone, near Moogooree homestead. This has not been proved by later mapping; we can find no definite evidence of angular discordance between the two units. Both the Harris Sandstone and Austin Member are of varying thickness and crop out discontinuously, and each unit appears to have been substantially scoured before or during deposition of the overlying glacigene diamictites.

We tentatively retain the Harris Sandstone as a separate unit, possibly unconformable beneath the Lyons Formation; because no evidence of glacial influence has been found within it, and there is some remaining doubt regarding its correlation with the Austin Member of the Lyons Formation.

WOORAMEL GROUP

Condon (1965b) defined the Jimba Jimba Calcarenite (a bioclastic limestone with subordinate quartz sand) as a formation within the Wooramel Group and conformable between the Moogooloo Sandstone below and the Billidee Formation above. At that time, the type section west of Gascoyne Junction and a section in BMR 8 (Mount Madeline) well (Fig. 2) were the only known occurrences of this lithology within the Wooramel Group. Since then, outcrops of identical lithology have been found at the top of the Billidee Formation on Dairy Creek Station (about 4 m thick) and in the middle of the Billidee Formation on Mount Sandiman Station (about 60 m thick). In both cases, the calcarenite is clearly conformable with adjacent strata, and is not a structurally isolated remnant of Callytharra Formation, which is very similar in outcrop.

The outcrops on Mount Sandiman Station consist of lenses of fossiliferous, variably coarse-grained, quartzose calcarenite, separated by dark, ferruginized siltstone and fine-grained silty sandstone. The calcarenites appear to have formed as shoals of coarser grained material on a low- to moderate-energy marine shelf. We consider that the other occurrences formed in the same manner, as isolated areas of carbonate shoals. Their distribution and variable stratigraphic position within the Billidee Formation indicates that coarse-grained carbonate debris was only available in limited amounts at any one place or time.

These lithologically identical calcarenites cannot be grouped as one member within the Billidee Formation because they are stratigraphically separate. However, they are clearly related and represent a specific subenvironment within the overall environment of deposition of the Billidee Formation. Therefore we propose to redefine the Jimba Jimba Calcarenite in its type area as a member within the Billidee Formation and to consider the other occurrences (which may well be isolated lenses) as facies equivalents of the Jimba Jimba Calcarenite Member but not to name them at this time.

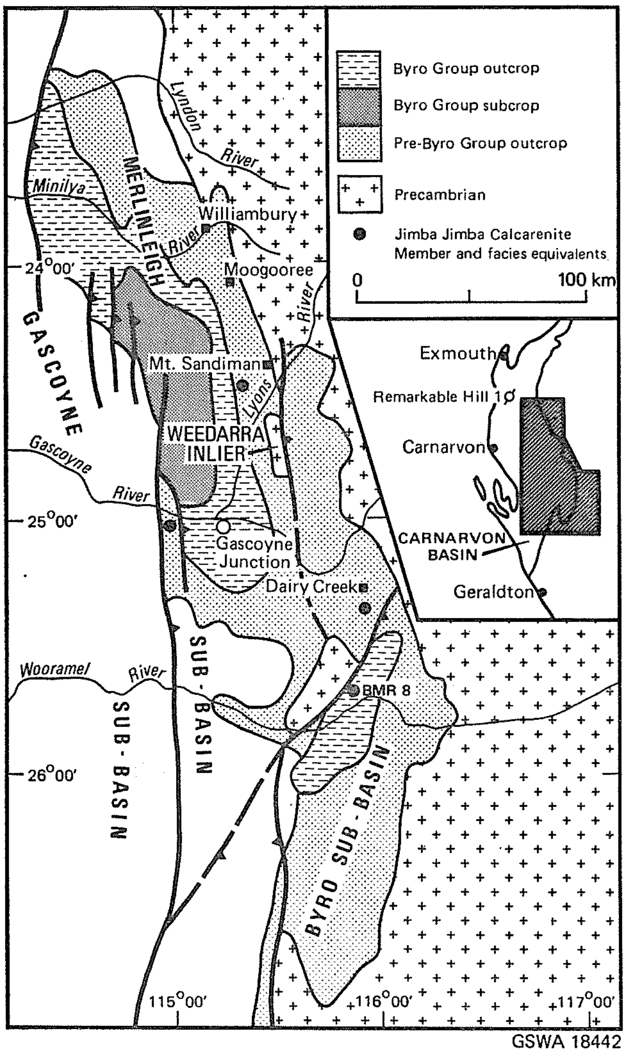

Figure 2 Locality map, showing distribution of the Byro Group and Jimba Jimba Calcarenite Member of the Billidee Formation.

BYRO GROUP

The Byro Group was divided into the (lower) Newman Subgroup and the (upper) Minilya Subgroup by Condon (1962), who recognized an unconformity between the Bulgadoo Shale below and the Cundlego Formation above. As evidence, Condon (1965b) stated "... this unconformity is well shown on the map south-west of Gascoyne Junction, although the relationship has not been observed in outcrop." This has not been substantiated by remapping of the relevant areas of the Wooramel 1:250 000 Geological Sheet. The anomalous dips recorded in the upper part of the Bulgadoo Shale by Condon (1965b) are due to soil creep and salt heaving (caused by weathering).

Elsewhere, as in the type section along the Minilya River, and in the reference section at the northern end of Kennedy Range, the base of the Cundlego Formation is defined as a thin (average 0·15 m) conglomerate bed. Such beds are common in the Cundlego Formation, and are interpreted as intraformational, transgressive lag conglomerates, which do not constitute evidence of a disconformity (Moore, Denman and Hocking, 1980). Thus, the Cundlego Formation is considered to rest conformably on the Bulgadoo Shale throughout the area of outcrop.

Since the sediments of the Newman and Minilya Subgroups are lithologically and sedimentologically similar, and the boundary between them is apparently conformable, without any major faunal change (Dickins, 1970), we propose that the names Newman and Minilya Subgroups be abandoned.

The Byro Group in the Byro Sub-basin was divided into the Madeline Formation, Bogadi "Greywacke" and Warra Warringa Formation by Konecki, Condon, Dickins, and Quinlan (1958). Condon (1967) considered that all three were lateral equivalents of the Coyrie Formation (Table 2), but Konecki, Dickins and Quinlan (1958), Playford and Cope (1971), and Playford and others (1975) only correlated the Madeline Formation with the Coyrie Formation, equating the Bogadi "Greywacke" with the Mallens Sandstone (amended herein), and the Warra Warringa Formation with the Bulgadoo Shale. Although there is no continuity of outcrop or subcrop between the two areas, the formations are lithologically and sedimentologically very similar, and contain comparable faunas. We interpret these similarities as indicating original continuity of deposition in a basin with very uniform marine conditions and laterally persistent environments. A slightly finer grain-size in the Merlinleigh Sub-basin outcrops is attributed to deposition in an environment which is marginally further offshore than in the Byro Sub-basin (Moore, Denman and Hocking, 1980). The names "Madeline Formation", "Bogadi Greywacke" and "Warra Warringa Formation" are therefore abandoned in favour of the Coyrie Formation, Mallens Sandstone and Bulgadoo Shale, which have historical precedence.

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SEDIMENTOLOGY OF THE BYRO GROUP (LOWER PERMIAN), CARNARVON BASIN, WESTERN AUSTRALIA

by P. S. Moore, P. D. Denman and R. M. Hocking

ABSTRACT

The Lower Permian (Artinskian) Byro Group is a sequence of shale, siltstone and sandstone which crops out in the south-eastern Carnarvon Basin. The sedimentology of the group can be expressed in terms of six facies which represent deposition in the offshore, transition, and shoreface environments. The oscillation between these environments was controlled both by natural progradation of the coastline and by tectonic readjustments of the sedimentary basin. The facies reflect a balance between wave processes, which predominated in the shoreface zone, and biogenic processes, which predominated below effective wave base in the offshore and transition zones.

INTRODUCTION

The Lower Permian (Artinskian) Byro Group, as defined by Condon (1954, p. 60) is the sequence of siltstone, shale and sandstone between the sandy Wooramel Group below and the sandy Kennedy Group above. It crops out in the Byro and Merlinleigh Sub-basins of the Carnarvon Basin (Fig. 1). The stratigraphy of the group is simplified by Hocking and others (1980). As now defined (Table 1) the Byro Group consists of eight formations, all of which are represented in the Merlinleigh Sub-basin. Only the Coyrie Formation, Mallens Sandstone and Bulgadoo Shale are preserved in the Byro Sub-basin.

Although the original choice of formation boundaries was strongly influenced by palaeontological zoning (Teichert, 1950, 1951, 1957), the boundaries as now mapped correspond to lithological changes. The eight formations differ mainly in the ratio of sandstone to shale and siltstone. A slightly coarser grain-size, with respect to lateral equivalents in the Merlinleigh Sub-basin, suggests that the Byro Sub-basin sequence was deposited marginally closer to the shoreline. However, we believe the lithological, sedimentological and faunal similarities of the Byro Group sequences in the Byro and Merlinleigh Sub-basins indicate original continuity of marine deposition between these separate areas of outcrop.

FACIES ANALYSIS

For simplicity, the sequence in the Byro Group is discussed in terms of facies, six of which are distinguished. They are grouped into two major facies associations (fine-grained association and sandstone association), and a simplified facies model, showing the major depositional environments, is presented in Figure 2. Terminology is based on Howard (1972) and Reading (1978).

FINE-GRAINED FACIES ASSOCIATION

Dark-grey to black shales and fine to medium-grained grey siltstones occur in all formations of the Byro Group, except the Mallens Sandstone. Units range in thickness from a few centimetres to several tens of metres. The finer-grained, darker units are commonly rich in selenite and are pyritic.

Black-shale facies (lower offshore)

The black-shale facies consists of evenly laminated, dark-grey to black shale and fine siltstone. Burrows are rare or absent, and body fossils mainly comprise small articulated chonetids and ostracods. Pyrite-infilled foraminifera from the Baker Formation (Condon, 1967), and concentrations of foraminifera from the Quinnanie Shale (Crespin, 1958) are also attributed to this facies. The black shales are commonly pyritic or contain limonitic imprints of original pyrite. Secondary gypsum (selenite) is extremely abundant, and deep-red, pale-grey, and black ferruginous concretions up to 1 m across are common. The black-shale facies is best represented by outcrops of the Bulgadoo and Quinnanie Shales. It is also well represented in the upper part of the Wandagee Formation and in the more northwesterly outcrops of the Baker Formation.

The black shales were deposited in a very quiet-water, offshore-marine environment, under strongly reducing conditions. Phosphate concentrations of up to 1·25 per cent are recorded by Russell (1965), and suggest slow deposition in a restricted basin (Pettijohn, 1975, p. 434). Recent weathering of the pyritic and weakly calcareous shales in the presence of water is believed to have released iron and sulphate ions. Reprecipitation of the iron produced ovoid limonitic concretions and minor jarosite. The release of the sulphate ions created an acidic environment, favouring the dissolution of calcite and the eventual precipitation of secondary gypsum (selenite). We believe that all the gypsum in the Byro Group was formed in this manner.

The small size of the fossils and the pyritic nature of the black shale suggest that this facies was formed in a restricted environment of deposition. A broad marine shelf, with a pyritic shale facies in the deeper, quieter water zone (as outlined by Reading, 1978) is favoured over the more specialized silled-basin hypothesis of Condon (1967). According to Reading (1978) mud-dominated offshore shelf deposits probably accumulated preferentially in areas of low wave and current agitation, particularly where suspended sediment concentrations were high.

Grey-siltstone facies (upper offshore)

The grey-siltstone facies consists mainly of evenly laminated to very thinly bedded, fine- to coarse-grained, mid-grey siltstone (Fig. 4A) with abundant, small curved burrows including *Chondrites* and minor *Planolites*. In the upper part of the Bulgadoo Shale at the type section along the Minilya River, the grey-siltstone facies contains thin sandstone interbeds, bearing the bipinnate, branching trace fossil *Lophoctenium* (Fig. 4B). Body fossils are uncommon, and are mainly small, articulated chonetid brachiopods. The grey-siltstone facies characterizes outcrops of the Baker Formation, especially in the eastern Kennedy Range area, and is also well developed in the lower portions of coarsening-upward cycles (generally 1.5-6.0 m thick) in the Cundlego and Wandagee Formations. It forms a minor part of most other formations in the Byro Group.

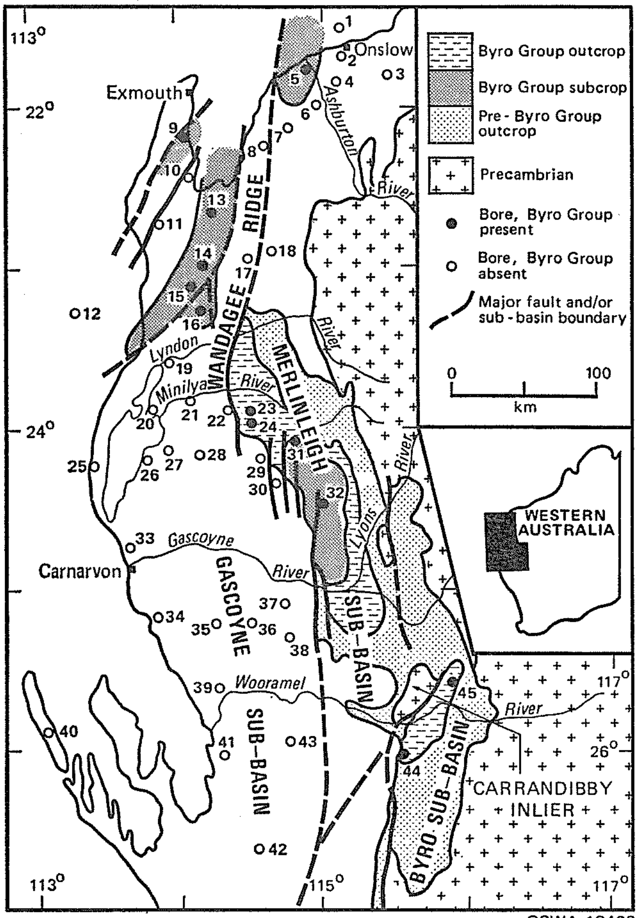

Figure 1 Surface and inferred subsurface distribution of the Byro Group.
Bores used in the compilation are: (1) Direction Island 1; (2) Cane River 1; (3) Cane River 5; (4) Minderoo 1; (5) Onslow 1; (6) Cunaloo 1; (7) Wonangarra 1; (8) Yanrey 1; (9) Learmonth 1; (10) Rough Range 1; (11) Whaleback 1; (12) Pendock 1; (13) BMR 5: Giralia; (14) Giralia 1; (15) Cardabia 2: WB; (16) Cardabia 1: WB; (17) Marrilla 1; (18) East Marrilla 1; (19) Chargoo 1; (20) Minilya 3: WB; (21) Minilya 8: WB; (22) Wandagee 1; (23) Wandagee 2; (24) Quail 1; (25) Cape Cuvier 1; (26) Gnarraloo 1; (27) Minilya 5: WB; (28) Jeeribuddy 1: WB; (29) BHP Wandagee 6; (30) BHP Wandagee 7; (31) BMR 6 & 7: Muderong; (32) Kennedy Range 1; (33) Pelican Hill 1: WB; (34) Brickhouse 4: WB; (35) Marron 1: WB; (36) Marron 2: WB; (37) Yalobia 1: WB; (38) Yalobia 3: WB; (39) Wodra 1: WB; (40) Dirk Hartog 17B; (41) Yaringa 1; (42) Hamelin 10: WB; (43) Woodleigh 4: WB; (44) Byro Deep 2; (45) BMR 9: Dairy Creek. WB indicates water bore. All others are petroleum bores.

The grey siltstones were deposited in a low-energy, moderately reducing marine environment without marked current or wave activity. The sediment contained abundant organic matter and supported an active fauna of deposit-feeding organisms and rare filter-feeders. Thin interbeds of planar-laminated to very low-angle cross stratified fine sandstone are associated with the facies in the better developed sections, and are interpreted as thin storm-deposits carried into the quieter, deeper parts of the basin during increased wave and current activity. The presence of *Lophoctenium* in some of the sandy interbeds is further evidence of deposition under quiet, relatively deep-water conditions, since this trace fossil is characteristic of the *Nereites* ichnofacies (Seilacher, 1978, Fig. 6). The grey-siltstone facies is interpreted as a shoreward equivalent of the black-shale facies.

SANDSTONE FACIES ASSOCIATION

Greyish-green to brown, very fine- to medium-grained sandstones and silty sandstones are common in the Byro Group, and are best developed in the Mallens and Nalbia Sandstones. Four facies are recognized and are discussed below in order of increasing grain-size. The four sandstone facies are interpreted as representing laterally adjacent sedimentary environments, which developed shoreward of the fine-grained facies association.

Bioturbated sandstone facies (transition zone)

The bioturbated sandstone facies consists of evenly bedded, greyish-green to brown, poorly to moderately sorted, fine to very fine-grained sandstone and silty sandstone. The most characteristic feature of the facies is the intense bioturbation which commonly obliterates the original bedding features entirely. Body fossils are mainly bivalves, brachiopods and gastropods. The facies is best developed in the Nalbia Sandstone, particularly in the middle portion, and is also developed sporadically throughout the Mallens Sandstone. Thin intervals of bioturbated sandstone (generally less than 1 m thick) occur in the Coyrie, Wandagee and Cundlego Formations.

The bioturbated sandstone facies is the result of deposition on a marine shelf below effective wave base, where the rate of sedimentation was sufficiently slow to allow extensive reworking of the sediment by burrowing organisms. Two subfacies are recognized, based on the degree of bioturbation and the trace-fossil assemblage. The quieter water, more offshore subfacies is characterized by an abundance of simple *Zoophycos*, in association with other inclined and subhorizontal burrows, and is well developed in the middle portion of the Nalbia Sandstone (Fig. 4C). *Scalarituba* and *Rhizocorallum*, occur uncommonly and *Cosmorphaphe* rarely in this subfacies. The moderate organization and complexity of the feeding burrows represent intense exploration for food by infaunal organisms which lived in an environment characterized by a low oxygen level and a soupy sediment surface (Simpson, 1970; Seilacher, 1978).

The second subfacies is characterized by less intense bioturbation, and by the presence of small, bulb-shaped hollows interpreted as bivalve burrows (Fig. 4D). The tubular cavity through which the siphon was extended is rarely preserved, indicating that the substrate was being gently reworked by waves and currents. Subvertical worm burrows are also

	MERLINLEIGH SUB-BASIN	BYRO SUB-BASIN
	KENNEDY GROUP	
BYRO GROUP	Baker Formation	
	Nalbia Sandstone	
	Wandagee Formation	
	Quinnanie Shale	
	Cundlego Formation	
	Bulgadoo Shale	Bulgadoo Shale
	Mallens Sandstone	Mallens Sandstone
	Coyrie Formation	Coyrie Formation
	WOORAMEL GROUP	WOORAMEL GROUP

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Table 1 Stratigraphy of the Byro Group in the Byro and Merlinleigh sub-basins (after Hocking and others, 1980).

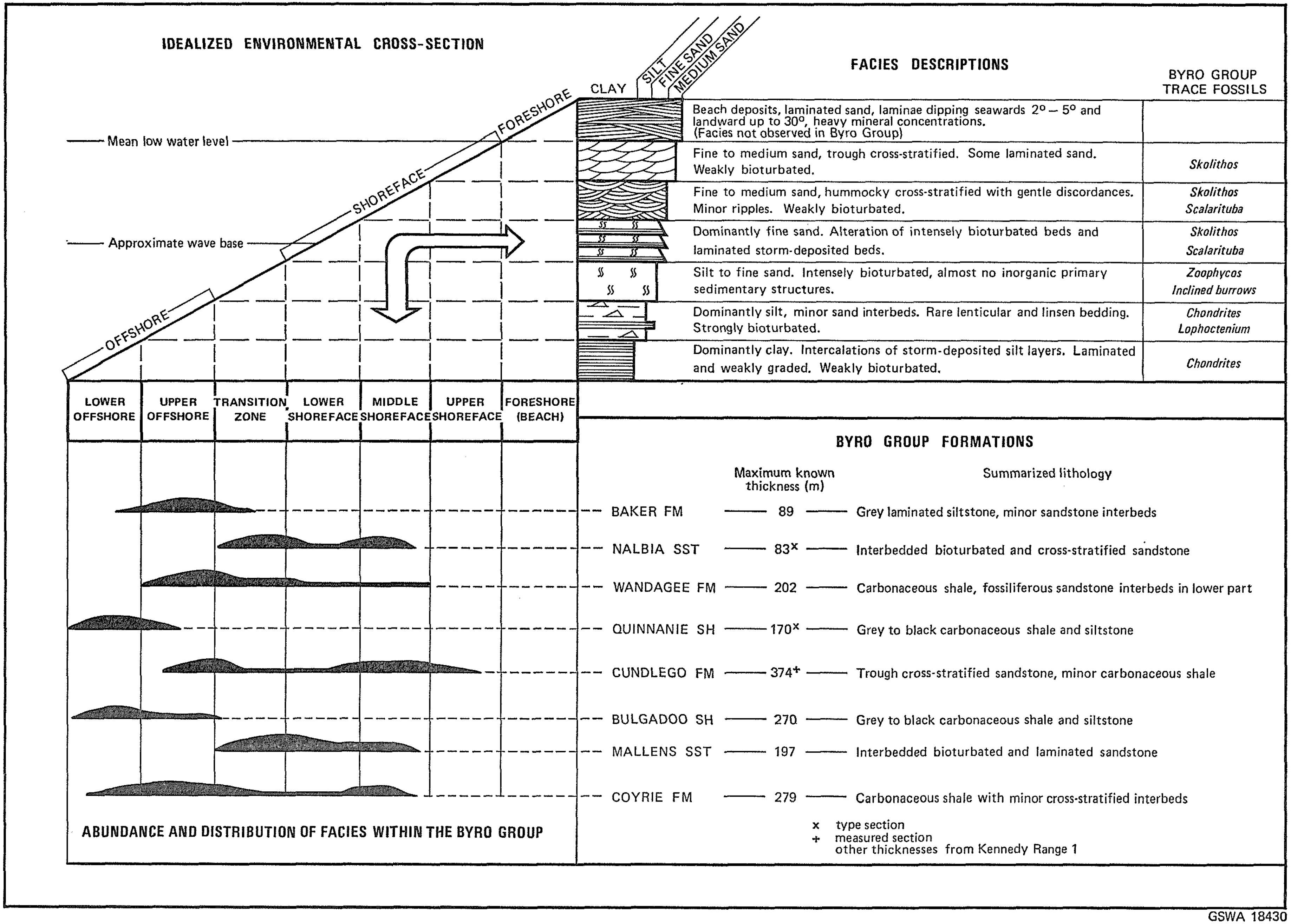

Figure 2 Depositional model and facies distributions for the Byro Group.

present, and they commonly originate from the base of abandoned bivalve burrows (*cf.* Warme and McHuron, 1978, Fig. 7a). The sand-dwelling association of *Oriocrassatella*, *Schizodus*, *Stuchburia* and *Astartila* dominates the bivalve assemblage. Gastropods which occur in this facies of the Nalbia Sandstone probably had a mobile existence in clear water on a firm bottom (Dickens, 1963).

Laminated-to-burrowed sandstone facies (*lower shoreface*)

The laminated-to-burrowed sandstone facies is very distinctive and consists of units which are plane laminated to very low-angle cross-stratified near the base, becoming intensely bioturbated towards the top (Fig. 4E). Units range in thickness from about 0.3 m to many metres, however the basal laminated portion is generally 0.2–0.5 m thick, and rarely exceeds 0.8 m. The sediment is fine- to very fine-grained, moderately sorted and micaceous. Each unit rests on the underlying one with a slightly erosive contact. Rarely, subvertical (escape) burrows penetrate the erosion suface, but the laminated sandstones are generally devoid of burrows in the lower portion. Bioturbation increases upwards, and commonly an interval containing large *Skolithos* is overlain by intensely bioturbated sandstone. Body fossils are mainly disarticulated brachiopods and bivalves. The facies is well developed in the Mallens Sandstone and is also present at rare intervals in the Nalbia Sandstone and Coyrie and Cundlego Formations.

The distinctive, laminated-to-burrowed facies is considered by Howard (1966, 1972) and Reading (1978) to be indicative of deposition at, or slightly below, storm-wave base, where storm deposits alternate with quiet-water sedimentation. During periods of quiescence, incoming sediment is extensively bioturbated by infaunal and epifaunal organisms. During a major storm, wave base is temporarily lowered, and the upper portion of the substrate is reworked. In addition, offshore-directed storm-generated density currents may carry sand into deeper, quieter water environments (Walker, 1979). Thus, the storm deposit rests erosionally on the underlying bioturbated sanstone. Following the storm, conditions of normal sedimentation resume, but the burrowing organisms are generally unable to penetrate more than about 0.2–0.3 m into the substrate and after severe storms an interval of laminated sandstone is preserved which is devoid of bioturbation in the lower part. The thickness of the overlying intensely bioturbated sandstone reflects both the position in the lower shoreface environment in which the sequence was deposited, and also the time duration between major storms.

Hummocky cross-stratified facies (*middle shoreface*)

The hummocky cross-stratified facies is very extensively developed and consists of intersecting sets of very low-angle cross-stratified fine-grained sandstone (Fig. 4F). Harms and others (1975) termed this bedform "hummocky cross-stratification". Bedsets are generally only 0.1–0.3 m thick, and are internally laminated, with rare current lineations. Each set rests erosionally on the underlying sequence, however the bounding surface between sets rarely slopes at more than about 15°. Cross-stratification is subparallel to the base of the set, however where the base is scoured, the laminations tend to drape into the scoured troughs. The dip directions of erosional set boundaries and of the overlying laminae are widely scattered. The tops of hummocky cross-stratified sandstone units may bear wave ripples and contain sinuous, subhorizontal burrows. Small current-drag features and dewatering structions are rare. Trace fossils are also rare, comprising mainly *Scalarituba* and small ?*Skolithos*. Body fossils are mainly concentrated as thin, lenticular coquinas. The bivalve association of *Oriocrassatella*, *Schizodus*, *Stuchburia* and *Astartila* dominates the assemblage and is considered by Dickins (1963) to be indicative of an unconsolidated, sandy, current-swept bottom. The hummocky cross-stratified facies is best developed in the Mallens Sandstone and Cundlego Formation, and is also present in parts of the Coyrie Formation and in the lower and upper portions of the Nalbia Sandstone. Thin sandstone interbeds in the Baker Formation and uppermost Bulgadoo Shale are hummocky cross-stratified.

The paucity of trace fossils and the abundance of shallow scour sufaces in this facies indicate constant reworking of sand in the marine environment. Walker (1979) and Hamblin and Walker (1979) believe that hummocky cross-stratification is a good indicator of deposition below fair weather wave base but above storm-wave base, with the hummocky topography being controlled by storm waves. The lack of consistently orientated or well-formed directional features suggests deposition on a shallow marine shelf, seawards of the breaker zone. As noted by Harms and others (1975, p. 88), ". . . stormy seas, dominated by locally generated waves, have complex surface patterns, and the bottom wave surges and current drift can be varied in their directions". Hummocky cross-stratification is formed in response to relatively strong wave action; certainly greater than that required to produce wave ripples in an equivalent depth of water. Rare current lineations indicate temporary periods of upper-regime flow, and, given the average grain-size of fine sand, indicate wave-generated current velocities reaching at least 0.65 m/s (Harms and others, 1975, Figs. 2–5). The resulting bedforms comprised poorly organized sets of shallow swales and low hummocks 2–5 m apart and 0.2–0.6 m high.

Trough-cross-stratified sandstone facies (?*upper shoreface*)

The trough-cross-stratified sandstone facies consists of multiple, intersecting sets of trough-cross-stratified, fine- to medium-grained, well-sorted sandstone. Troughs are generally 2–4 m wide (average 2.5 m) and 0.2–0.5 m deep. Ripple-laminated and planar-laminated sandstone interbeds are rare. The facies contains only minor subvertical burrows, and body fossils are limited to rare spiriferied and bivalve coquinas. The trough-cross-stratified sandstones are mainly restricted to the Cundlego Formation although thin units of trough-cross-stratification are present in the Nalbia Sandstone on the east side of Kennedy Range. The facies is also poorly developed in the Mallens Sandstone, where isolated, broad, shallow troughs are interbedded with hummocky cross-stratified sandstones.

The close association with hummocky cross-stratification and the presence of marine body fossils and trace fossils in the facies suggest that the trough-cross-stratification was formed by the migration of low-amplitude megaripples in a moderate-to-high-energy nearshore environment. The orientation of 45 cross-sets was measured in excellent exposures of the Cundlego Formation in the bed of the Minilya River, and considerable variability was noted; megaripple migration in westerly, southwesterly and northerly directions (Fig. 3A),

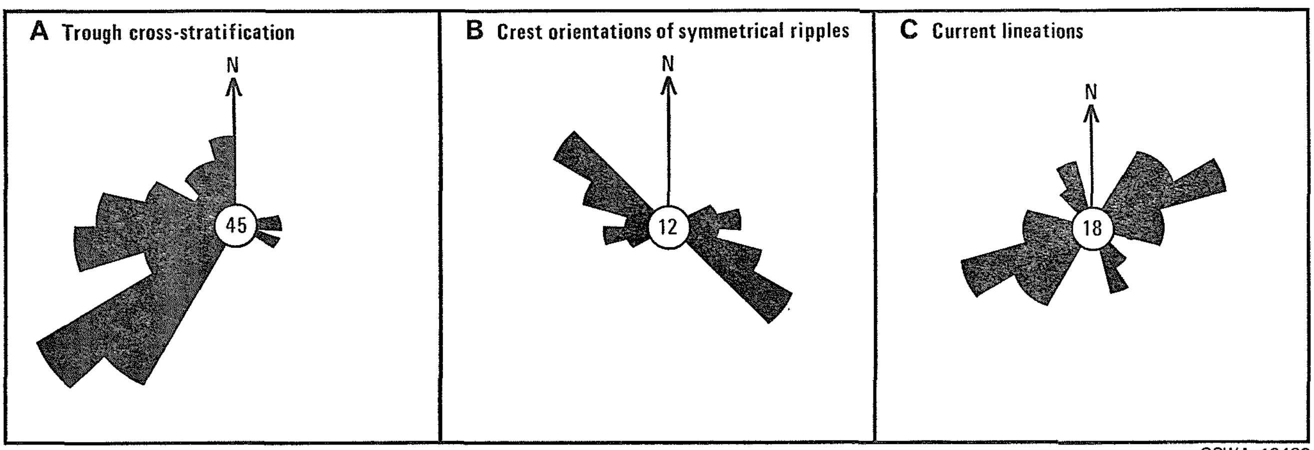

Figure 3 Palaeocurrents, Cundlego Formation, Minilya River. Lengths of arc segments are proportional to number of readings in each segment. Total number of readings shown in central circle. Symmetrical wave ripple crests from the hummocky cross-stratified facies were probably aligned subparallel to the shoreline. Current lineations indicate flow perpendicular and in minor cases parallel to the coastline and trough cross-stratification is directed mainly to the southwest and west (offshore).

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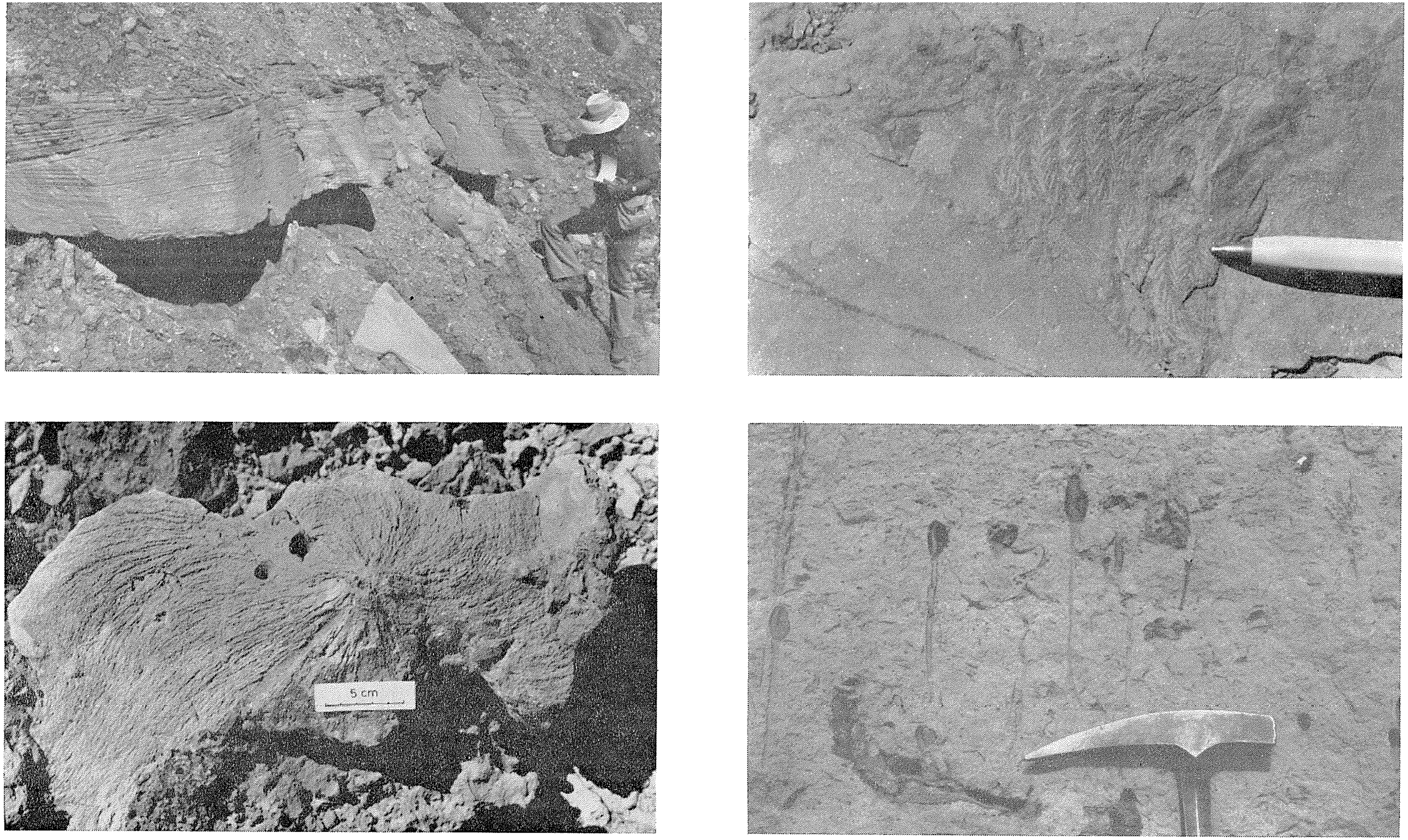


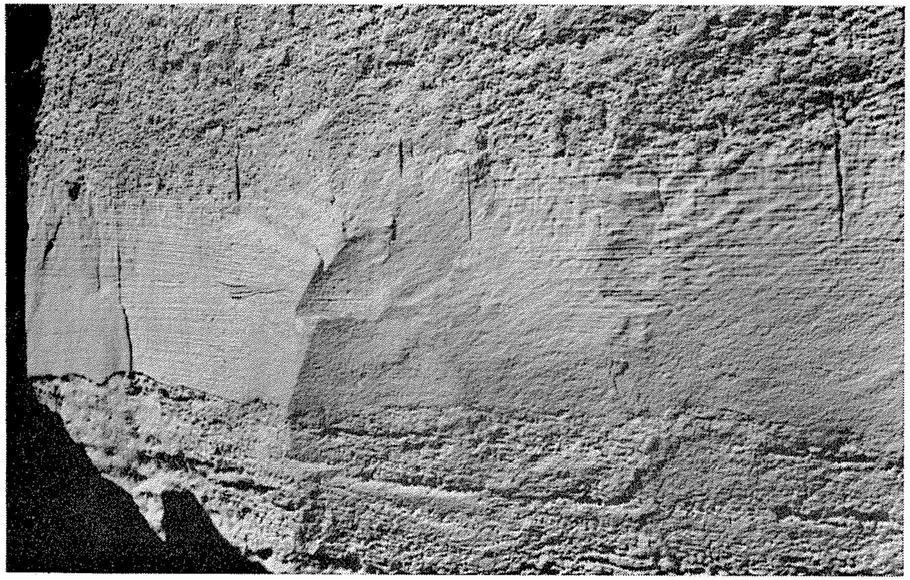
Figure 4 (A) Very low angle cross-stratified sandstone, interpreted as a storm deposit, interbedded in friable and poorly outcropping, bioturbated grey siltstone. Grey-siltstone facies, Baker Formation type section, northern Kennedy Range.

(B) Thin sandstone interbedded with trace fossil *Lophoctenium*. Grey siltstone facies, Bulgadoo Shale type section near the contact with the Cundlego Formation, Minilya River.

(C) Simple *Zoophycos* showing conical, spiral form. Bioturbated sandstone facies, middle portion of Nalbia Sandstone in Blackheart Valley section, northern Kennedy Range.

(D) Evenly bedded sandstone with bulb-shaped cavities interpreted as bivalve burrows. Note subsequent burrowing by worms, with subvertical worm burrows originating from, or penetrating, earlier-formed cavities. Bioturbated sandstone facies, lower portion of Nalbia Sandstone in prominent cliff, 1 km northwest of Blackheart Valley section, northern Kennedy Range.

E



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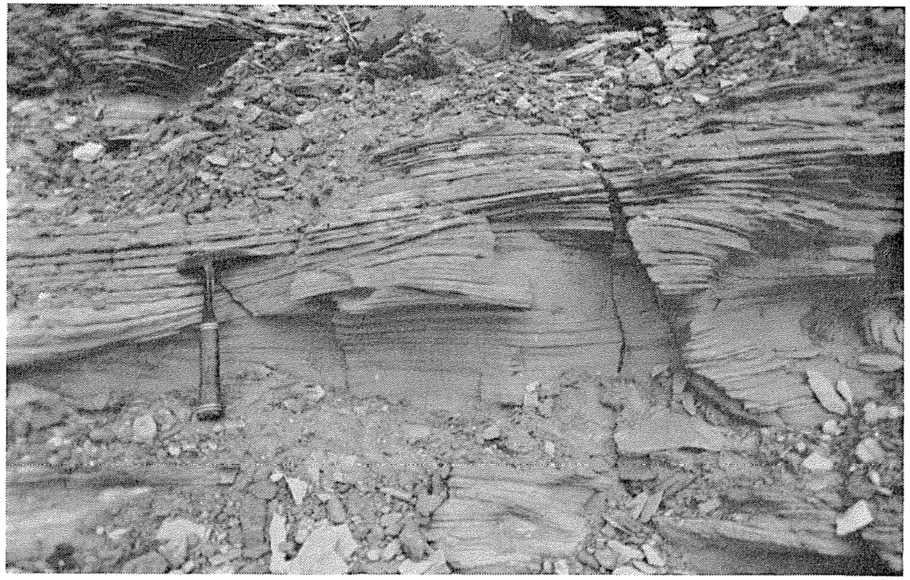

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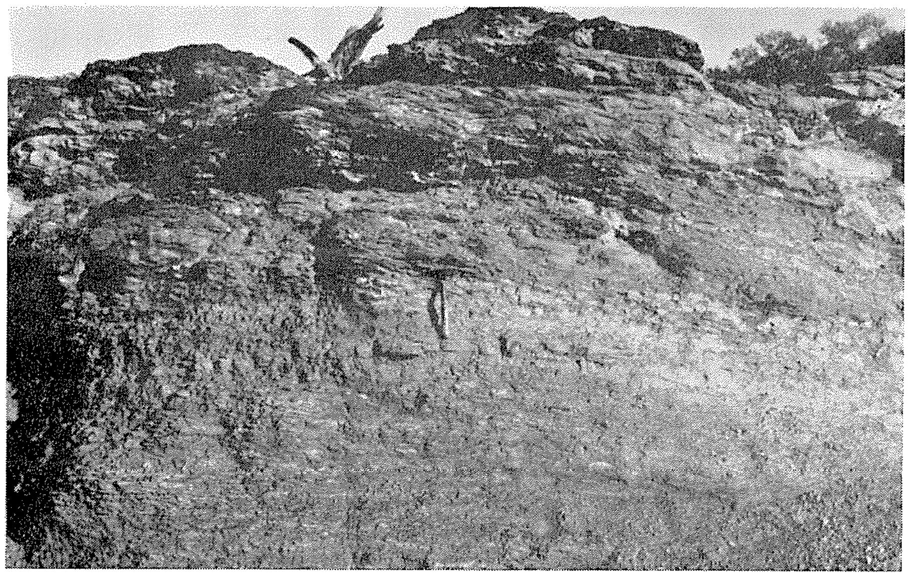

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(E) Laminated-to-burrowed facies, upper portion of Mallens Sandstone, 200 m east of Kimbers Well, northern Kennedy Range. Intensely bioturbated sandstone overlain erosively by 0·8 m thick unit of laminated sandstone with *Skolithos* in the upper part. Passes gradationally into intensely bioturbated sandstone.

(F) Hummocky cross-stratified sandstone facies, basal Nalbia Sandstone in prominent cliff, 1 km northwest of Blackheart Valley section, northern Kennedy Range. Note undulose bedding and low-angle truncation surfaces.

(G) Coarsening-upward cycle in Wandagee Formation type section, adjacent to Minilya River. Grey siltstone passes gradationally into fossiliferous, bioturbated sandstone. The cycle has a sharp top.

presumably in response to longshore and offshore directed currents, is inferred. This paleocurrent pattern characterizes upper shoreface deposits of barred coastlines (Hunter and others, 1979). In this environment, offshore-directed trough-cross-stratification is produced by seaward-flowing rip currents, and longshore-directed cross-stratification reflects current flow along bar troughs. However, unlike the thin sequences predicted by Hunter and others (1979), cross-stratified units in the Cundlego Formation may be many metres thick. Thus, although we favour an upper shoreface, barred coastline origin for the bulk of the trough-cross-stratification (Fig. 2), the possibility remains that this facies formed further offshore, on an open marine shelf where currents were controlled by factors other than shoaling waves (*cf.* Walker, 1979; Daily and others, in press).

DEPOSITIONAL MODEL

Modern counterparts of the sequence of facies preserved in the Byro Group are documented by Bernard and others (1962), Howard (1971), Howard and Reineck (1972), Reineck and Singh (1971) and Kumar and Sanders (1976). The sequences discussed in these papers occur along moderate-energy linear clastic shorelines and in the adjacent offshore environment. Figure 2 summarizes the depositional model which has evolved as a result of these studies, and shows its relationship to the sequence of facies preserved in the Byro Group.

An example of an ancient sequence similar in character to the Bryo Group is the Upper Cretaceous Blackhawk Formation of Utah (Howard, 1966, 1972), although in this example the transition facies contains cross-bedded sandstones. Other related examples are presented by Harms and others (1965) for the Fox Hills Sandstone of Wyoming; by Masters (1967) for the Mesa Verde Formation of Colorado; and by Hamblin and Walker (1979) for two Jurassic formations in the Rocky Mountains. Coarsening-upward cycles, resulting from natural progradation of the shoreface, are recognized in all of these examples. The cycles described show considerable variation in thickness, in that the fine-grained (offshore) part of the cycles may be up to several hundred metres thick. However, the sandy shoreface-foreshore part is invariably thin—a maximum of about 12 m. Harms and others (1975) concluded that the thickness of coarsening-upward cycles is influenced by wave-energy regime, tidal range and relative rates of progradation and subsidence.

In general, the six Byro Group facies do not occur in well-developed cycles. However, cyclicity is noticeable in the Coyrie and Cundlego Formations, the uppermost Bulgadoo Shale and the lower half of the Wandagee Formation. The cycles (2–20 m thick) typically consist of a coarsening-upward unit of grey, bioturbated siltstone containing thin interbeds of laminated sandstone in the upper portion (upper offshore facies), capped by an interval (0.5–6.0 m thick) of hummocky cross-stratification. Wave ripples may be developed on the upper surface of the hummocky cross-stratified unit, which is overlain by grey fine-grained siltstones of the succeeding cycle. These cycles are interpreted as representing regressive events on the outer part of the marine shelf. The bioturbated transition facies and the laminated-to-burrowed lower-shoreface facies are generally not developed. This indicates that the regression occurred rapidly, typically as a result of major storm events, but in some cases apparently in response to tectonic readjustment of the basin, since, in these examples, the hummocky cross-stratified sandstones are too thick to represent single storm episodes (e.g. basal Mallens Sandstone, parts of the Cundlego Formation and basal Nalbia Sandstone). In the Cundlego Formation, the hummocky cross-stratified facies may be overlain by an interval of trough-cross-stratification, indicating continued regression, with the development of the upper-shoreface facies.

Some of the coarsening-upward cycles in the Cundlego Formation are separated by a thin pebble-to-cobble conglomerate 0.05–0.25 m thick, consisting of subangular to subrounded clasts of sandstone and siltstone, with minor fossil fragments (brachiopods, bivalves and rare crinoids and bryozoans) in a silty matrix. The clasts are eroded fragments from the underlying facies. It is probable that periods of basinal stability, or rarely, mild uplift, promoted the development of coarsening upward, prograding shoreline sequences. New coarsening-upward sequences were initiated by periodic, rapid subsidence, with the only preserved record of the rapid transgressions being the thin lag conglomerates. Similar examples of coarsening-upward cycles with thin, trangressive lag conglomerates at the base are described by Walker and Harms (1975) from the Upper Devonian Catskill Formation of Pennsylvania.

Coarsening-upward cycles in the lower half of the Wandagee Formation are characterized by the typical absence of hummocky and trough-cross-stratification. The cycles are 3–8 m thick and consist of grey fine siltstone in the lower portion which becomes progressively coarser and more strongly bioturbated upwards and passes into a thin unit (average 0.8 m) of poorly bedded, bioturbated and richly fossiliferous brown sandstone (Fig. 4G). The coarsening-upward cycles in this case represent a passage from the offshore environment into the transitional environment, probably associated with natural progradation of the shoreline. In rare cases, thin units of

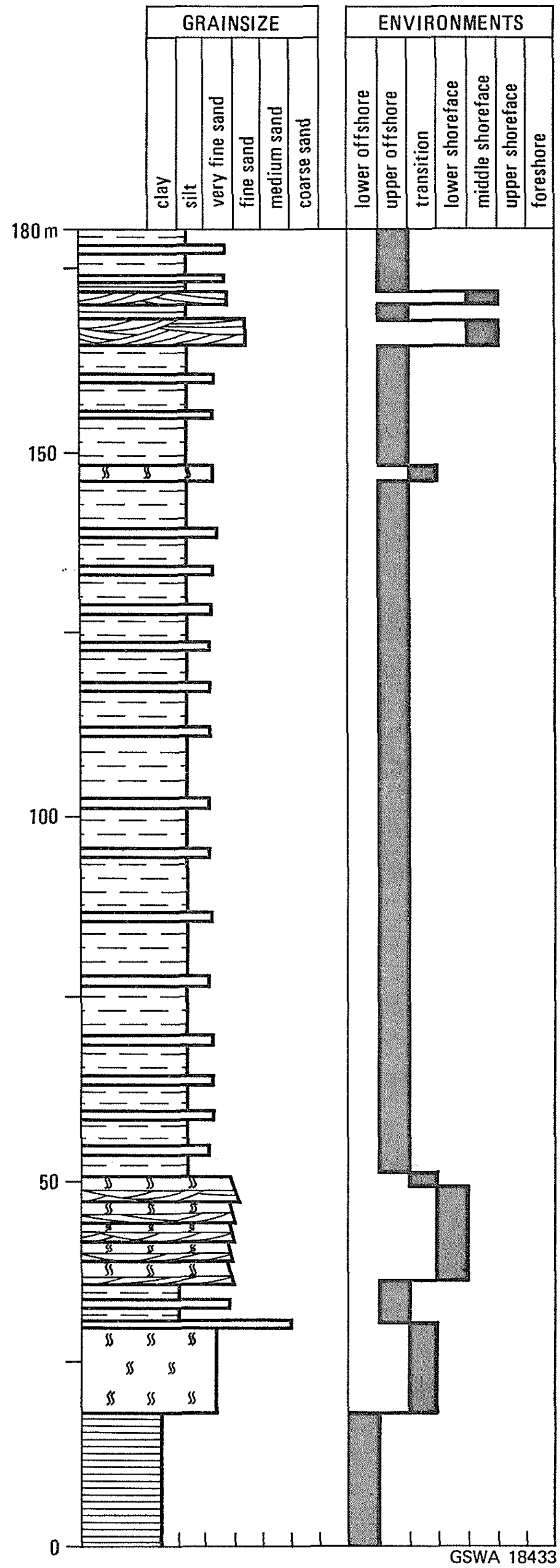

Figure 5 Stratigraphic log, Coyrie Formation type section, northern Kennedy Range. For explanation of the symbols, see Figure 2.

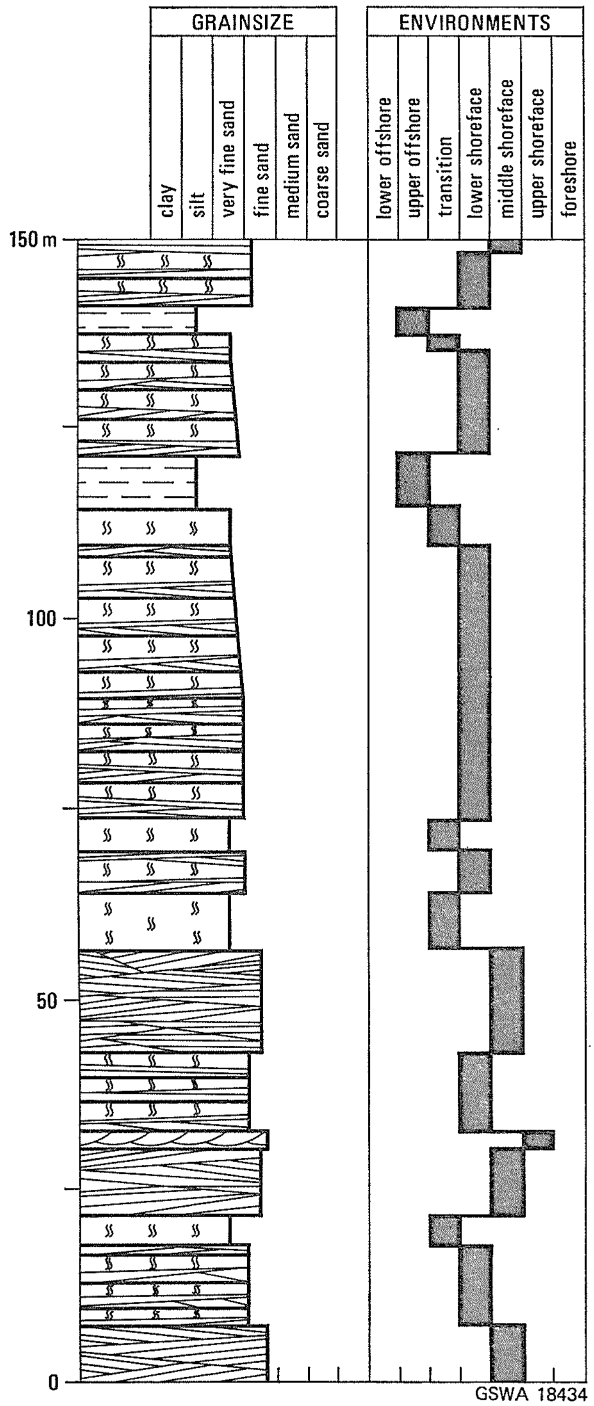

Figure 6 Stratigraphic log, Mallens Sandstone type section, northern Kennedy Range.

symmetrically rippled or laminated sandstone are present in the upper part of the cycles, indicating the development of the lower shoreface facies. The limited thickness of the cycles and the abundance of articulated and relatively unbroken fossils suggest that the sedimentation occurred slowly in a quiet-water environment. In the type section of the Wandagee Formation beside the Minilya River, fossils commonly occur as lag-concentrates. Their preservation in cores of ferruginous nodules caused Condon (1967) to interpret these accumulations as fossiliferous mud-balls. However, the enclosing ferruginous nodules are clearly of post-depositional (diagenetic) origin.

Many cycles in the Wandagee Formation contain lag concentrates of fossils (especially brachiopods) at the base. The relationships of the fossils to the adjacent coarsening-upward cycles is clearly shown in an excellent exposure in Salt Gully Creek, 16 km west of Gascoyne Junction, where spiriferids are concentrated in shallow hollows which average 1·5 m long, 0.8 m wide and 0.15 m deep (Fig. 4H). The hollows represent part of the original topography of the sea floor on the outer sandy shelf (transition facies), and were preserved by the rapid transgression which capped the sequence with grey (offshore facies) siltstone. The fossils were either washed into the hollows by natural processes immediately prior to the transgression or (more likely) were killed by the sudden influx of mud as the transgression progressed, and were subsequently washed into nearby topographic lows. In the Salt Gully Creek exposures, the hollows are all elongate in approximately the same direction (mean of 140° from 11 readings). This suggests that the elongation of the hollows is in some way related to the orientation of the palaeo-shoreline. It is possible that the hollows were wave-generated swales and were thus aligned parallel to the shoreline, but as yet we have no firm evidence to substantiate this theory. The lag concentrates of fossils are similar to the lag conglomerates of pebbles described from the Cundlego Formation, and both are interpreted as indicating repeated subsidence of the basin.

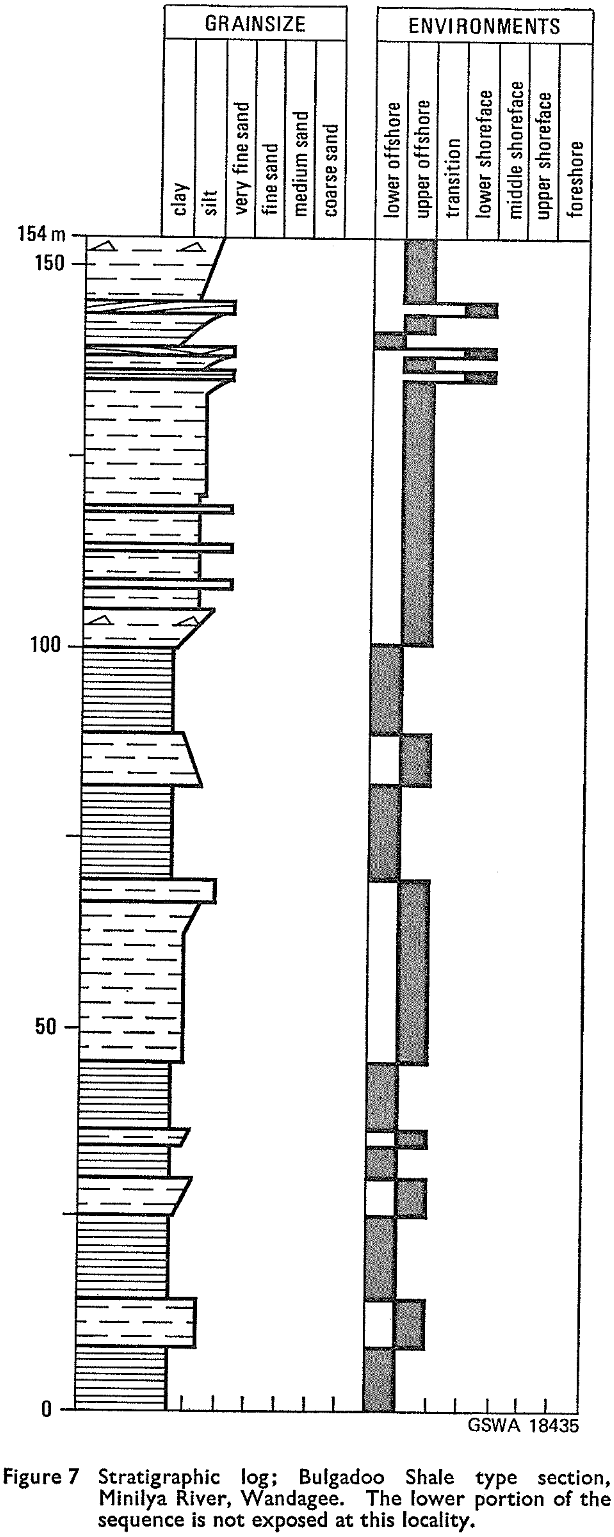

Figure 7 Stratigraphic log; Bulgadoo Shale type section, Minilya River, Wandagee. The lower portion of the sequence is not exposed at this locality.

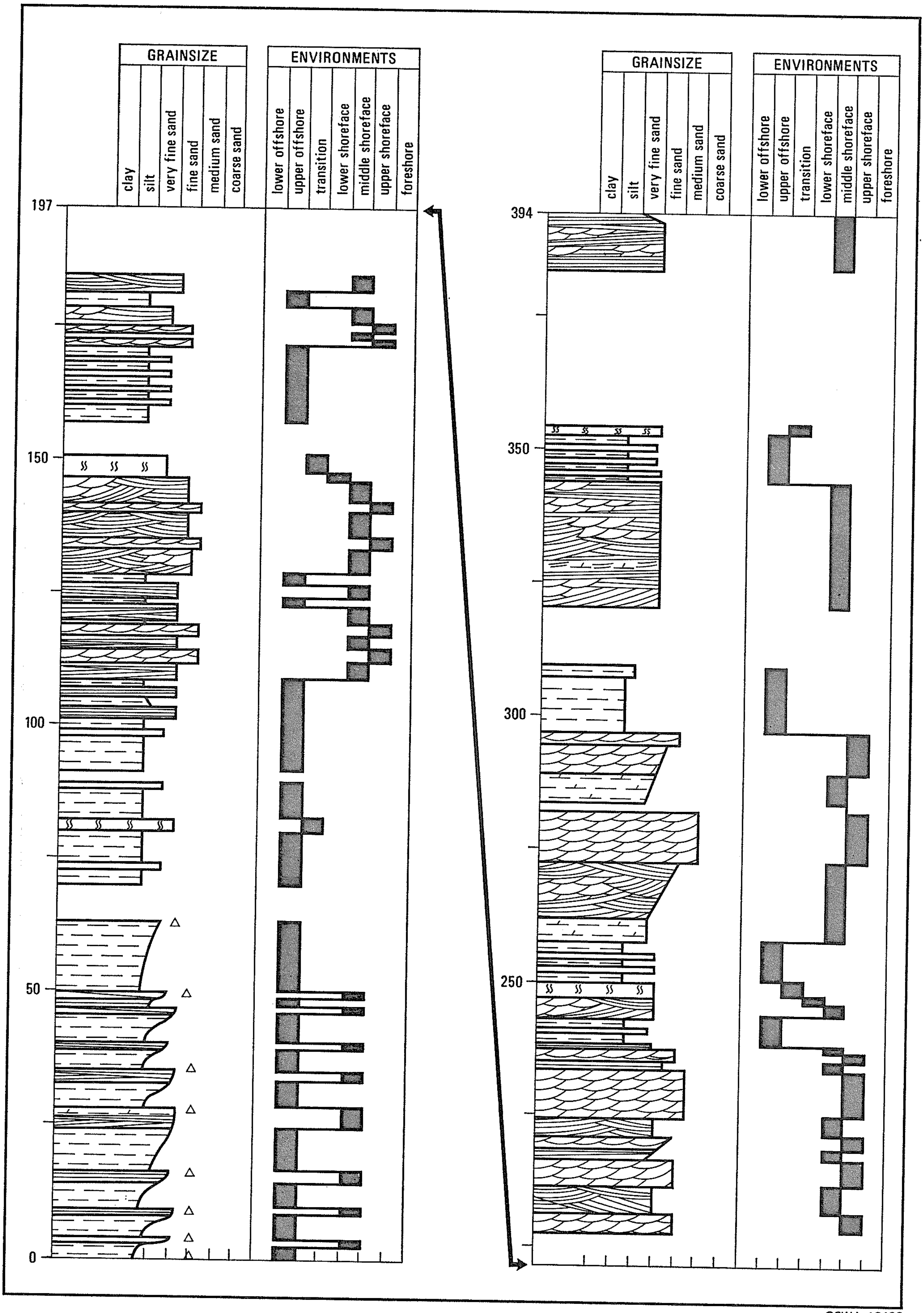

Figure 8 Stratigraphic log, Cundlego Formation reference section, Minilya River. This section is in part fault repeated, and the column shown here is our interpreted reconstruction of the original sequence, based on Condon's (1967) type section, nearby. Major faults causing repetition occur at approximately 65 m and 152 m. (△'s indicate pebble bands.)

PALAEOGEOGRAPHY

Little is known about the palaeogeography of the Carnarvon Basin during deposition of the Byro Group. Condon (1967, Fig. 123) attempted a basic palaeogeographic reconstruction for the upper part of the group, but the position of his palaeo-shoreline is highly speculative and in part relies on his structural interpretation of the Carnarvon Basin, which did not recognize most of the major faulting. We believe that there is no evidence to suggest emergence of the Carrandibby Inlier during deposition of the Byro Group, nor is there any evidence to support Condon's (1967) view that the Gascoyne and Merlinleigh Sub-basins were partly or largely isolated by a basinal sill at this period of time. Furthermore, there is little preserved record of the Byro Group west of the Wandagee-Ajana Fault System (Fig. 1), so the nature of the facies and the location of the westerly shoreline (if one existed nearby) during deposition of the Byro Group remains unknown. Thomas and Smith (1976, p. 154) concluded that the uniformity of the Byro Group facies over a wide area indicates that it was deposited during a tectonically quiet period and that only relatively uniform, fine-grained material was being transported from the land. However, we do not see the need for deposition to have been in restricted arms of the sea, as they imply.

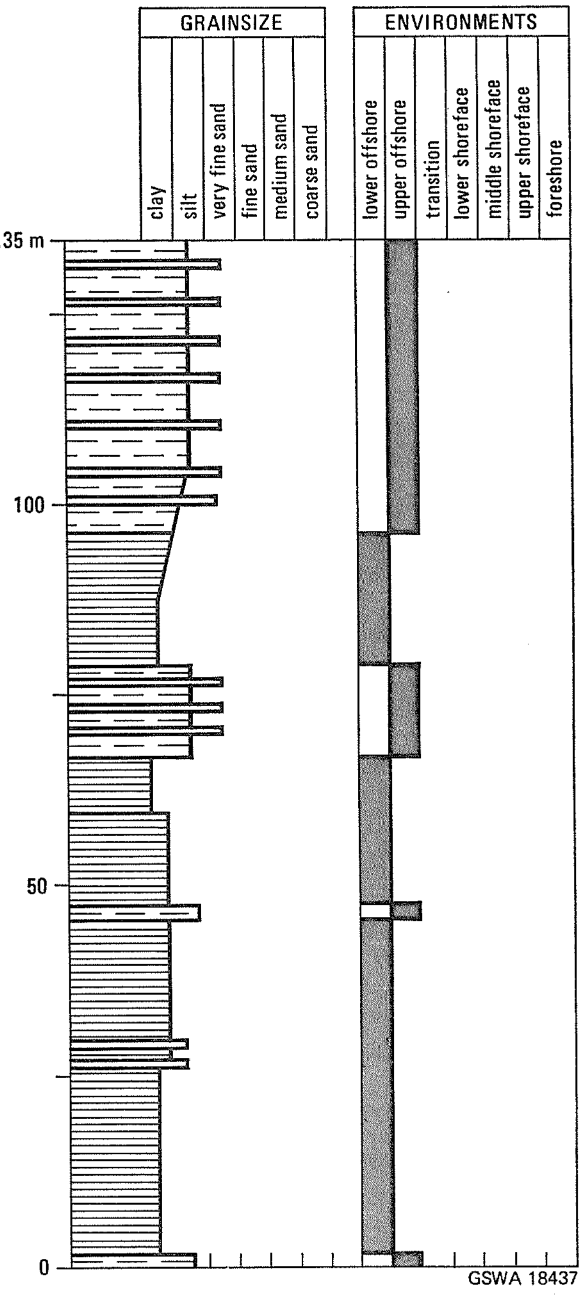

Figure 9 Stratigraphic log, Quinnanie Shale type section, Minilya River, Wandagee.

The foreshore (beach) environment is not represented in the sequence of facies preserved in the Byro Group outcrops, but we envisage that during periods of maximum regression, the eastern shoreline probably lay a short distance east of the present outcrop belt along the Kennedy Range.

SYNTHESIS

The Byro Group was deposited in the Carnarvon Basin during a period of relative tectonic stability. The sediments accumulated on a broad marine shelf and in the adjacent 'offshore' environment, and the preserved sequence of facies

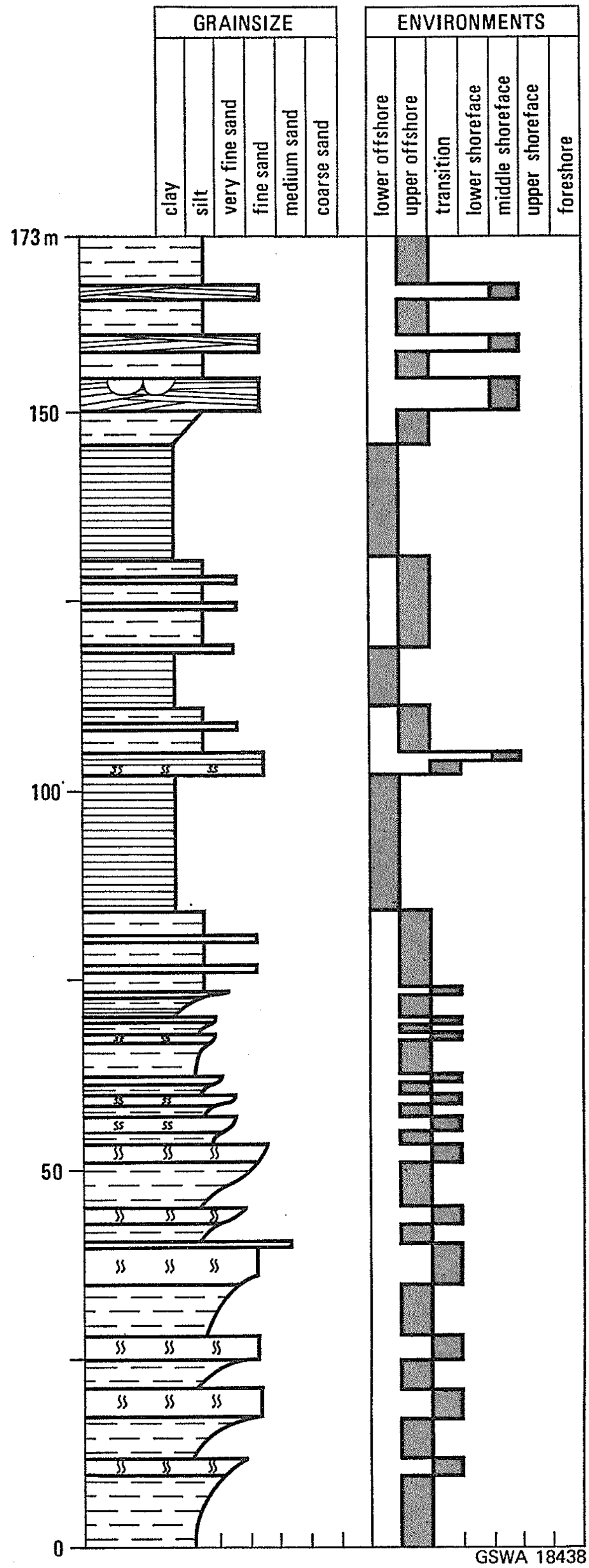

Figure 10 Stratigraphic log, Wandagee Formation type section, Minilya River, Wandagee.

developed in response to the interplay of wave activity and biogenic reworking. According to Crespin (1958) most genera of foraminifera in the Coyrie Formation, Mallens Sandstone and Bulgadoo Shale are cold-water forms, and amelioration of the climate occurred prior to or during the deposition of the Cundlego Formation.

The first unit of the Byro Group to be deposited was the Coyrie Formation (Fig. 5) which comprises an interbedded sequence of offshore, transition and minor shoreface rocks. Grey offshore shales and siltstones predominate in the lower portions of the sequence and a gradual regression is indicated by an increase upwards in the abundance of hummocky cross-stratification.

The overlying Mallens Sandstone (Fig. 6) was deposited in a generally shallower water environment, largely in the middle shoreface zone, and the persistence of the laminated-to-burrowed facies suggests that sedimentation and subsidence were very evenly balanced. Reading (1978) suggested that this facies is best developed along coastlines of moderate wave energy. Certainly the bivalve association described by Dickins (1963) is primarily suited to life on a soft, sandy current-swept substrate.

Deposition of the Mallens Sandstone in the outcrop area was terminated by a marine transgression. The contact with the Bulgadoo Shale is transitional, and the sequence fined upwards as the transgression progressed. The sediments of the Bulgadoo Shale were deposited mainly in an offshore environment (Fig. 7), and very restricted conditions for at least part of the sequence are supported by Thomas's (1958) study of the brachiopod association. The upper part of the Bulgadoo Shale is silty, indicating the start of a regression which was responsible for deposition of the overlying Cundlego Formation.

The dominant facies in the Cundlego Formation (Fig. 8) are the upper offshore (grey-siltstone) and the middle shoreface (hummocky cross-stratified sandstone) facies. The paucity of bioturbated sandstones in the Cundlego Formation suggests that the sequence was deposited relatively rapidly in a subsiding basin. As suggested previously, coarsening-upward cycles may have been tectonically controlled in part, although Reading (1978) suggested that similar sequences could result along shorelines of high wave energy.

The Quinnanie Shale (Fig. 9) is considered by Condon (1954, 1967) to be laterally equivalent to the upper part of the Cundlego Formation. Since the Quinnanie Shale is absent from the southern outcrop areas, this suggests that the basin was relatively shallow in this region, and became deeper towards the north and northwest. The black shale is attributed to the lower offshore facies, and a restricted environment of deposition is supported by the general fossil assemblage (Thomas, 1958) and particularly by the presence of *Lingula* (Moore and others, 1952, p. 222).

Stable, quiet-water conditions prevailed during deposition of the Wandagee Formation (Fig. 10) as indicated by the abundance of body fossils and bioturbated units. Coarsening-upward cycles, dominated by the offshore and transition facies, developed in response to shoreline progradation, and new cycles were initiated by periodic subsidence. The upper part of the formation was deposited under slightly deeper water conditions, with dominance of the offshore facies.

Deposition of the overlying Nalbia Sandstone (Fig. 11) was probably initiated by tectonic uplift of the basin margins and adjacent source areas, since a thick unit of hummocky cross-stratified middle shoreface sandstone occurs at the base. The overlying sequence of bioturbated transition facies sandstones indicates a gradual deepening of the basin as a sand-dwelling bivalve-gastropod association (upper transition zone) is succeeded by intensely bioturbated (lower transition zone) sandstones rich in *Zoophycos*. A gradual regression is indicated in the upper part of the formation, and the hummocky cross-stratified facies dominates in the upper 20–30 m. A comparison was made between the type section at the northern end of Kennedy Range and outcrops along the edge of the range, about 30 km to the southeast. It was noted that the incidence of *Zoophycos* was less, and hummocky cross-stratification greater, in the southeastern outcrops, suggesting that this area was relatively close to the shoreline.

The Baker Formation (Fig. 11) mainly consists of the upper offshore facies, and developed in response to a marine transgression. The relative abundance of brachiopods in the sequence in comparison with bivalves, and the nature of the brachiopod association suggests a relatively deep-water, somewhat restricted environment of deposition (Thomas, 1958). Hummocky cross-stratified interbeds are interpreted mainly as thin storm deposits, and do not represent changes in relative sea level. The sequence becomes sandier and coarser grained towards the southeast, presumably as the basin margin is approached.

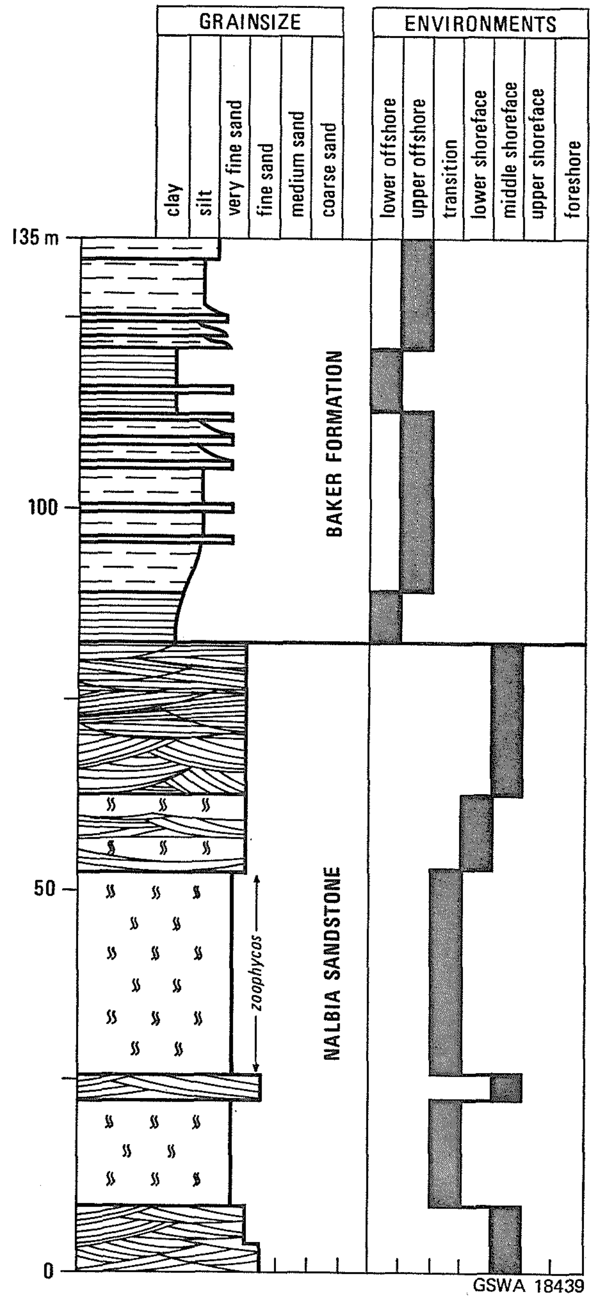

Figure 11 Stratigraphic log: Nalbia Sandstone and Baker Formation, Blackheart Valley, northern Kennedy Range.

Deposition of the Byro Group was terminated by a major regression, associated with the extensive development of the hummocky cross-stratified middle shoreface facies in the lower portions of the Kennedy Group.

CONCLUSIONS

The Byro Group was deposited in a marine environment, and can be divided into six facies which represent deposition in the offshore, transition and shoreface zones. Modern and fossil counterparts are moderately well documented in recent literature, but to the best of our knowledge, the Byro Group is the thickest (1 660 m) sequence of this kind to be examined in detail so far. The shoreface to offshore transition is extremely well developed, and suggests that the sequence was deposited in a wave-dominated environment, and that a great deal of sedimentation occurred as a result of storms. Laminated sandstone interbeds in the offshore facies lend support to Walker's (1979) hypothesis that distribution of sand below wave base is primarily by offshore-directed storm-induced density currents. We have found no evidence of tidal or oceanic-current redistribution of sand in the zone below wave base.

Offshore-directed cross-stratification in the Cundlego Formation is attributed to density or rip currents in the nearshore zone. However, the low angle of the cross-strata and the fine grain-size of the cross-stratified sandstone facies are inconsistent with deposition in high-energy barred-coastline environments of the southern Oregon type (Hunter and others. 1979). It appears from our evidence that density or rip currents are capable of producing cross-stratification, possibly in a more offshore environment, and certainly possess different characteristics to examples from the southern Oregon coast. Further study of this facies is warranted.

Coarsening upward cycles are present in the Byro Group, although cyclic sedimentation is not as well developed as in many of the classic sequences documented to date. The cycles are interpreted as representing regressive events due to shoreline progradation. In addition, we have identified thin lag conglomerates at the base of some cycles which we interpret as transgressive lag conglomerates. Although transgressive conglomerates are known to occur at the base of coarsening-upward cycles in fine-grained deposits (Harms and Walker, 1975), this is the first time that they have been documented from a sandy marine sequence of this type.

The recognition of upper and lower zones in both the offshore and transition environments represents a degree of discrimination not presented by previous workers. However, we believe that the black-shale facies (lower offshore environment) will only develop in response to moderately restricted circulation. Possible environments of deposition are silled basins and some epicontinental seas, although this facies is known to occur in the offshore zone along open coastlines where oceanic currents are very weak. There is no supporting evidence for a silled-basin origin for the Byro Group facies, and the question of whether the Carnarvon Basin was epicontinental at that time remains unresolved, since very similar sediments to those of the Byro Group are known along shorefaces exposed to the open ocean.

The presence of *Lophoctenium* in the upper offshore zone raises doubts as to the validity of this trace fossil as an indicator of deep-water conditions, and the recognition of *Zoophycos* in the lower transition zone emphasises that factors other than water depth (such as degree of bottom turbulence and availability of nutrients) probably also control its distribution.

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SEDIMENTOLOGY OF THE KENNEDY GROUP (PERMIAN), CARNARVON BASIN, WESTERN AUSTRALIA

by P. S. Moore, R. M. Hocking and P. D. Denman

ABSTRACT

The Permian Kennedy Group is a shallow-marine sequence which consists of, in ascending order, the Coolkilya Sandstone, Mungadan Sandstone and Binthalya Formation. It is the youngest exposed Permian group in the Carnarvon Basin and is restricted to the eastern portion of the basin. Eight facies are recognized and indicate deposition in silty offshore, sandy-shelf, and shoreface environments, of which the second is the most prominent. Facies associations suggest two distinct but related depositional models:

(1) a moderate palaeoslope model with a comparatively narrow transition zone of bioturbated sandstone separating offshore and shoreface environments, applicable to the Coolkilya Sandstone, and

(2) a broad sandy shelf with a very low palaeoslope, containing three distinct facies separating offshore and shoreface environments, applicable to the Mungadan Sandstone and Binthalya Formation.

This progressive change in the nature of the overall sedimentary environment is attributed to stabilization and infilling of the Carnarvon Basin in the Kungurian, with the consequent development of a broad, sandy, shallow-marine shelf.

INTRODUCTION

The Lower to ?Upper Permian Kennedy Group, as defined by Condon (1954) and amended by Hocking and others (1980) consists of three formations of fine- to coarse-grained sandstone and minor siltstone (Table 1). Outcrop is restricted to the Kennedy Range area and Wandagee Hill (Fig. 1) in the central Carnarvon Basin. This paper discusses the sedimentology and palaeogeography of the Kennedy Group, and comments on the stratigraphy and distribution of the sequence.

Condon (1962a, 1967) considered the Kennedy Group to rest unconformably on the Baker Formation, but a transitional contact is clearly exposed along the eastern flank of Kennedy Range. The transition from grey pyritic shale and siltstone into laminated and bioturbated fine-grained sandstone represents a change from a quiet-water, muddy, offshore environment to a moderate-energy, sandy, lower-shoreface environment, thus indicating a minor regression. Results of the stratigraphic bore BMR 6, which Condon (1967) also cites as evidence for the unconformity, are inconclusive and open to several interpretations (Perry, 1965; Belford, 1968). At the southern end of Kennedy Range near Calvary Well (Fig. 1), Condon (1967) reports a major unconformity at the base of the Kennedy Group. However recent detailed mapping indicates that this contact is a fault.

The Coolkilya Sandstone is of known Kungurian age (Condon, 1967). Dickins (1970) has suggested that the Binthalya Formation may be upper Kazanian; however, Playford and others (1975) indicated that the formation is probably basal Kazanian. Neither the Binthalya Formation nor the Mungadan Sandstone contain age-diagnostic fossils. Cockbain (1980) assigns the Coolkilya Sandstone to the Roadian, a substage of the upper Artinskian (which is broadly equivalent to the lower Kungurian).

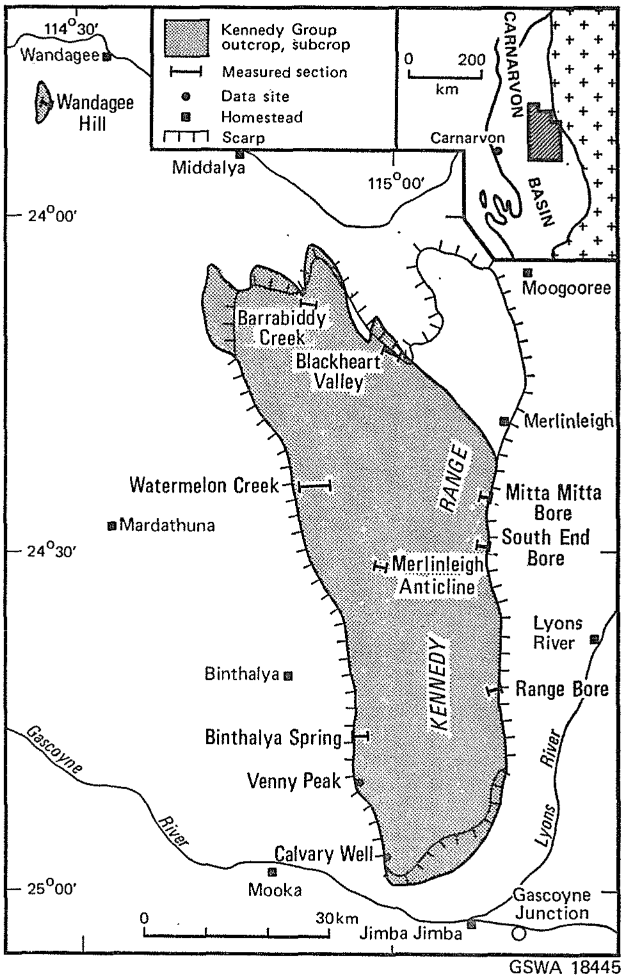


Figure 1 Distribution of the Kennedy Group and positions of measured sections.

FACIES ANALYSIS

Stratigraphic sections were measured through portions of the Kennedy Group at eight localities (Fig. 1), and eight facies were identified. The results of this study are summarized in Figures 2 and 5. In these figures, three related, silty, offshore facies have been grouped together for convenience and simplicity. The relative abundance of the facies at any single data site is a function of both the geographic and stratigraphic position of that site. Two stratigraphic sections of the Coolkilya and Mungadan Sandstones illustrate this spatial variation in facies abundance, with the transition from Range Bore

TABLE 1. KENNEDY GROUP STRATIGRAPHIC TABLE

Age	Group	Formation	Maximum known thickness (m)	Lithology
PERMIAN	KENNEDY GROUP	Binthalya Formation	(a) 544	Siltstone to fine-grained quartz sandstone; poor to moderate sorting.
		Mungadan Sandstone	(b) 116	Fine to coarse quartz sandstone, minor siltstone; moderate to good sorting.
		Coolkilya Sandstone (d)	(c) 285	Siltstone to medium-grained quartz sandstone; poor sorting.
	BYRO GROUP			

(a) type section. (b) measured section. (c) from Kennedy Range 1 (Lehmann, 1967). (d) modified from "Coolkilya Greywacke" by Hocking and others (1980).

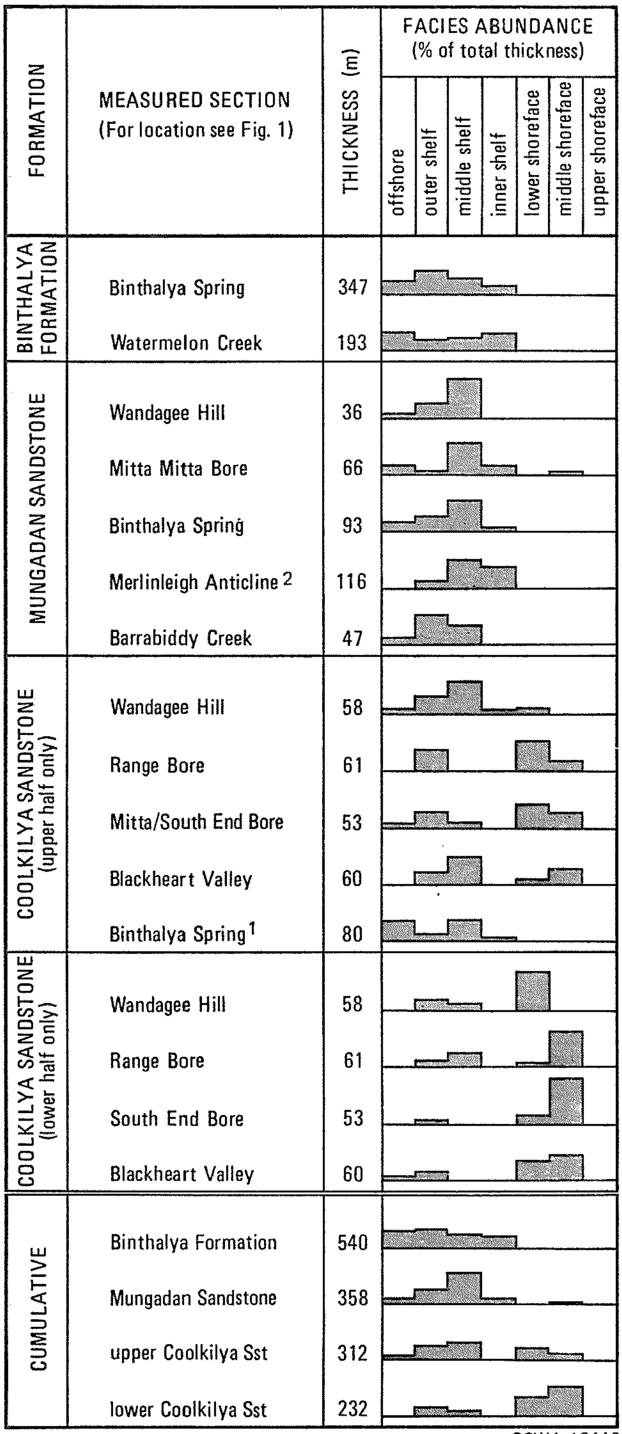


Figure 2 Thicknesses and facies abundances in measured sections of the Kennedy Group: (1) Lower part not exposed; total formation thickness unknown; (2) Incomplete section; probably fault repeated in part.

(Fig. 3A) to Wandagee Hill (Fig. 3B) reflecting the more offshore location of the latter area. In addition, a 347 m thick section of the Binthalya Formation is represented in Figure 4.

FINE-GRAINED FACIES ASSOCIATION

Two major siltstone facies are recognized: one with rippled sandstone lenses and the other without. All gradations between the two end members occur, and the facies spectrum represents the result of deposition in a moderately reducing, offshore-marine environment. A third facies, comprising coarse sandy siltstone, is mainly restricted to minor intervals in the Mungadan Sandstone along the eastern edge of the Kennedy Range. The black-pyritic-shale facies (lower-offshore environment) recognized in the underlying Byro Group (Moore and others, 1980) has no equivalent in the Kennedy Group outcrops (Figs. 3 and 4).

Grey-siltstone facies (offshore)

The grey-siltstone facies consists of evenly laminated to very thinly bedded, medium- to coarse-grained pale-grey siltstone and sandy siltstone (Fig. 6A) containing common small curved burrows and minor small subvertical burrows. The grey-siltstone facies is present in all three formations. Units are generally only 0·5–4·0 m thick.

The grey siltstones were deposited below wave base in a quiet-water, reducing marine environment. In contrast with the equivalent facies in the Byro Group, laminated sandstone interbeds are rare, indicating relatively slow deposition in an area isolated from the effects of major storms.

Lenticular-and-linsen-bedded facies (offshore)

Lenticular-and-linsen-bedded units (cf. De Raaf and others, 1977), constitute minor facies mainly in the Binthalya Formation. The facies consists of isolated ripple-lenses and connected ripple-trains of fine sandstone in a grey, coarse-siltstone matrix (Fig. 6F). The ripple-lenses generally have an undulatory base, and are symmetrical or near-symmetrical in form. Internal laminae are strongly curved and may be form-discordant. The surrounding, grey siltstone is evenly laminated, the entire facies is bioturbated, and small curved burrows are common.

The lenticular-and-linsen-bedded facies developed in a low-energy, reducing environment, which received small inputs of sand, probably during periods of storm activity. The ripple-lenses contain many features typical of wave-formed structures (De Raaf and others, 1977). Reineck and Singh (1972) have suggested that such ripples develop as thin storm sand layers which are reworked by wave agitation related to the same storm. Thus, the facies probably represents active deposition at approximate maximum wave-base.

Coarse-sandy-siltstone facies (?offshore)

The coarse-sandy-siltstone facies is a very minor facies which has been observed in the Mungadan Sandstone along the eastern edge of the Kennedy Range and at rare intervals in the Binthalya Formation along Watermelon Creek. It is characterized by the intimate association of white, very coarse-grained sandstone and white (?leached) shale or fine siltstone. In some cases, the sand grains are dispersed in a silty matrix, but more commonly the sandstone forms thin, even beds or lenses separated by centimetre-thick bands of white fine siltstone. The siltstone bands are generally discontinuous over a metre or less, and in a few cases, have been reworked to form mudstone intraclasts.

Deposition took place mainly by suspension-settling in a low-energy environment, although the presence of coarse, traction-deposited sandstones indicates the nearby proximity of a much higher energy environment. It is tentatively suggested that this facies is a variation of the more typical offshore-siltstone facies; and that the modification results from a greater-than-normal palaeoslope (causing the juxtaposition of high- and low-energy regimes) and/or the proximity of a major supply of coastal sand. Likely environments are thus: offshore from a distributary system, or in a protected environment adjacent to a barrier island (Goldberg, 1979).

SANDSTONE FACIES ASSOCIATION

Bioturbated-sandstone facies (lower transition or outer shelf)

Bioturbated sandstone is a major component of the Coolkilya Sandstone and Binthalya Formation, and is present in the Mungadan Sandstone, particularly in the northwestern outcrops (Fig. 2). The facies consists of intensely bioturbated, greyish-brown to reddish-brown, poorly sorted, fine- to very fine-grained sandstone and silty sandstone. Disarticulated bivalves and brachiopods, mostly preserved as lenticular coquinas, are rare. A great variety of subvertical, inclined and subhorizontal burrows is present, and *Zoophycos* occurs in the middle portion of the Coolkilya Sandstone.

The bioturbated-sandstone facies formed below effective wave base, where sedimentation was slow enough to allow extensive reworking of the sediment by infaunal and epifaunal organisms.

Evenly-bedded-and-ripple-laminated-sandstone facies (mid-shelf)

The evenly-bedded-and-ripple-laminated-sandstone facies is common in the Kennedy Group, especially in the Mungadan Sandstone and Binthalya Formation. It consists of thin (0·2–0·7 m) intervals of evenly bedded to ripple-laminated, fine- to medium-grained sandstone (Fig. 6D), commonly with oscillation ripples developed on the upper surface. The units

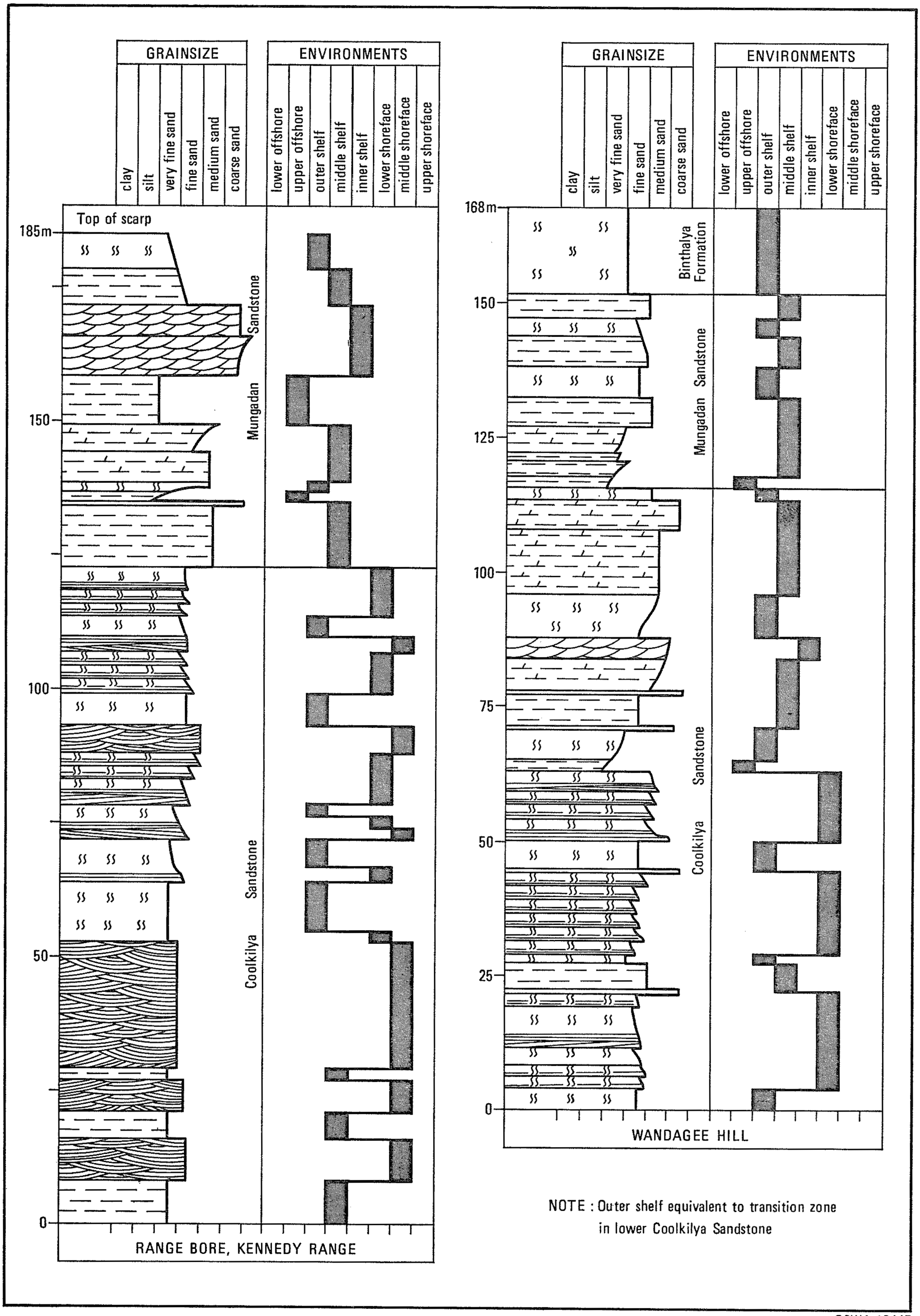


Figure 3 Stratigraphic logs, Coolkilya and Mungadan Sandstones, Range Bore and Wandagee Hill, showing lateral facies variation. For explanation of the symbols see Figure 5.

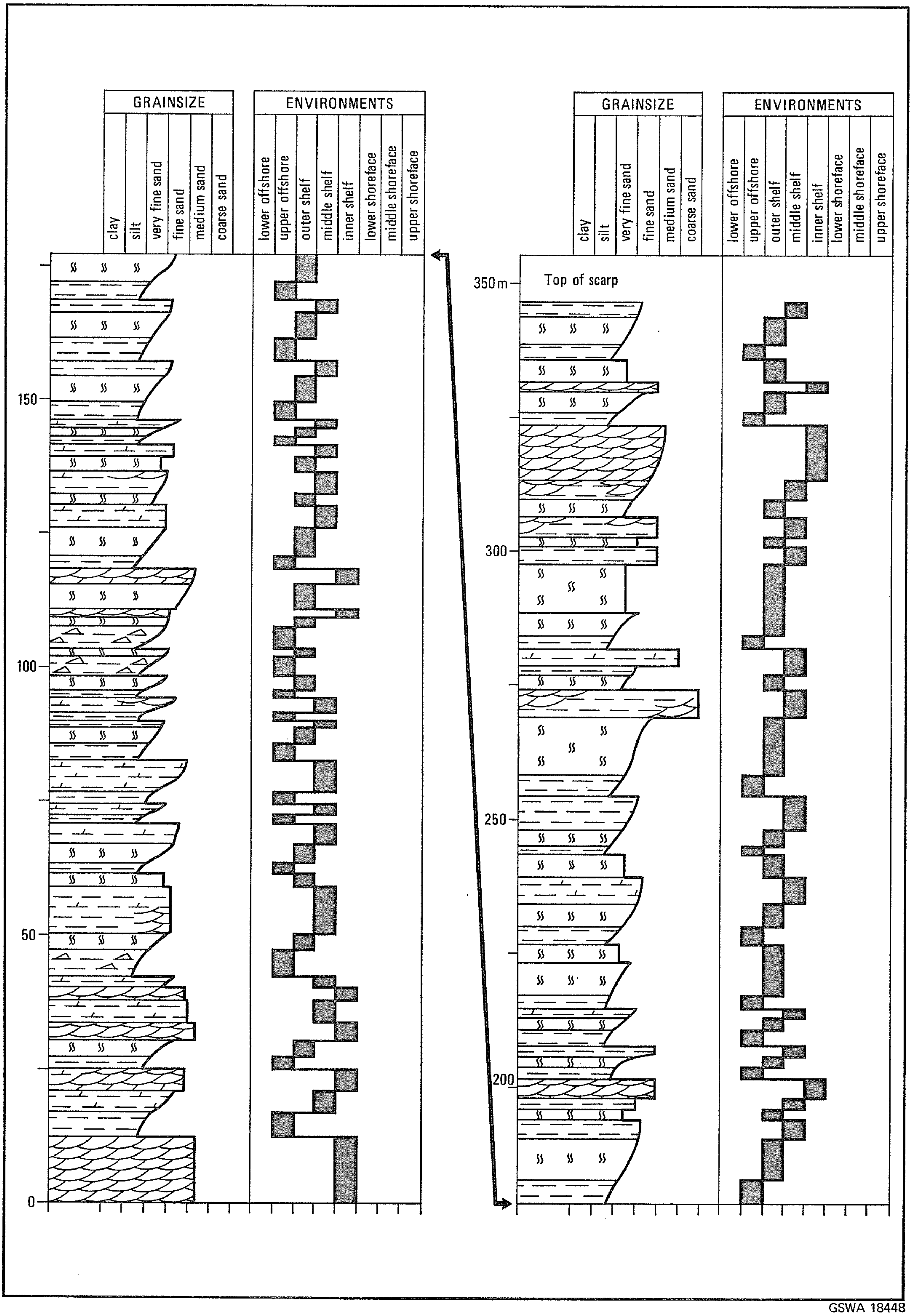


Figure 4 Stratigraphic log, Binthalya Formation, 800 m south of Binthalya Spring. For explanation of symbols, see Figure 5.

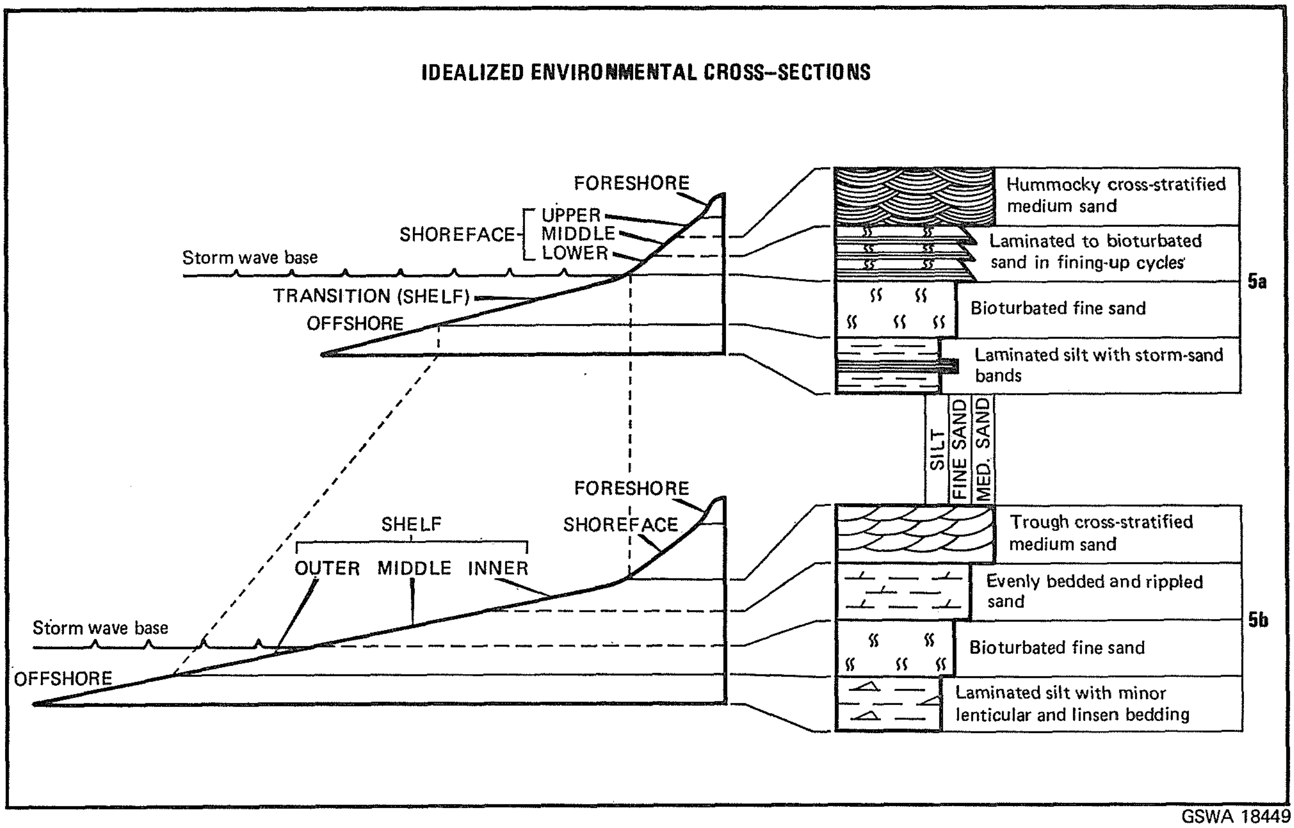


Figure 5 Depositional models for the Kennedy Group.
(a) Lower portion of bioturbated sandstone separates the offshore and shoreface environments.
(b) Mungadan Sandstone and Binthalya Formation. A broad sandy shelf separates the shoreface and offshore environments. The upper Coolkilya Sandstone shows features which are intermediate between these two models.

are weakly bioturbated, although rippled surfaces and major bedding planes in places contain excellent examples of *Scalarituba* (Fig. 6G), *Rhizocorallum* (Fig. 6H) and *Cosmorphaie* (Fig. 6I).

The evenly bedded and rippled sandstones were deposited above wave base in response to moderate wave and/or current activity. Deposition occurred too quickly for the sediment to be extensively bioturbated. Oscillation ripples developed on the surface of the sandstone beds during periods of relative quiescence.

Cross-stratified-sandstone facies (inner shelf)

The cross-stratified-sandstone facies consists mainly of multiple, intersecting sets of trough-cross-stratified, fine- to coarse-grained sandstone (Fig. 6E). Solitary troughs and small tabular cross-beds are also present. Troughs are generally 1·5–2·5 m wide and 0·3–0·6 m high, and contrast to the broader, shallower troughs of the Byro Group sequences (Moore and others, 1980). Cross-stratification is common in parts of the Binthalya Formation, and occurs sporadically in the Coolkilya and Mungadan Sandstones.

The trough-cross-stratified sandstones were formed by the migration of megaripples in a moderate to high-energy, nearshore-marine environment. Minor tabular cross-sets were formed by the migration of sand waves (Harms and others, 1975).

Laminated-to-burrowed-sandstone facies (lower shoreface)

The laminated-to-burrowed-sandstone facies consists of units of fine to very fine sandstone which are planar laminated to hummocky cross-stratified near the base, becoming intensely bioturbated towards the top (Fig. 6C). The units are 0·4–1·5 m thick, and have a slightly erosive base. *Skolithos* is prominent in the bioturbated intervals. The laminated-to-burrowed facies is poorly represented in the Kennedy Group, occurring mainly in the lower portion of the Coolkilya Sandstone. Units are generally thin in comparison with their counterparts in the Byro Group (Moore and others, 1980).

The laminated-to-burrowed units were probably deposited at approximate wave base. The thin, traction-deposited sandstones formed in response to storm activity and alternate with bioturbated sandstones formed during quiet-water sedimentation, when burrowing organisms were able to rework the upper part of the substrate (Howard, 1972).

Hummocky-cross-stratified-sandstone facies (middle shoreface)

This facies consists of laminated to very low-angle cross-stratified sandstone, occurring in thin (0·1–0·4 m) sets separated by minor discordances (Fig. 6B). Body fossils (mainly disarticulated bivalves) are rare and trace fossils are mainly of small subvertical burrows. The hummocky-cross-stratified sandstone facies is confined to the lower portion of the Coolkilya Sandstone.

This facies developed in response to constant reworking of sand in a shallow-marine environment above mean wave base. Reading (1978) believes that it characterizes the middle shoreface zone of a moderate-energy, linear clastic shoreline.

DEPOSITIONAL MODELS

The sequences of facies developed in the Kennedy Group cannot be explained by a single depositional model. Rather, the Kennedy Group is best considered in terms of two distinct but related models, one which characterizes the deposits of the Coolkilya Sandstone, and the other which explains the sequences in the Mungadan Sandstone and Binthalya Formation.

The depositional model presented for the underlying Byro Group (Moore and others, 1980) is readily applicable to the lower portion of the Coolkilya Sandstone; however, it is less applicable to the upper part and is commonly quite inconsistent with the sequences of facies developed in the Mungadan Sandstone and Binthalya Formation. A diagrammatic summary of the model is presented in Figure 5A. The offshore siltstones are not represented in the Coolkilya Sandstone itself, but are present at the top of the conformably underlying Baker Formation. The sequence of facies produced by natural progradation of the shoreline is grey siltstone at the base, followed successively by bioturbated silty sandstone, laminated-to-burrowed sandstone and hummocky cross-stratified sandstone. Such sequences ideally coarsen upwards, although individual units of laminated-to-burrowed facies may fine upwards. During deposition of the lower portion of the Coolkilya Sandstone and the underlying Byro Group, the transition zone, or the sandy part of the marine shelf, was probably only of moderate width because of the combined effects of a limited supply of sand and a relatively steep palaeoslope. Distribution of sand was primarily by wave action, and much of the sandy sequence reflects the influence of storms. The transition environment is characterized by quiet-water deposition, and there is no evidence that currents redistributed the sand in this zone below wave base. A feature of this model is the presence of the laminated-to-burrowed facies, which can only develop where relatively quiet-water deposition occurs immediately seaward of the shoreface zone.

The absence of the laminated-to-burrowed facies in the Mungadan Sandstone and Binthalya Formation (Fig. 2) is considered to be very significant. In these formations, small-scale (1·5–15 m thick) coarsening-upward cycles are common, particularly in the southeastern outcrops (Figs. 6A and 6D) and a complete cycle (Fig. 5B) is presented as a basic depositional model for this part of the sequence. The coarsening-upward cycles reflect a progressive increase in depositional energy in which bioturbated, sub-wave base sandstones on the outer shelf pass gradationally into wave and ?current worked, evenly bedded and rippled sandstones. These in turn may pass laterally into medium- and large-scale cross-stratified sandstones formed by megaripple and minor sand-wave migration. Although there is minor herringbone cross-stratification in the sequence (Fig. 6E), there are no other features indicative of tidal influence. In particular, the fining upward "BC" sequences typical of sandy intertidal and subtidal deposits (Klein, 1971) are notably absent. The cycles are not deltaic in origin either. Beds are laterally very continuous, there is an absence of prominent channelling, and the widespread distribution of the facies is inconsistent with deltaic deposition (Broussard, 1975). Thomas and Smith (1976) suggested that the Kennedy Group was deposited in estuarine and lacustrine environments. However, the lateral persistence of the Kennedy Group facies over such a large area, and the considerable thickness of the sequence are inconsistent with deposition in these environments (Lauff, 1967; Greer 1975; Picard and High, 1972). Furthermore, there is no evidence of abnormal salinity conditions or restricted circulation patterns which characterize lacustrine deposition (Matter and Tucker, 1977).

The coarsening-upward cycles of Figure 5B are thus interpreted as resulting from the natural progradation of the shoreline. The relatively consistent thickness of the cycles and the considerable stratigraphic thickness over which they occur (Figs. 3 and 4) suggest that the depositional basin was undergoing gentle downwarp, so that the rates of subsidence and sedimentation were approximately balanced.

Three possible depositional models may be considered to explain the evolution of the Mungadan Sandstone and Binthalya Formation cycles. The first of these is that the cycles represent shoreline oscillations along a barred coastline. Rip currents are prominent along barred coastlines, and their deposits have a high preservation potential. Furthermore, according to Komar (1976) rip currents are the principal way in which offshore-orientated large-scale cross-stratification is generated in the non-deltaic marine environment. The coarsening-upward sequences described by Hunter and others (1979) in their barred-coastline model are similar to cycles in the Binthalya Formation where cross-stratification is preserved. However, such a model is inconsistent with the extensive regional distribution of the cross-stratified facies in the Kennedy Group. Although Davidson-Arnott and Greenwood (1976) have shown that the maximum seaward extent of rip currents is probably enhanced by the development of multiple bars, present data suggest that even in this situation, rip currents are wholly confined to the nearshore zone, within about 1 km of the foreshore. However, we have found no evidence of the foreshore environment in any of the Kennedy Group outcrops, as should be expected in such a sequence. For example, outcrops of Mungadan Sandstone in the Merlinleigh Anticline (Fig. 1) are prominently cross-stratified with a major offshore mode (Fig. 7C), yet in outcrops 20 km to the southeast (roughly shorewards) in the same formation there is no evidence of the strandline.

A second possible model is presented by Anderson (1976). The sequence from evenly bedded siltstone through linsen-bedded and ripple-laminated sandstone into large-scale cross-stratified sandstone can develop on open marine shelves swept by strong currents. Although the currents are generated by oceanic tides, they may be essentially unidirectional, and bedforms indicative of tidal oscillation may be absent. However, in this model, the currents typically flow sub-parallel to the shoreline (Belderson and Stride, 1966) and ripples, where preserved, are highly asymmetrical (linguoid), unlike the oscillation ripples of the Mungadan and Binthalya sequences. Furthermore, in marked contrast to the Kennedy Group sequences, fossil examples of the 'tidal path circulation' model do not show examples of cyclicity (Anderson, 1976) and indeed, none are likely from theoretical considerations of the model.

The third and simplest model, and the one that we favour, is of a broad, prograding sandy marine shelf which consisted of bioturbated and rippled sand in the outer zone and megaripples in the inner zone. Long-crested, symmetrical and near-symmetrical wave ripples on the outer shelf were probably aligned with their crests parallel to the shoreline (Picard. 1967: Picard and High, 1968). The orientation of wave ripple crests (Fig. 7) and the regional distribution of facies (Fig. 2), indicate that the shoreline lay to the southeast of the outcrop area during deposition of the Mungadan Sandstone and Binthalya Formation (Fig. 7). The ripples were formed in a low-energy zone near approximate wave base, which on a broad sandy shelf, may have been a considerable distance offshore in moderately deep water. For example, Draper (1967) concluded that waves in certain cases can move bottom sediments at depths of over 100 m in the open-shelf environment. Similar observations at even greater depths on shelves adjacent to northwestern Australia, South America and Thailand are reported by the Australian Institute of Petroleum Limited (1979).

In zones of higher energy, presumably shoreward of the rippled zone, megaripples were a common bedform and migrated in a variety of directions but mainly to the northwest. This predominantly offshore orientation is unusual, particularly in a non-barred, wave-dominated system where megaripples most commonly face shorewards (Clifton and others, 1971). However, Banks (1973) and Daily and others (in press) have suggested that offshore-directed, storm-generated currents may be prominent in the evolution on nearshore sequences on broad marine shelves, and their deposits should have a high preservation potential. Walker (1979) and Walker and Hamblin (1979) argue that the storm-generation of offshore-directed density currents is a major geological process, and is capable of producing cross-stratification. However, our understanding of this important process is far from complete.

Thus, we conclude that the Mungadan Sandstone and Binthalya Formation developed mainly on a broad sandy shelf, and the sequence of facies reflects a shoreward increase in grain-size and scale of preserved sedimentary structures in response to increased depositional energy. The abundance of long-crested oscillation ripples in an environment considered to be seaward of the zone of megaripple migration (Fig. 5B) suggests that the cross-stratification was produced in a zone above storm wave base, and therefore possibly formed mainly in response to offshore directed, storm-generated currents. Minor redistribution of sand by tidal currents is probable.

PALAEOGEOGRAPHY AND GEOLOGIC HISTORY

Palaeogeographic maps for four time intervals during deposition of the Kennedy Group are presented in Figure 7. The position of boundaries between depositional environments is based primarily on the regional distribution of facies, but also takes account of the fact that oscillation (wave) ripples are typically aligned with their crests sub-parallel to the coastline.

Deposition of the Coolkilya Sandstone was initiated by a mild regression which terminated Byro Group deposition and promoted shoreface sedimentation in a belt along what is now the eastern side of Kennedy Range (Fig. 7A). Thick sequences of hummocky cross-stratification (middle shoreface environment) occur in the lower half of the Coolkilya Sandstone at Range Bore, South End Bore and Blackheart Valley, and constitute a narrow zone which defines the orientation of the palaeo-shoreline. Around Wandagee Hill, which was further offshore, sedimentation was mostly in the lower shoreface and transition environments. Palaeocurrent data are rare in these deposits.

A broadening of the sandy shelf began during the deposition of the upper part of the Coolkilya Sandstone (Fig. 7B), probably as a result of an increase in the supply of sand. This increased supply rate may have been due to uplift of distant source areas, particularly to the south and southeast. The lower shoreface environment is still prominently represented in outcrops at Range Bore, South End Bore and Mitta Mitta Bore, but sandy, bioturbated and ripple-laminated shelf facies are dominant in outcrops to the west. Palaeocurrent data are sparse, but shoreward and longshore migration of megaripples (large scale cross-stratification) is indicated. Oscillation ripples have a variety of orientations.

Continued mild transgression and further broadening of the sandy marine shelf are indicated by the development of the Mungadan Sandstone (Fig. 7C). The predominance of quartz and moderate to good sorting of the sand suggest considerable reworking of the sediment by waves and currents, although poorly sorted silty sandstones were still being deposited in a more offshore environment at Wandagee Hill. The gradual change in facies from northwest to southeast suggests that land lay to the southeast beyond the area of outcrop, and this interpretation is supported by the orientation of wave-ripple

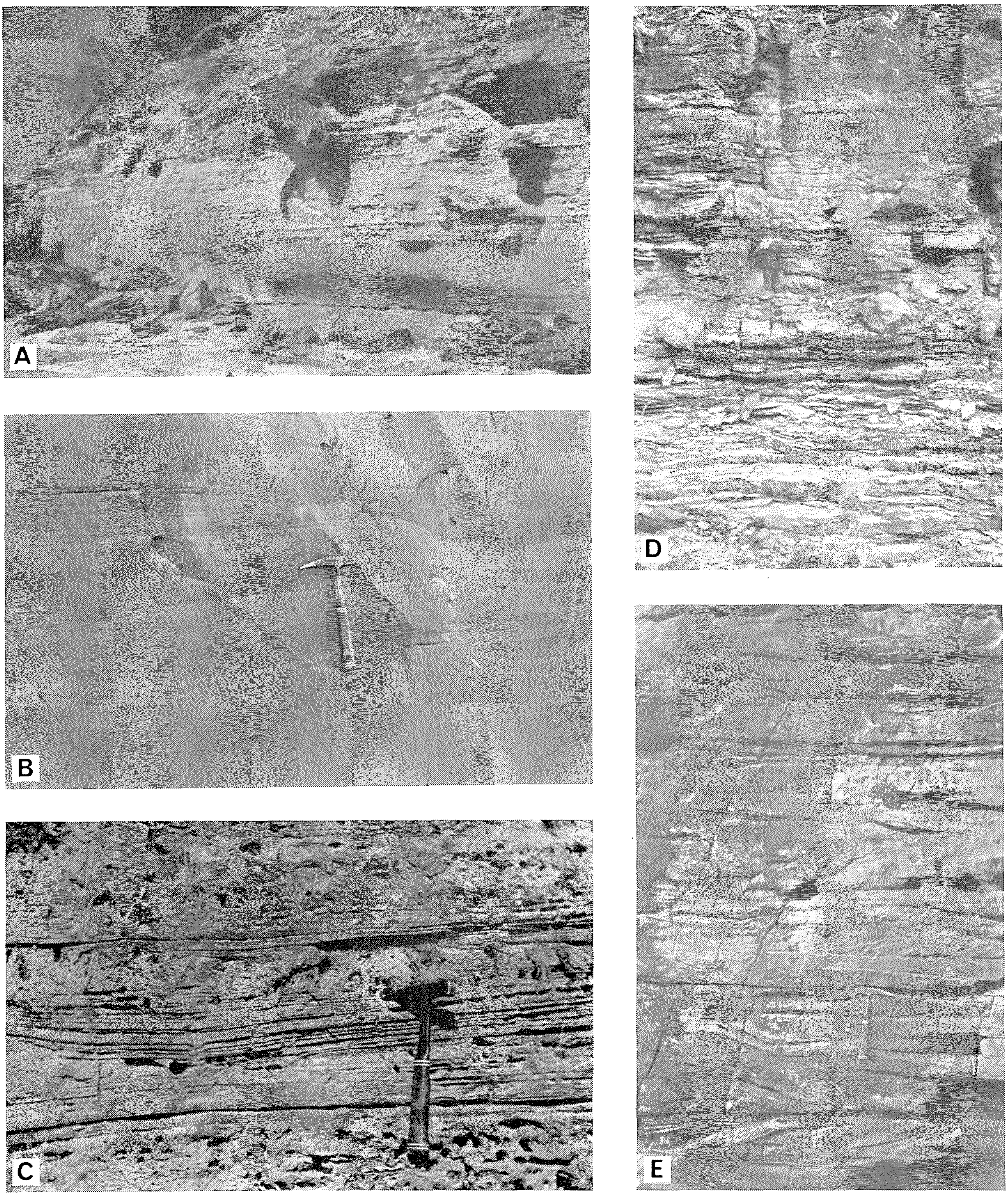


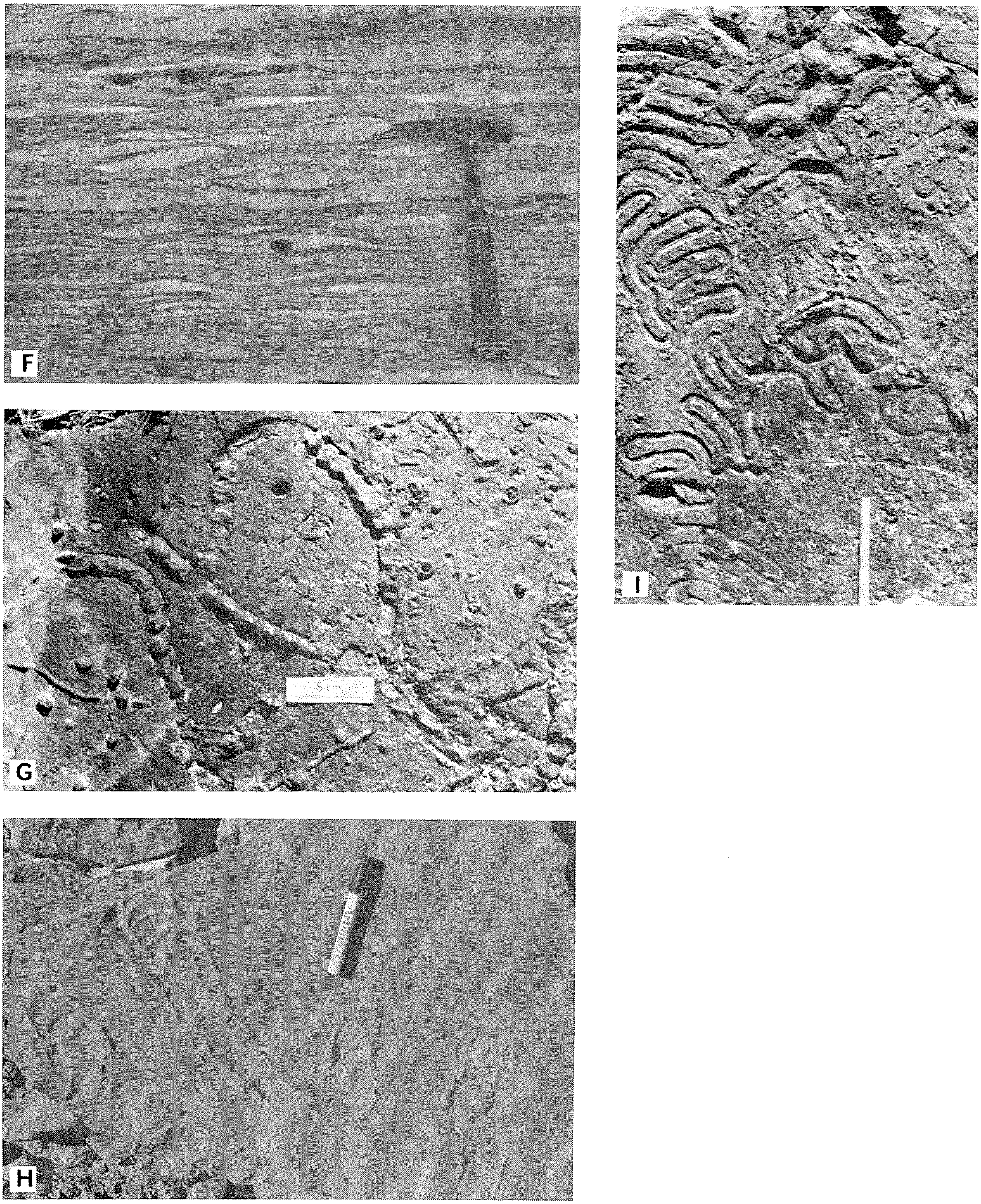
Figure 6 (A) General view of grey-siltstone facies, coarsening-upward into poorly outcropping bioturbated sandstone. Binthalya Formation, south bank of Watermelon Creek, western Kennedy Range.

(B) Hummocky cross-stratified facies, consisting of low-angle intersecting sets of cross-stratification with minor shallow scours. Very weakly bioturbated Lower Coolkilya Sandstone, west side of Blackheart Valley, northern Kennedy Range.

(C) Thin units of laminated-to-burrowed facies. Middle portion of Coolkilya Sandstone at Range Bore, eastern Kennedy Range.

(D) Evenly bedded-sandstone facies, showing coarsening-upward tendency from underlying grey siltstones. Cycle has a sharp top and is overlain by grey siltstone. Mungadan Sandstone in measured section 800 m south of Binthalya Spring, southwestern Kennedy Range.

(E) Cross-stratified-sandstone facies, with common herringbone structures. This sequence was probably deposited under the influence of tidal currents. Offshore (ebb) -directed palaeocurrents predominate. Basal Mungadan Sandstone, south side of WAPET road, Merlinleigh Anticline.



(F) Rippled-sandstone lenticles in grey siltstone. Lenticular-and-linsen-bedded facies, Binthalya Formation, north bank of Watermelon Creek, western Kennedy Range.

(G) *Scalarituba* in evenly bedded-sandstone facies. Lower part of Binthalya Formation in measured section 800 m south of Binthalya Spring, southwestern Kennedy Range.

(H) *Rhizocorallum* on wave-rippled bedding surface. Evenly bedded sandstone facies, basal Binthalya Formation, south side of WAPET road, Merlinleigh Anticline.

(I) Sinuous feeding burrow of *Cosmorphaie*. Evenly bedded facies, Binthalya Formation, north bank of Watermelon Creek, western Kennedy Range.

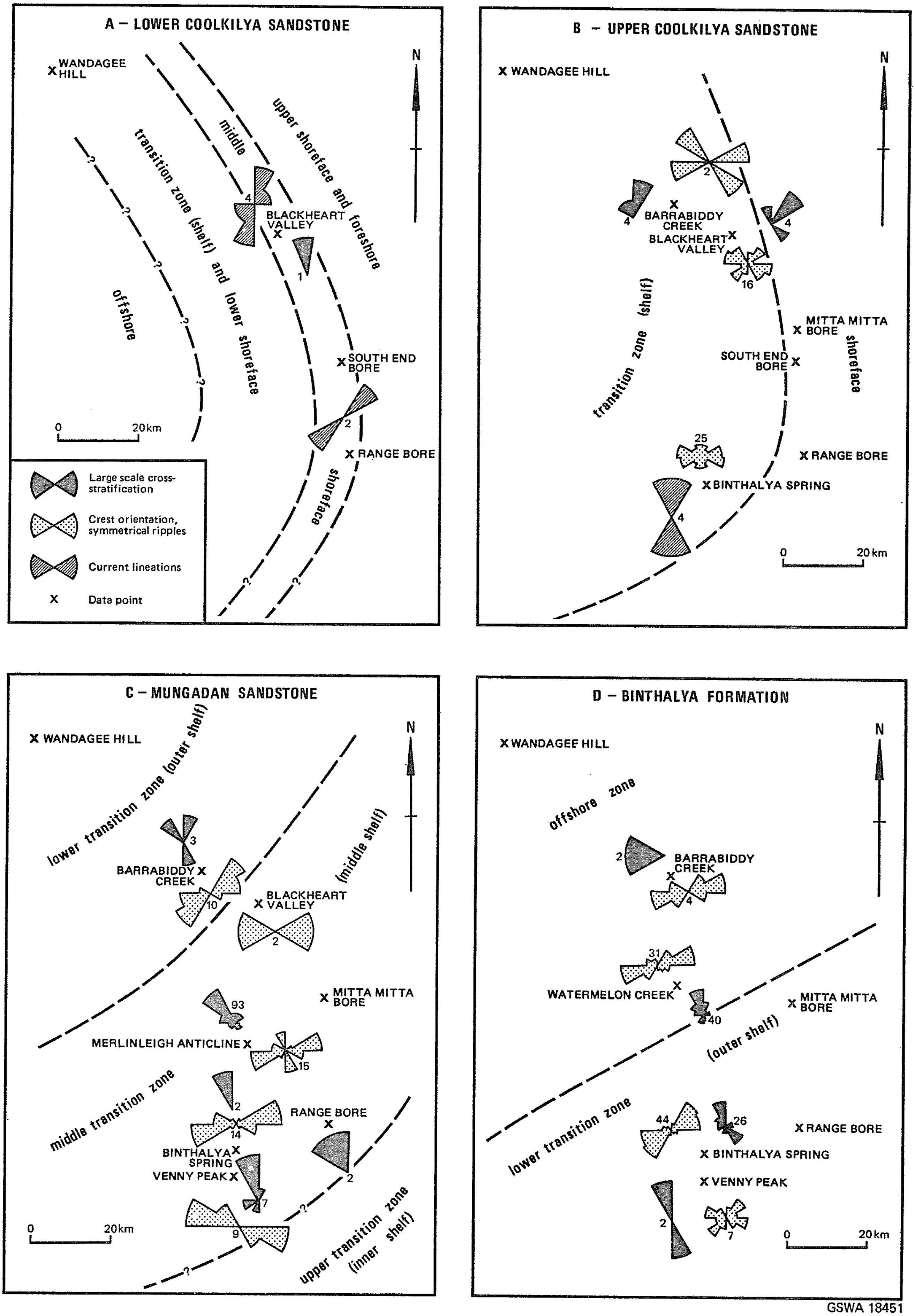


Figure 7 Palaeogeographic maps for four time intervals during deposition of the Kennedy Group.

crests in the sequence. Offshore-orientated large-scale cross-stratification probably resulted mainly from storm-generated currents, as discussed previously.

Offshore siltstones are common in scattered outcrops of the basal Binthalya Formation in the north and northwest, and a palaeogeographic reconstruction for this period of time is shown in Figure 7D. Further reorientation of the shoreline is suggested by the alignment of wave-ripple crests. Megaripple migration was predominantly on and off shore, presumably in response to onshore wave attack and offshore storm-generated currents.

CONCLUSIONS

The Kennedy Group, a siliciclastic sandy sequence with minor siltstone, was deposited on a very broad, sandy marine shelf and in the adjacent offshore and shoreface environments. Sequences of this type are poorly documented in recent literature, and a great deal remains to be learned about the sandy marine shelf. One critical question is how the sand is distributed in this zone below mean wave base.

In the Kennedy Group, we have distinguished three facies in the sandy-shelf environment. Bioturbated sandstones formed where wave and current activity were weak, whereas rippled and evenly bedded sandstones indicate more rapid deposition and stronger reworking by physical processes. Minor cross-stratified sandstones indicate current flow in a moderate to high-energy environment. Although in many cases these three facies are randomly interbedded, coarsening-upward cycles are present, particularly in the southeastern outcrops. We interpret these cycles as representing regressive events associated with shoreline progradation. Thus, bioturbated sandstones dominate on the outer shelf, rippled and evenly bedded sandstones dominate on the mid-shelf, and cross-stratified sandstones, representing megaripple migration, dominate on the inner shelf. The abundance of wave ripples in the sequence suggests that wave activity was an important process for sand distribution. Some cross-stratification probably has a tidal origin, but the majority is attributed to offshore-directed, storm-generated currents. Note however, that although several prominent workers have recently suggested storm currents as a means of generating offshore-directed cross-stratification on marine shelves, the process has yet to be demonstrated in the modern environment.

A progressive broadening of the sandy shelf during deposition of the Kennedy Group is indicated by a gradual change in the style of sedimentation and the preserved sequence of facies. The broadening was associated with, and possibly caused by, an increase in the rate of sand supply, which in turn was probably related to rejuvenation and increased erosion of relatively distant source areas to the southeast. The orientation of the palaeoslope swung from roughly north-south at the commencement of Kennedy Group deposition to northeast-southwest during deposition of the Binthalya Formation, possibly heralding the end of this phase of sedimentation.

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ENVIRONMENTAL CONTROLS ON THE MORPHOLOGY OF MODERN STROMATOLITES AT HAMELIN POOL, WESTERN AUSTRALIA

by Phillip E. Playford

ABSTRACT

Environmental factors are generally dominant in controlling the external morphology of stromatolites at Hamelin Pool, but biological factors also influence some external features, and they largely control the internal stromatolite fabrics.

Many Hamelin Pool stromatolites are elongate parallel to the wave-translation direction. However, the prevailing winds are also believed to influence the growth direction of some forms. Columnar stromatolites that are inclined to the south and seif (linear) stromatolites that trend nearly north-south, are thought to have developed in response to the prevailing southerly winds. The seif stromatolites show characteristics suggesting that they have formed as a result of wind-induced paired helical vortices (Langmuir circulation) in water.

The Hamelin Pool stromatolites generally require a hard substrate on which to grow. This consists variously of indurated Pleistocene beach ridges, Tertiary quartzite, and calcrete over Cretaceous calcilutite or Pleistocene limestone. Where stromatolites have grown on Pleistocene beach ridges they tend to form curvilinear reefs, with parallel lines of stromatolites in each reef controlled by resistant beds in the underlying beach ridges. In other areas large domal stromatolites have grown over eroded remnants of indurated solution pipes cutting Cretaceous calcilutite.

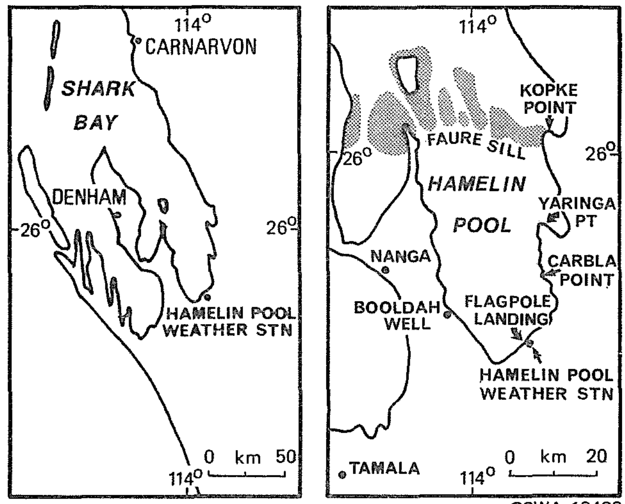

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Figure 1 Locality maps, Hamelin Pool area.

INTRODUCTION

The algal stromatolites growing today around the margins of Hamelin Pool are believed to be the most diverse and abundant forms known from modern seas. They are of considerable importance as modern analogues of ancient stromatolites, and have consequently been the subject of extensive research over the past 20 years (Logan, 1961; Logan and others, 1974; Playford and Cockbain, 1976; Hoffman, 1976, Monty; 1976; Golubic, 1976; Playford, 1979; Bauld and others, 1979).

Hamelin Pool is a hypersaline marine embayment, barred from the rest of Shark Bay by a limesand and seagrass bank known as the Faure Sill (Fig. 1). The restricted tidal exchange through this sill, combined with low precipitation and high evaporation, have resulted in hypersaline conditions in Hamelin Pool, with salinities in the range 55 000 to 70 000 mg/L throughout the year. As a result, the Hamelin Pool biota is very restricted compared with that of the more open-marine areas elsewhere in Shark Bay. The virtual absence in Hamelin Pool of gastropods that graze on algae is believed to be the main factor allowing stromatolites and flat algal mats to flourish there. Further details of the Hamelin Pool environment and descriptions of the geology are given by Logan and others (1970), Playford and Cockbain (1976), van de Graaff and others (in press), and Butcher and others (in press).

Early work on the Hamelin Pool stromatolites emphasized the role of environmental factors in controlling stromatolite morphology. Subsequent research has confirmed the strong influence of these factors on the gross external features of stromatolite morphology, but has also shown that internal fabrics are largely governed by the stromatolite-building algal assemblages.

The present paper is intended as a progress report on aspects of recent work at Hamelin Pool by the Geological Survey, concentrating on some of the main environmental controls on stromatolite morphology.

THE STROMATOLITES

Algal stromatolites and flat algal mats are growing today over wide areas of the sublittoral platform and adjacent intertidal zone in Hamelin Pool, extending to water depths of at least 3·5 m (Playford and Cockbain, 1976). The living intertidal forms are commonly backed by older dead stromatolites, which extend to about 1 m above sea level. Tectonic, rather than eustatic, emergence of these old stromatolites seems probable.

However, not all stromatolites in the intertidal zone and on the sublittoral shelf are living; a significant proportion are dead. Some can be shown to have died through being overwhelmed by sediment, such as moving sand megaripples, and to have later been uncovered. In some cases uncovered dead forms have afterwards been recolonized by stromatolitic algae, allowing growth to recommence over all or part of the stromatolites. However, many dead stromatolites, both intertidal and subtidal, are bare of living stromatolitic algae, even though they seem to be in favourable positions for renewed growth. The reason for this is unknown.

Observations utilizing non-corrosive nails (placed as markers) and photographs taken over intervals of several years show that the Hamelin Pool stromatolites are extremely slow growing; indeed most living intertidal forms seem to be virtually static, with growth of the algal mats approximately balanced by erosion through wave action. The maximum net growth rate of a marked stromatolite, amounting to no more than 0·5 mm per year, has been recorded from a subtidal colloform-mat stromatolite. Field experimental data obtained by Bauld and others (1979) showed the highest primary productivity in subtidal colloform mat (113 mg C $m^{-2}h^{-1}$) and the lowest in intertidal smooth mat (17 mg C $m^{-2}h^{-1}$).

The slowness of growth suggests that many individual stromatolites are hundreds of years old. However, it seems possible that conditions for stromatolite growth in Hamelin Pool today are not as favourable as they were in the recent past. This possibility is supported by the occurrence of extensive areas of dead stromatolites in both intertidal and subtidal areas.

Most, but not all, living stromatolites at Hamelin Pool, both intertidal and subtidal, are being lithified penecontemporaneously. The nature of the cementing process has not been studied, and the reason why some stromatolites remain virtually uncemented is unknown. Time may be a factor, but there is no evidence at present to indicate that uncemented stromatolites have grown more rapidly than cemented forms.

Early workers did not recognize biological controls on stromatolite morphology at Hamelin Pool, claiming instead that growth forms are controlled solely by environmental factors (Logan, 1961; Logan and others, 1964). However, subsequent research has shown that although environmental factors have exerted a dominant influence on gross external stromatolite morphology (to be discussed in the next section) the stromatolite-building algal mats also influence external morphology to some extent, and they largely control the internal fabrics. Figure 2 illustrates the distribution of the three principal mat types that build stromatolites at Hamelin Pool, the dominant algal species in each mat, and associated surface features and internal fabrics of the stromatolites. However, considerable additional work remains to be done before there is an adequate understanding of the biological influences on the morphology of these stromatolites. The Hamelin Pool stromatolites may well provide the key to explaining why fenestral fabrics are common in shallow-water Phanerozoic stromatolites, but are apparently absent from Precambrian forms.

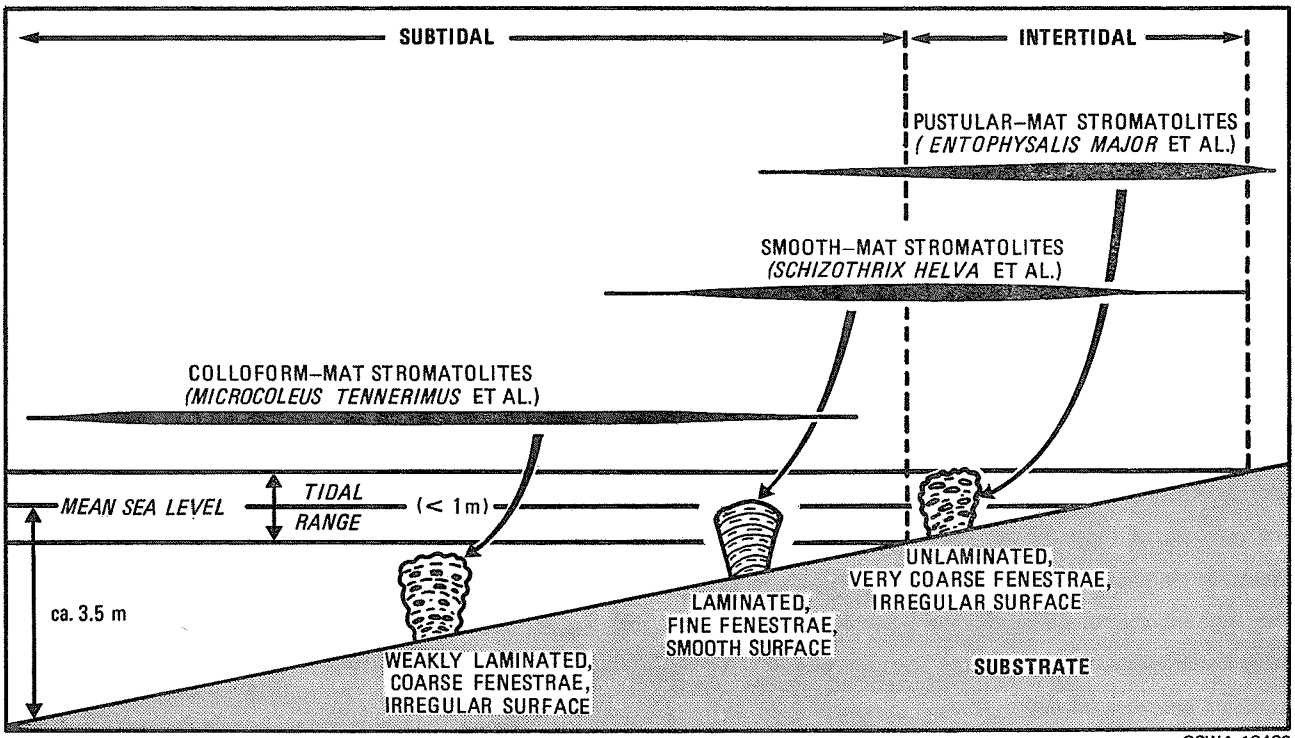

Figure 2 Diagram illustrating distribution of stromatolite-building algal mats and their dominant algal species, and some associated morphological features of the stromatolites.

ENVIRONMENTAL CONTROLS ON STROMATOLITE MORPHOLOGY

The three environmental controls on stromatolite morphology and distribution at Hamelin Pool to be discussed in this paper are the wave-translation direction, prevailing wind direction, and nature of the substrate (Fig. 3).

WAVE-TRANSLATION DIRECTION

The fact that stromatolites at Hamelin Pool, both intertidal and subtidal, are commonly elongate in the wave-translation direction (Figs. 8A, B) has been documented by Logan and others (1974) and Playford and Cockbain (1976). Many authors have applied this principle in explaining the origin of elongate stromatolites in the ancient record, and the analogy seems to be generally valid. However, there is evidence that the prevailing wind direction and nature of the substrate also influence the elongation and trends of some stromatolites at Hamelin Pool, and these factors should be borne in mind when interpreting environmental controls on the morphology of ancient stromatolites.

WIND DIRECTION

The prevailing wind direction over most of the Shark Bay area is from the south to south-southwest, as shown by records at Carnarvon (Fig. 4) and personal observations at Denham, Tamala, Nanga, and Dirk Hartog Island. These winds are especially strong and persistent during the summer. However, records from Hamelin Pool weather station show that winds there are weaker and more variable, and the prevailing wind direction is southeast to south (Fig. 4). This is because the weather station is situated near the southeastern end of Hamelin Pool, which is more subject to land-influenced atmospheric circulation than other parts of the Shark Bay area.

Playford and Cockbain (1976) reported that small "leaning" columnar stromatolites in the Carbla Point area are inclined to the south, although they occur in lines parallel to the direction of wave translation (Fig. 8C, D). They hypothesized that this inclination has developed in response to prevailing southerly winds. The inclined stromatolites are constructed by a combination of smooth and pustular mats. They show fine lamination on the north and top sides of the columns, and no lamination on the south sides. However, further observations will be neccessary to confirm the hypothesis of wind control and to determine the growth mechanism involved.

Some striking stromatolite growth forms that are thought to be wind controlled are developed in places along the west side of Hamelin Pool, especially in the Booldah Well area (Figs. 5, 9). They were termed seif stromatolites by Playford (1979), having been previously referred to as stromatolite ridges by Playford and Cockbain (1976). These stromatolites are built by pustular mat as elongate flat-topped ridges 1–3 m wide and about 0·3 m high, separated by bare sandy areas, usually about 5–10 m apart. They extend up to 800 m offshore, from lower intertidal to shallow subtidal areas. The ridges are subparallel (Figs. 5, 9), and the average elongation is nearly north-south. They show "tuning-fork junctions", normally opening to the south (upwind). It is suggested that they have formed in response to paired helical vortices (Langmuir circulation) in shallow water, induced by strong southerly winds (Fig. 6). Their resemblance in form to subaerial seif dunes, which result from paired helical vortices in air (Crowe, 1975), is striking. However, further observations and experimentation are required to confirm the suggested origin of these stromatolites.

Near Booldah Well there is a track 300 m long which was cut through the seif stromatolites about 65 years ago by camel-drawn wagons (Mac Hoult, pers. comm., 1976). They were used here until the mid-1930s to load wool and sandalwood from Nanga Station onto lighters anchored in shallow water just beyond the belt of stromatolites. However, although they have not been in use for more than 40 years there has been very little regrowth of stromatolites over the track. Indeed, where single sets of wheel marks deviate from the main track they are still clearly visible cutting through the stromatolite ridges (Figs. 9C, 10A). This illustrates the fragility and very slow growth of stromatolites in this area, and it raises the question of whether the seif stromatolites may have developed in their present form at some time in the recent past when conditions for algal growth were more favourable, and southerly winds were stronger, than today. However, the seif stromatolites near Booldah Well are younger than the dead and emergent stromatolite reefs which occur along the shoreline in this area (Figs. 5, 9B).

Indurated flat algal-mat limestone between the shoreline and the seif stromatolites near Booldah Well is also criss-crossed by individual wagon tracks (Fig. 10B); the tracks appear almost as clear today as when they were formed more than four decades ago.

SUBSTRATE

The nature of the substrate is an important factor controlling the development of stromatolites at Hamelin Pool. They generally require a hard substrate, preferably with an irregular surface, on which to grow. In various areas this may consist of calcretized Cretaceous chalk (Toolonga Calcilutite),

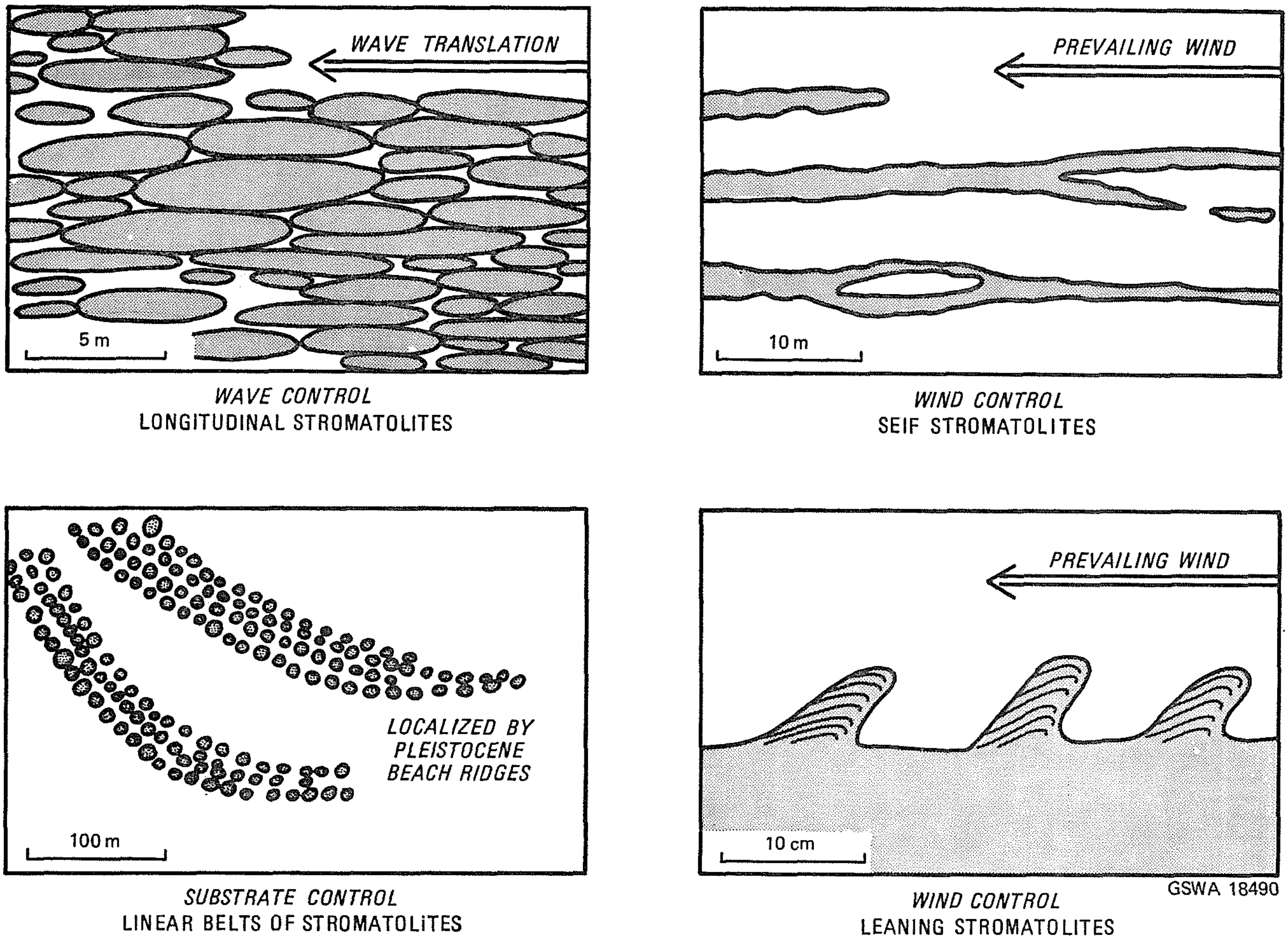

Figure 3 Diagram illustrating some environmental controls on stromatolite morphology at Hamelin Pool.

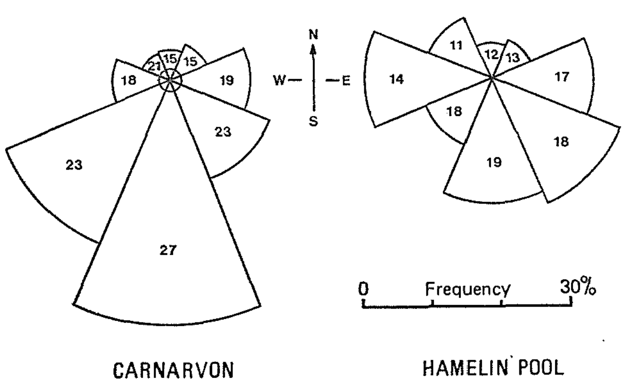

Figure 4 Annual wind-rose diagrams for Carnarvon and Hamelin Pool weather station. Figures show average wind velocities (kilometres per hour). The circle in the centre of the wind rose for Carnarvon illustrates the percentage of calms (1·5%). Calms at Hamelin Pool weather station average 0·2%.

Tertiary quartzite (Lamont Sandstone), and calcretized or otherwise indurated Late Pleistocene beach ridges or marine limestone (Bibra Limestone). Stromatolites are commonly best developed around headlands rather than in front of bays, because the headlands are localized by rocky outcrops which form a suitable substrate on which stromatolites can grow. Small closely spaced headlands, with associated stromatolites, on the east side of Hamelin Pool are localized by Tertiary quartzite (Lamont Sandstone), while the more widely spaced headlands on the west side are generally controlled by indurated Pleistocene beach ridges.

However, rocky substrates also occur just below the modern sediments and on contemporary hardgrounds in front of some bays, and in such cases stromatolites develop there also. Where there is no rocky substrate flat algal mats tend to develop rather than columnar stromatolites.

Curvilinear stromatolite reefs, often subparallel to the modern shorelines, are conspicuous features of the shallow sublittoral platform in many areas (Fig. 11). The reefs are localized by successive beach ridges of the Late Pleistocene Bibra Limestone, which have acted as foundations for stromatolite growth. Each reef may consist of many parallel lines of stromatolites (Fig. 11C, D), in some cases meeting at angles in the form of giant "cross bedding". These lines of stromatolites are controlled by indurated beds in the underlying Pleistocene beach ridges, which stood up as linear features on the sea floor when the stromatolites began growing.

There are many examples of such reefs controlled by Bibra Limestone beach ridges around the shore of Hamelin Pool, conspicuous examples being 21 km north of Booldah Well (Fig. 11A), 10 km north-northeast of Yaringa Point (Figs. 7, 11B–D), and 1 km north of Flagpole Landing.

Another form of substrate control on stromatolite morphology at Hamelin Pool is that resulting from eroded calcrete-rimmed solution pipes in the Cretaceous Toolonga Calcilutite (van de Graaff and others, in press). These solution pipes extend downwards for several metres below the calcreted Pleistocene land surface on top of the formation. They are filled with cemented rubbly soil and are rimmed by strongly indurated calcrete, in turn surrounded by soft chalky calcilutite. Consequently, where the Toolonga Calcilutite is truncated by marine erosion on tidal flats, the solution pipes are differentially eroded out as circular mounds (Fig. 10C). These have been overgrown in some areas by stromatolite-building algal mats to form conspicuous domal stromatolites, circular in plan, which are considerably larger than any other stromatolites in the area (Fig. 10D).

CONCLUSIONS

Environmental factors exert a major influence on the morphology and distribution of modern stromatolites at Hamelin Pool. Living stromatolites extend from the intertidal zone to depths of 3·5 m or more on the sublittoral platform, and their shapes and trends are largely controlled by the wave-translation direction, prevailing wind direction, and nature of the substrate. It is suggested that each of these environmental factors may have relevance in interpreting the environment of deposition of ancient stromatolites.

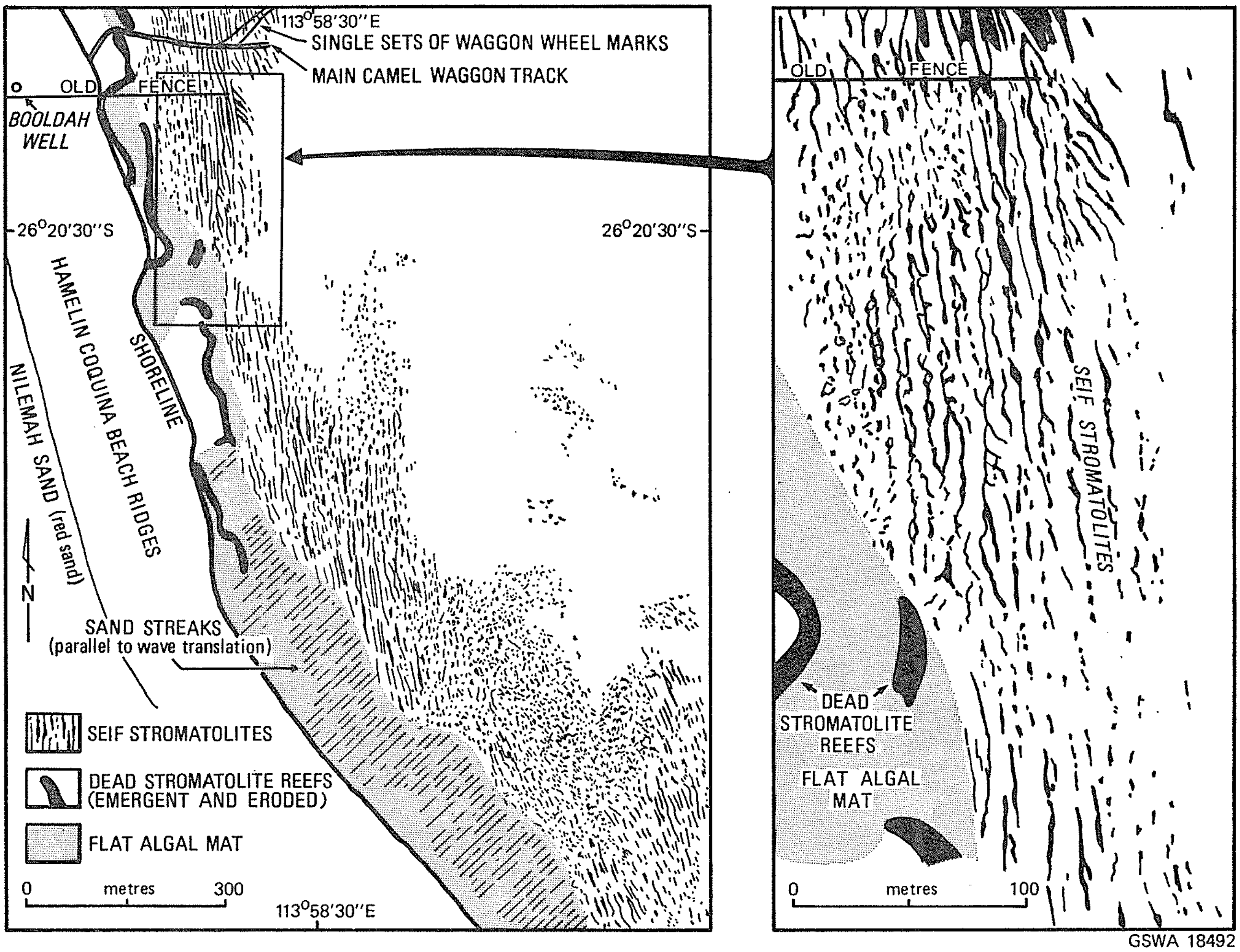

Figure 5 Maps illustrating distribution of seif stromatolites near Booldah Well, on the west side of Hamelin Pool.

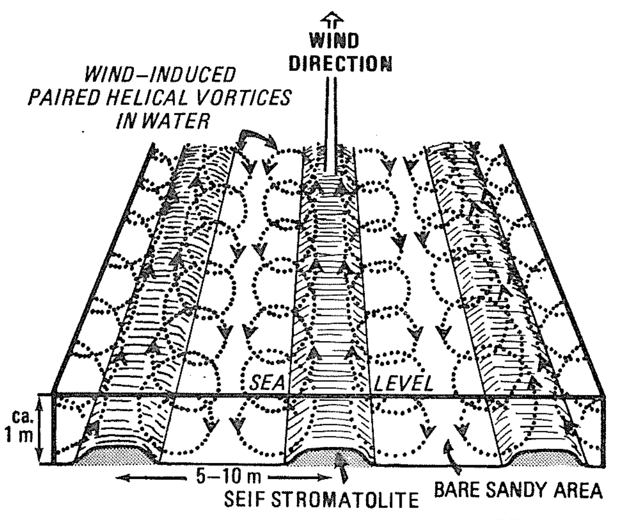

Figure 6 Diagram illustrating hypothetical control of seif stromatolites by wind-induced paired helical vortices (Langmuir circulation) in water.

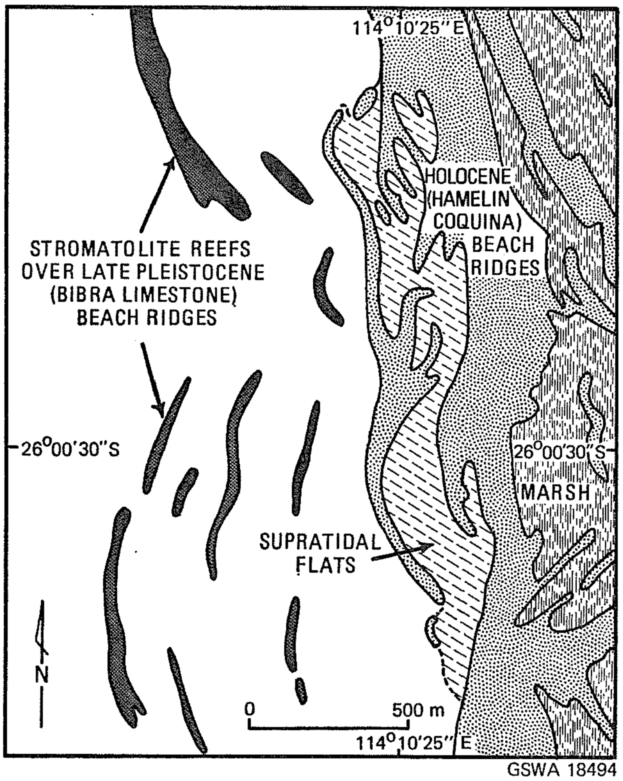

Figure 7 Map of area 10 km north-northeast of Yaringa Point showing stromatolite reefs localized by Late Pleistocene (Bibra Limestone) beach ridges.

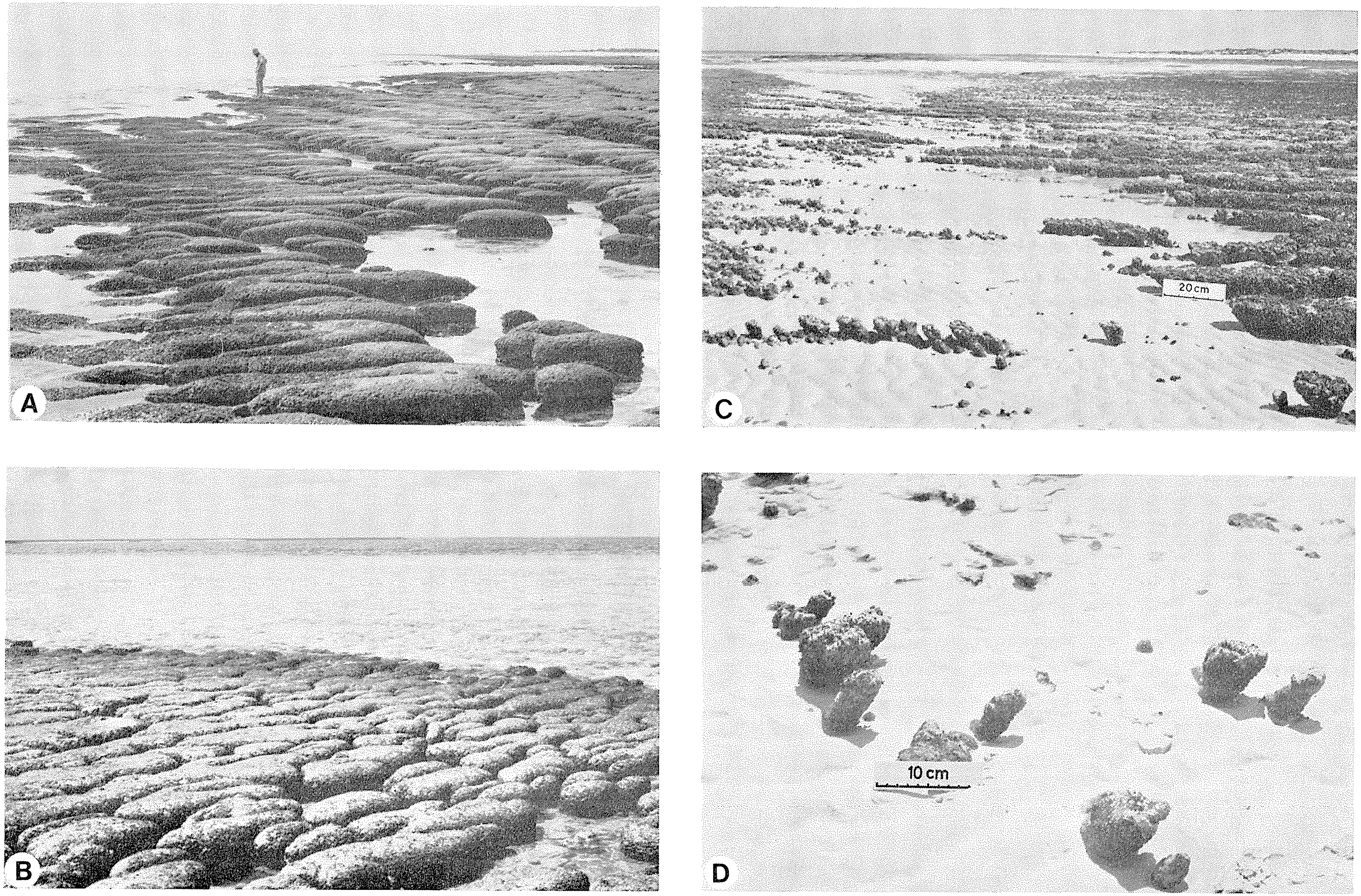

Figure 8

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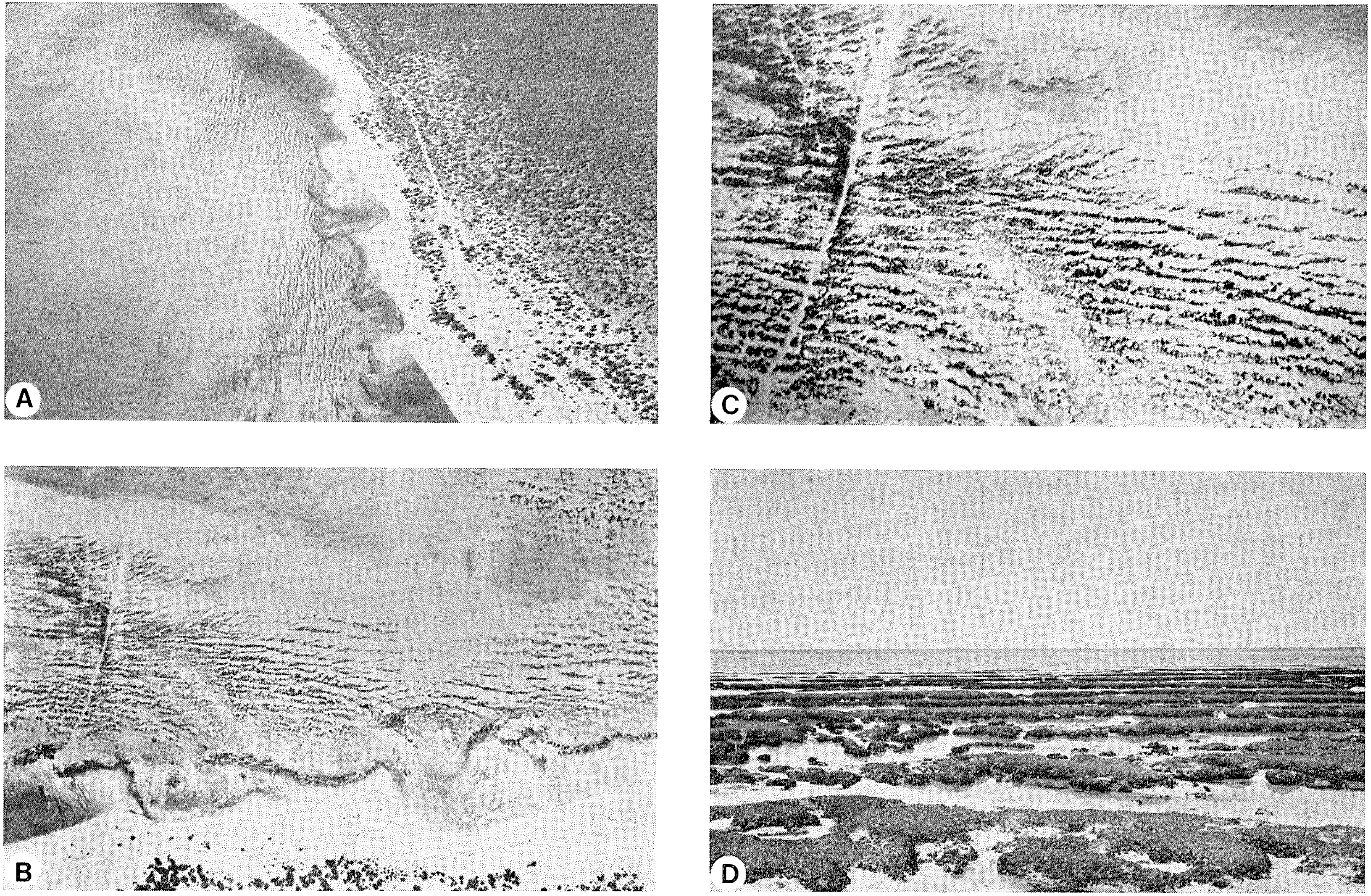

Figure 9

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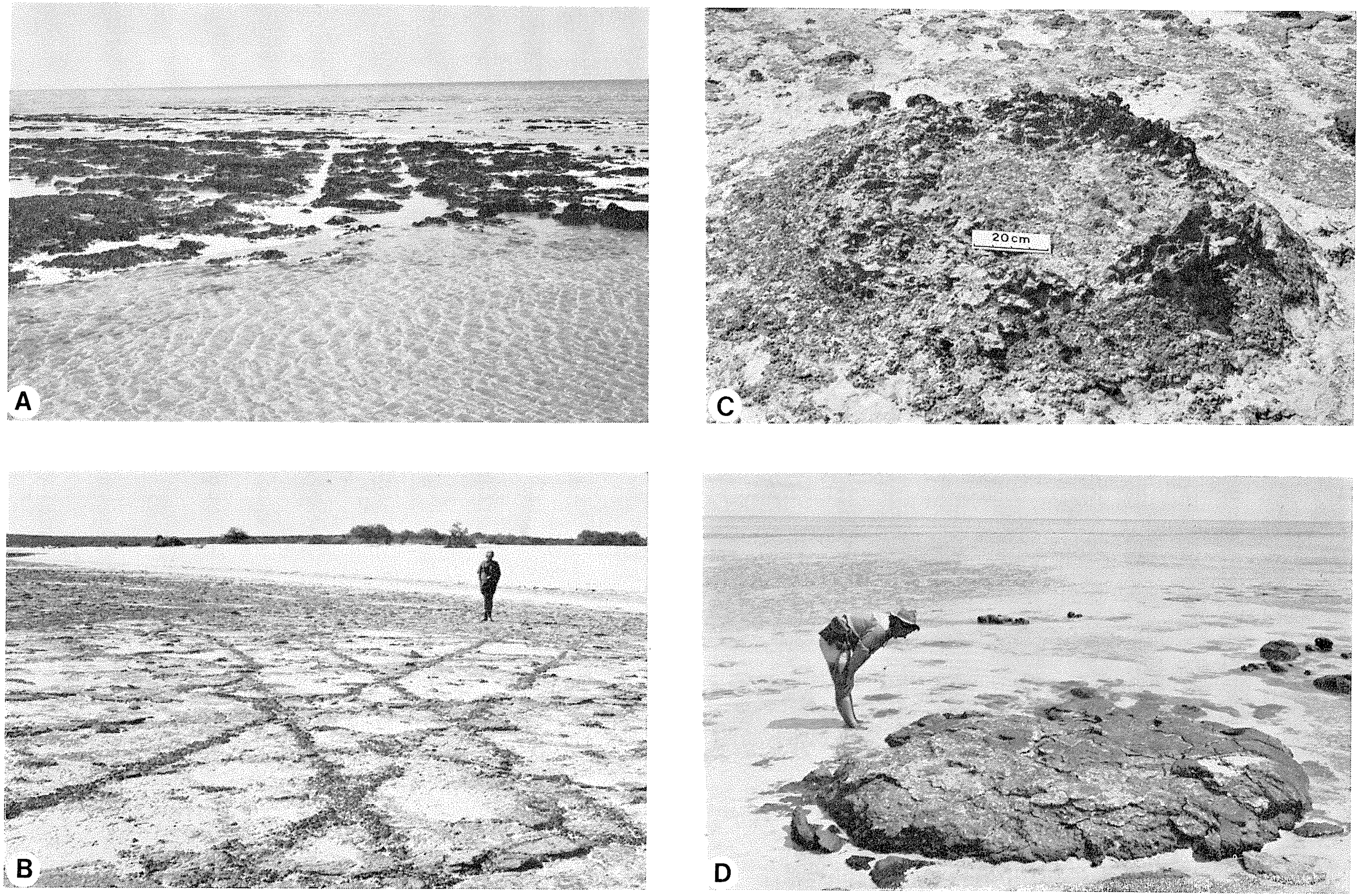

Figure 10

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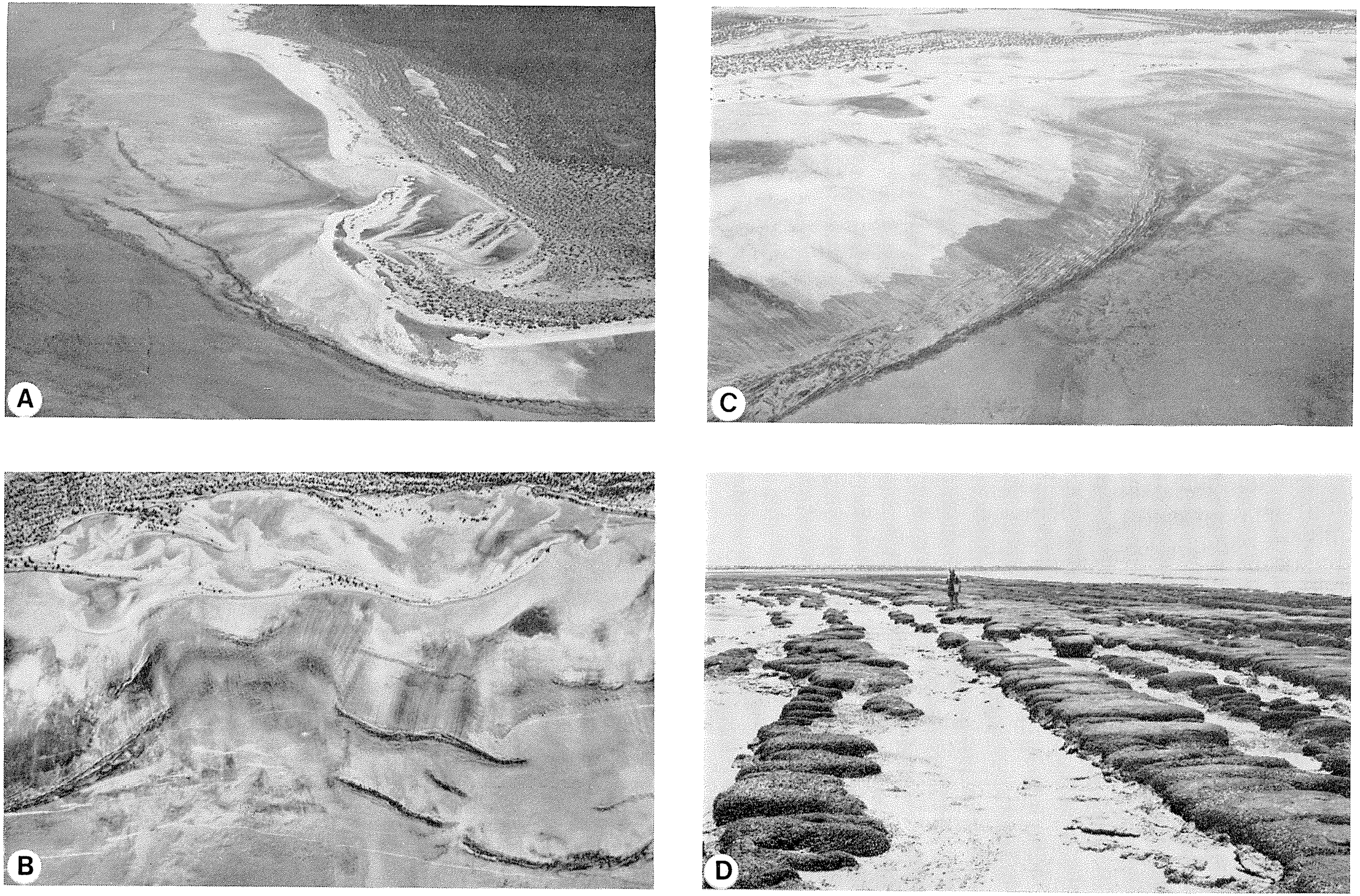

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Figure 11

Figure 8 (A) Stromatolites elongate in the direction of wave translation, 4 km south of Yaringa Point. The stromatolites occur in belts controlled by Late Pleistocene beach ridges.

(B) Stromatolites elongate in the direction of wave translation, 150 m south of Carbla Point.

(C) Inclined stromatolites 1 km southeast of Carbla Point. They occur in lines parallel to the direction of wave translation, but individual stromatolites are inclined steeply to the south, towards the prevailing winds.

(D) Closer view of inclined stromatolites 1 km southeast of Carbla Point.

Figure 9 (A) Oblique aerial view looking south near Booldah Well, showing seif stromatolites aligned nearly north-south, parallel to the prevailing southerly winds. A camel-waggon track through the stromatolites, last used more than 40 years ago, is visible in the foreground. The photo covers essentially the same area as is shown in Figure 5.

(B) Vertical air photo (north to the left) of seif stromatolites near Booldah Well, covering part of the area shown in the foreground of photo A. Note the "tuning fork" junctions opening to the south (towards the prevailing winds) and the dead stromatolite reefs adjoining the shoreline.

(C) Vertical air photo showing more detail of the seif stromatolites near Booldah Well (north to the left). Note single sets of waggon wheel marks diverting to the left of the main track (see also Figure 10 (A)).

(D) Seif stromatolites exposed at very low tide near Booldah Well. This photo was taken at about the centre of the area shown in photo B.

Figure 10 (A) Single set of camel-waggon wheel marks cutting through seif stromatolites off the main waggon track (in the foreground) near Booldah Well. These wheel marks, made more than 40 years ago, illustrate the fragility and slow growth rates of these stromatolites. Photo taken at extremely low tide.

(B) Camel-waggon wheel marks on indurated flat algal-mat limestones near Booldah Well. The wheel marks are filled with living pustular mat.

(C) Calcrete-rimmed solution pipe, filled with indurated rubbly soil, cutting through soft chalk of the Toolonga Calcilutite, 1·5 km northeast of Flagpole Landing. The resistant pipe forms a low mound on the intertidal flat, and similar pipes have formed foundations for large domal stromatolites (see photo D).

(D) Domal stromatolite, near Flagpole Landing, which has grown over an indurated solution pipe of the type shown in photo C.

Figure 11 (A) Oblique aerial view looking southwest, 21 km north of Booldah Well, showing stromatolite reefs (dark bands in the left and lower parts of the photo) controlled by underlying Late Pleistocene beach ridges. Successive modern beach ridges are seen on the right, behind the present shoreline.

(B) Vertical air photo (north on the left) of the area 10 km north-northeast of Yaringa Point, showing stromatolite reefs (dark bands in the central and lower parts of the photo) controlled by Late Pleistocene beach ridges, and backed by modern beach ridges.

(C) Oblique aerial view looking southeast over the area 10 km north-northeast of Yaringa Point showing a stromatolite reef (in the foreground) which has grown over Late Pleistocene beach-ridge deposits. Lines of stromatolites follow resistant bedding in the beach ridges (see also Photo D). This reef is the same as that shown in the lower left of photo B.

(D) Lines of stromatolites which have grown on resistant beds in underlying Late Pleistocene beach ridges. This is part of the stromatolite reef depicted in photo C. The elongation of individual stromatolites is parallel to the direction of wave translation.

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CLASTIC DYKES NEAR THE SOUTH COAST OF WESTERN AUSTRALIA

by R. Thom

ABSTRACT

Several clastic dyke occurrences near the south coast of Western Australia are described or reviewed, and comments are given on their possible age, mechanism of formation, and significance.

All dykes are composed of feldspathic wacke, are similar in appearance, and are considered to be of the one age. Lithologically they contrast with the nearby Mount Barren and Stirling Range Beds, from which they are probably partly derived. Field relationships suggest that the clastic dykes post-date the 1 200–1 300 m.y. tectonothermal event in the Albany-Fraser Province, and the emplacement of adamellite 1 100 m.y. ago. The dykes are considered to be due to the downward injection of water-saturated sediment, possibly during ancient seismic activity.

INTRODUCTION

Clastic dykes within Precambrian crystalline rocks have been reported or described at several localities (Fig. 1) in the southwest of Western Australia: at Ravensthorpe (Woodward, 1909), Dillon Bay (Clarke and others, 1954), Watheroo (Logan, 1958), Billeranga Hills (Arriens and Lalor, 1959), and Albany and Wagin (Kay, 1974). During recent geological mapping several clastic dykes were discovered near Warriup Hill and Cape Riche, and similar sedimentary material was found as boulders of uncertain significance near Denmark (J. S. Moncrieff, pers. comm.) and near Katanning (P. C. Muhling, pers. comm.). This article describes the occurrences at Warriup Hill, Cape Riche and Wagin; reviews the occurrences at Ravensthorpe, Dillon Bay and Albany; and comments on the possible age, mechanism of formation, and significance of the dykes.

DYKE OCCURRENCES

RAVENSTHORPE

The earliest known reference to clastic dykes in Western Australia is the following description by Woodward (1909, p. 15) of ferruginous sandstone occurring within the Ravensthorpe Quartz Diorite:

> "Near the Explosives Reserve one of these small outliers occupies so peculiar a position that at one time considerable doubt existed as to its origin since in its general character it presents a striking resemblance to a dyke; however upon a careful microscopic examination of the rock it proves to be a ferruginous sandstone, and therefore must have resulted from the infilling of an open fissure with sand from the surface."

This locality has not been re-examined, but the original thin section shows that the sandstone, which has a ferruginous cement, consists of small (0·02–0·4 mm) subrounded quartz

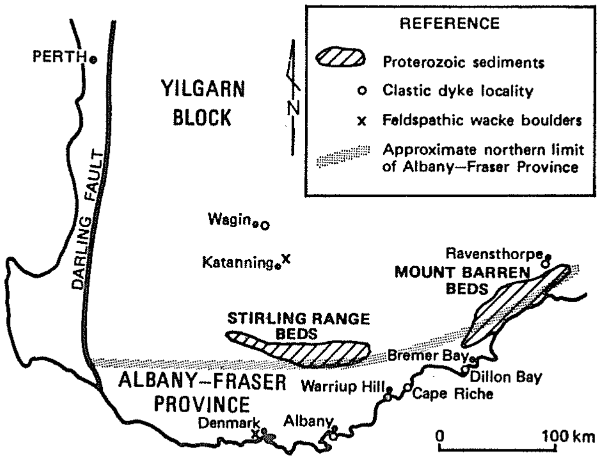

Figure 1 Location of clastic dykes.

grains, larger (0·3–0·8 mm) rounded quartz grains, including some with worn overgrowths, and a small proportion of feldspar. Most of the lithic clasts are of quartzite. This rock closely resembles the other feldspathic wacke dykes of the south coast (Table 1).

DILLON BAY

Clarke and others (1954) noted a sandstone dyke 15 inches (about 0·4 m) wide, on the west side of Dillon Bay, near Bremer Bay (the width was originally published incorrectly as 15 feet (about 4·5 m) wide). This dyke, which is subvertical and trends 350°, clearly cross-cuts the west-southwest gneissosity of the crystalline basement. The dyke lies within the wave-splash zone, and a carbonate crust obscures features such as the presence, type and distribution of larger clasts within the dyke. Samples collected from the dyke indicate that it is a feldspathic wacke with lithic clasts, comparable to the other dykes along the south coast.

ALBANY

Four well-lithified feldspathic wacke dykes at Albany have been described by Kay (1974), who observed that they simulate igneous intrusives. The subvertical dykes, which trend at

TABLE 1. COMPARISON OF FELDSPATHIC WACKES

	G.S.W.A. thin Section No.	Modal %				Type of lithic clast	Approximate grain size and roundness†				Sorting
		Qtz	Felds.	Matrix*	Lithic clasts		Quartz		Lithic clasts		
							mm		mm		
ALBANY	41589 41590	51 58	11 8	25 23	13 11	Mainly quartzite	0·1–1·5	(R)	> 0·5	(A)–(R)	Poor
CAPE RICHE	41585A 41585B 41586 41587 41588	40 36 34 49 40	13 19 22 14 13	24 23 19 15 15	23 22 25 22 32	Quartzite; mylonite; chert‡; minor phyllite, granitoid and schist	0·1–1·5	(A)	> 0·5	(A)	Poor
WARRIUP HILL	55274 41576	45 31	17 10	18 14	19 45	Quartzite; chert; minor schist and phyllite	0·1–1·5	(A)	> 0·5	(A)	Poor
DILLON BAY	41582 41583	55 59	12 14	9 9	24 18	Quartzite; mylonite; chert	0·1–1·5	(A)–(R)	> 0·5	(R)	Poor
DENMARK	48144A 48144B	46 48	14 12	16 20	24 20	Quartzite; minor schist	0·1–1·5	(A)	> 0·5	(A)	Poor
RAVENSTHORPE	909	62	5	25	8	Mainly quartzite	0·02–0·4 0·3–0·8 (bimodal)	(A)–(R) R	> 0·5	R	Poor
PUNTAPIN ROCK	41579 41580 41581	62 61 58	2 6 4	28 25 28	8 8 10	Quartzite; chert; quartz arenite; minor phyllite and granitoid	0·1–0·2 0·5–1·5 (bimodal)	(A)–(R) R	> 0·5	(R)–R	Poor

* Now mainly fine-grained phyllosilicates
† (A): Subangular, (R): Subrounded, R: Rounded
‡ Including jasper

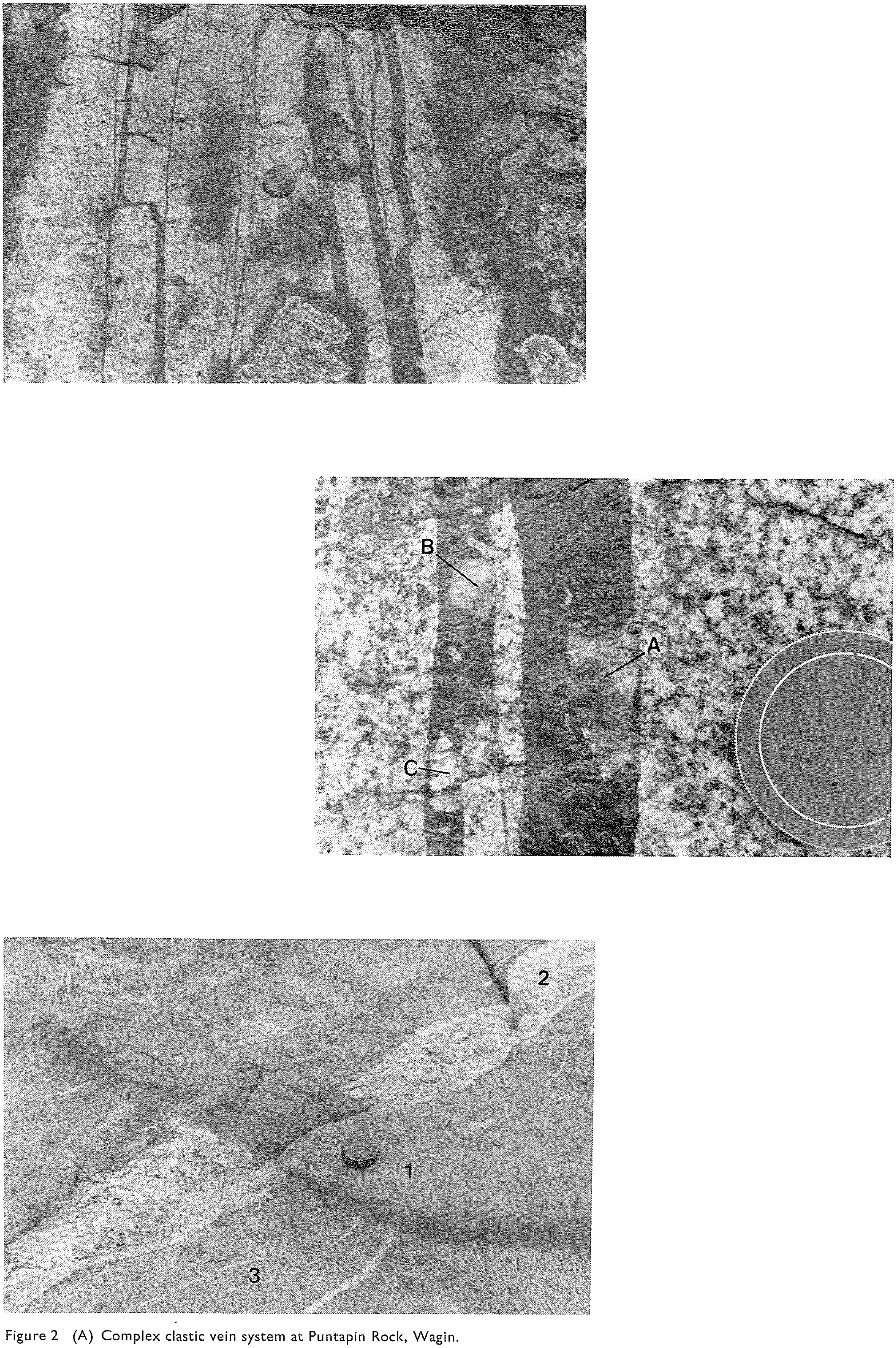

Figure 2 (A) Complex clastic vein system at Puntapin Rock, Wagin.
(B) Clasts of granitoid (A), quartzite (B) and feldspar (C) within narrow vein of feldspathic wacke, Puntapin Rock, Wagin.
(C) Feldspathic wacke dyke (1) cuts across pegmatite vein (2) and foliated hornblende-biotite granodiorite country rock (3). Headland southwest of Warriup Hill.

about 300°, distinctly cross-cut the west-southwest-trending foliation of the gneiss, and include fragments of country rock. Three of the dykes are less than 0·1 m wide and the largest is about 1 m wide.

The composition of the dyke rock is shown in Table 1. The matrix, which forms about 25% of the rock, now consists mainly of chlorite, biotite, muscovite and limonite, and Kay suggested that the predominance of chlorite in the matrix of the narrower dykes gives them their greyish-green colour, whereas the dark, purplish-brown colour of the widest dyke is due to the predominance of limonite and muscovite in the matrix. Kay considered the alteration of the original clay matrix to phyllosilicates and limonite to be authigenic, but he did not exclude the possibility of slight metamorphism. He also considered, from the presence of secondary mica and the degree of lithification, that the dykes may be of considerable age, but he knew of no comparable sediments in the Albany area.

WAGIN—PUNTAPIN ROCK

Puntapin Rock is a partially recrystallized Archaean adamellite, largely homogeneous, but with some deformed leucocratic veining. The strong northwest-trending foliation is cut by an easterly trending clastic intrusion, which has the form of a narrow, braided vein system in three offset lengths exposed over a total length of about 600 m. The width of individual sedimentary veins ranges from a few millimetres to a few tens of millimetres, and the zone of anastomosing veins is commonly about 0·2 or 0·3 m across (Fig. 2A). The sedimentary intrusion post-dates narrow, quartz-filled cross-fractures. Each of the three offset vein systems peters out into straight, parallel veins only a few millimetres wide.

For most of its length, the clastic infilling is fine grained, with random distribution of mesoscopic lithic clasts. In places, clasts up to 10 mm across occur in groups extending across the width of the dyke and laterally for 100 mm or more. Elsewhere, single clasts may occupy the entire width of narrow veins (Fig. 2B), but over much of the dyke mesoscopic clasts are absent. Most clasts are of jasper, chert or quartzite, and there are rare angular fragments of country-rock gneiss.

Lithologically the rock is a fine-grained poorly sorted wacke (Table 1), with quartz grains in two sizes; nearly 50% of the rock is fine-grained quartz (0·1–0·2 mm), and 5–15% of the rock is quartz in the 0·5–1·5 mm range. Lithic clasts are common in the 0·5–1·5 mm range, but may be even larger, up to about 20 mm.

WARRIUP HILL

A zone of clastic dykes occurs within Proterozoic gneiss and granite forming the coastal headland southwest of Warriup Hill (Fig. 1). The dykes trend at about 250°, with a northerly dip of about 45°. Branching and offsetting of these sedimentary intrusions makes their exact number difficult to determine, but there are at least six different dyke portions, each with a width greater than 150 mm (Fig. 2C). The widest dyke, which reaches 600 mm across, is also the longest, being exposed for over 200 m before passing below sea level on each side of the headland. Other dykes peter out at one or both ends within the headland, such that as one dyke dies out another begins some metres to the north or south. This offset arrangement, which may be either sinistral or dextral, is not fault displacement, as the dykes end in narrow, parallel dykelets or in zig-zag stringers (Fig. 3A) rather than abrupt truncations. Although the fissures that now contain the dykes may have been generated immediately prior to infilling (see section on mechanism of formation), some fractures in the country rock were pre-existing; one dyke abruptly changes course along an older cross-fracture for 1·5 m before resuming its overall trend (Fig. 3B).

The dykes are undeformed. Except at their extremities, dykes tend to maintain uniform widths, and although some dykes are sinuous, they are not considered to be folded.

Subrounded pebbles of jasper, quartzite, quartz, feldspar, chert and jaspilite, commonly up to 10 mm across, are prominent throughout the length of the dykes. Clasts tend to concentrate towards the middle of some dykes so that margins appear relatively fine grained. The dykes contain a few angular clasts which were apparently derived from the adjacent gneiss. Lithologically the dyke rock is a well-lithified, poorly sorted feldspathic wacke (Table 1). Muscovite, sericite, epidote, sphene, tourmaline and fluorite occur in small amounts, and iron oxide occurs as detrital grains and as a local cement. Dykelets and stringers owe their pale-greenish colour to the abundance of epidote, whereas the dark purplish-brown dykes have less epidote and more iron oxide. The presence of epidote and sericite indicates that the dykes, if not merely altered, are only mildly metamorphosed. The muscovite flakes are detrital, and have been deformed during compaction of the rock.

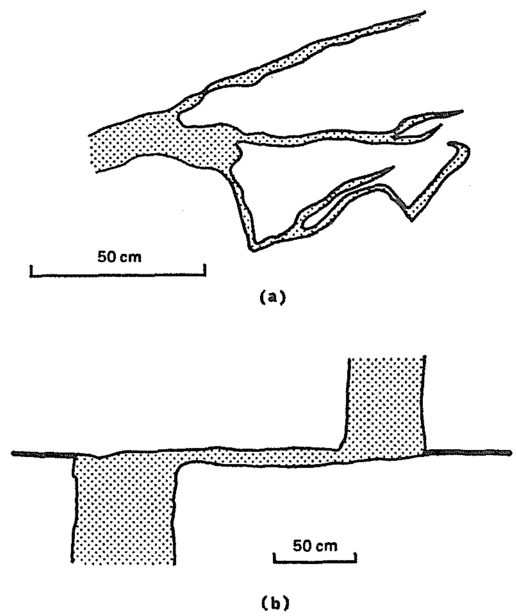

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Figure 3 (a) Sketch of clastic dyke passing into narrow zig-zag stringers at its termination. Warriup Hill locality.
(b) Clastic dyke changes direction along a pre-existing fracture (heavy black line) before resuming its overall trend. Warriup Hill locality.

CAPE RICHE

There are two adjacent clastic dyke occurrences near Cape Riche, both within deformed Proterozoic gneiss.

At the easternmost locality, feldspathic wacke occurs in two or three subparallel dykes trending 225°, dipping 75°SE, and exposed over about 20 m. The widest dykes, up to 150 mm across, are pinkish brown in colour and have straight, sharp margins. Narrower dykes, up to a few tens of millimetres across, are dark-greenish in colour and tend to anastomose.

At the other locality, a single dyke 650 mm wide, trending 240° and dipping 75°SE, is exposed over a distance of 55 m. In the middle of the dyke is a faint but distinct banding, probably due to flow, in which there is relative depletion of matrix in planes parallel to the dyke margin. There is also a dimensional preferred orientation of elongate quartz grains parallel to this direction. Near the contact the host gneiss is pinkish in colour and is no doubt the source of the fragments of pink gneiss within the clastic dyke. Few of these elongate clasts are oriented parallel to the dyke margins.

OTHER LOCALITIES OF FELDSPATHIC WACKE

Several boulders and a possible *in situ* exposure of feldspathic wacke were discovered in a gravel pit west of Denmark (J. S. Moncrieff, pers. comm.). It is not known whether the boulders represent clastic dykes or stratified sediment, but in the absence of evidence for considerable transportation they are assumed to be of local origin. In appearance and composition (Table 1) these boulders resemble the feldspathic wacke of the south coastal dykes.

A single boulder of feldspathic wacke was found in a boulder deposit, near Katanning (P. C. Muhling, pers. comm.). In view of the uncertainty of its origin, this boulder is not considered further here.

AGE OF THE CLASTIC DYKES

An approximate maximum age can be deduced for the dykes on the basis of local and regional geology. This is particularly so for the Warriup Hill locality, where there are three main types of country rock:

(a) *Gneiss, including augen gneiss and banded granodiorite gneiss.* These have been recrystallized, perhaps to upper amphibolite or granulite facies, and have undergone multiple deformation. Isoclines of variable orientation have been overprinted by smaller penetrative cross-folds plunging consistently to the southwest. These two groups of folds are considered to be Proterozoic on two grounds:

(i) They have been tentatively correlated with particular fold generations recognized in the Mount Barren Beds, which is considered to be a Middle Proterozoic succession.

(ii) The folds and the present metamorphic grade of the gneisses are believed to be products of the tectonothermal event throughout the Albany-Fraser Province which reset the ages of the gneisses at 1 200–1 300 m.y. (Wilson and others, 1960; Compston and Arriens, 1968; Arriens and Lambert, 1969; Bunting and others, 1976).

(b) *Hornblende-biotite granodiorite*. Although this rock has been partially recrystallized and has a prominent foliation, it is evidently a younger rock than the gneisses. It lacks gneissosity and polyphase folding, and cuts across the gneissosity and folds of the banded gneiss. On both these grounds it can be concluded that the granodiorite post-dates the main tectonothermal event, although the foliation and recrystallization may represent the waning stages of Proterozoic metamorphism put at about 1 100 to 1 150 m.y. (Stephenson and others, 1977). The clastic dykes are located mainly within this hornblende-biotite granodiorite.

(c) *Porphyritic adamellite*. Several varieties may be distinguished on the basis of biotite and phenocryst abundance, and on field relationships, but all varieties are characterized by mild deformation and metamorphism. The porphyritic adamellites cross-cut folds and other structures related to the main tectonothermal event. These porphyritic adamellites resemble the Albany Adamellite, which has been dated at 1 100 $\pm$ 50 m.y. (Turek and Stephenson, 1966), and they have been grouped with the same episode of magma emplacement (Stephenson and others, 1977). The porphyritic adamellites at Warriup Hill may be slightly older than those at Albany, as they show some deformation.

The clastic dykes cut the folds in the gneisses, intrude the hornblende-biotite granodiorite and cut veins emanating from the porphyritic adamellites. Moreover, as the dykes themselves are unaffected by the deformation that affected the granites, they are likely to be younger than 1 100–1 200 m.y.

Similarly, at Dillon Bay, Albany and Cape Riche clastic dykes cut deformed gneisses, and the dykes themselves, which lie well within the Albany-Fraser Province, post-date all the penetrative deformation and metamorphism. The clastic dykes at Puntapin Rock are unmetamorphosed, but this does not prove a maximum age of 1 200–1 300 m.y., as they are too far north to be affected by Proterozoic metamorphism centred on the Albany-Fraser Province. The dykes at Puntapin Rock cut nothing younger than Archaean.

RELATIONSHIP TO ADJACENT PROTEROZOIC SUCCESSIONS

Although most of the clastic dykes occur in the vicinity of the Mount Barren and Stirling Range Beds (Fig. 1), correlation of the material filling the dykes with these units is discounted because:

(a) The dykes are feldspathic, whereas the Mount Barren and Stirling Range Beds are without feldspar.

(b) The Mount Barren Beds exhibit a strong metamorphic gradient towards the south coast, whereas the dykes, which are only slightly metamorphosed, show no detectable variation in metamorphic grade over a wider geographical area.

(c) The Mount Barren and Stirling Range Beds are considered to be at least 1 300–1 400 m.y. old (Turek and Stephenson, 1966; Thom, 1977), whereas the deduced maximum age of the dykes is about 1 100 m.y.

(d) Lithic clasts within the dykes may be tentatively identified with particular lithologies in the Mount Barren and Stirling Range Beds. For example, most lithic clasts are of quartzite with highly sutured grains and mylonitic fabrics typical of quartzites in the Mount Barren Beds. The ubiquitous jasper may derive from jasper concretions within dolomite in the Mount Barren Beds. One dyke contains rounded clasts of pinkish-brown shale similar to shale near the base of the Stirling Range Beds. In some dykes quartz tends towards a bimodal size distribution; the larger quartz grains seem to have inherited some of their roundness and sphericity, and the presence of occasional worn overgrowths supports the view that these larger grains derive from pre-existing arenite. It seems likely that the Mount Barren and Stirling Range Beds were sources of detritus for the dyke sediment.

MECHANISM OF FORMATION

The clastic dykes described in this article occur within fractures in crystalline basement, and it is clear that the fractures were infilled from an overlying source of detritus. Two kinds of clastic dyke must be considered here:

(a) Clastic dykes which result from the gradual infill, grain by grain, under the influence of gravity, of pre-existing open fractures.

(b) Clastic dykes which result from the downward injection of overlying sediment and which, therefore, have the same composition as their parent sediment. The commonest mechanism invoked for this type involves momentary liquefaction of overlying water-saturated sand by earthquake shock, followed by downward forceful injection into fissures opened by the shock. The driving force for injection is the pressure of the overlying strata (Potter and Pettijohn, 1963). Dykes of this type are here called injection dykes.

The clastic dykes at Watheroo (Logan, 1958) and at Billeranga Hills (Arriens and Lalor, 1959) were proposed as injection dykes, because in both cases the dykes lack the stratification expected from the gradual infill of open joints, and because the lithology of the dykes closely resembles particular units in the local Proterozoic successions. In both cases the mechanism proposed is that of seismically induced basement fissuring followed by downward injection of water-saturated sediment, and Logan suggested that in the case of the Watheroo dykes the seismic activity may be related to the Darling Fault.

The clastic dykes near the south coast are also considered to be injection dykes. They lack horizontal stratification and show evidence of intrusion or flow, and they occupy dynamically produced brittle fractures. The zig-zag terminations of the dykes at Warriup Hill seem consistent with seismically induced brittle fractures, or possibly with propagation of fractures during forceful injection of overlying water-saturated sediment in a lateral and downward direction. The infilled anastomosing fracture at Puntapin Rock was clearly not a joint, but a complex fracture zone. Other evidence of flowage includes:

(a) the tendency for pebbles to be concentrated near the middle of some dykes, which is probably the result of wall-effect during flow;

(b) the presence of alternating matrix-enriched and matrix-depleted layering parallel to dyke margins, which is probably flow-banding; and

(c) the presence in some dykes of a dimensional preferred orientation of elongate quartz grains parallel to dyke margins.

It seems unlikely that the seismicity invoked to produce the dykes along the south coast would have been related to the Darling Fault.

CONCLUSIONS

The clastic dykes near the south coast of Western Australia are similar in appearance and composition and are thought to be of the one age. Their feldspar content and immaturity distinguish them from the Mount Barren and Stirling Range Beds, and there is some petrographic evidence that they are partly derived from these successions. On limited geochronological, structural and metamorphic grounds they have a maximum age of about 1 100 m.y.

The formation of injected sedimentary dykes of this type seems to require the presence of overlying water-saturated sediments during seismically induced basement fissuring. If the dykes near the south coast are of the one age, this seems to imply the former existence of overlying, stratified feldspathic wacke at least as extensive as the present distribution of the clastic dykes. This hypothetical sediment would be younger than the Mount Barren and Stirling Range Beds, with a maximum age of about 1 100 m.y., and with little deformation or metamorphism. The seismic activity which led to the formation of the dykes seems unlikely to have been related to the Darling Fault, as was suggested for the Watheroo dykes (Logan, 1958), but could have been related to some fault bounding the Albany-Fraser Province. Alternatively, it is interesting to note that the known clastic dyke localities in the southwest of Western Australia are within or adjoining the South West Seismic Zone (Doyle, 1971; Gordon, 1972), which may follow a crustal weakness already present in the Proterozoic.

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EVIDENCE FOR THE AGE AND CRYPTOEXPLOSIVE ORIGIN OF THE TEAGUE RING STRUCTURE, WESTERN AUSTRALIA

by J. A. Bunting, J. R. de Laeter* and W. G. Libby

ABSTRACT

The Teague Ring Structure, at the northeast margin of the Yilgarn Block, consists of a circular core of pyroxene-quartz syenite and granite, some 10 km in diameter, surrounded by a ring syncline, 18 to 20 km across, in Early Proterozoic sedimentary rocks of the Nabberu Basin. Rb-Sr data suggest that the age of the structure is probably 1 630 m.y. with a further event of unknown origin and significance at about 1 260 m.y. Quartz syenite from outside the structure gives a model age of 2 367 m.y. The presence of shatter cones, quartz deformation lamellae and pseudotachylite veins is indicative of shock metamorphism and hence suggests a cryptoexplosive origin for the structure. There is inconclusive evidence that the cause was non-random, and therefore may not have been a meteorite impact as suggested by the shock metamorphism. A possible terrestrial cause could be a volatile-generated explosion in an alkaline magma.

INTRODUCTION

The Teague Ring Structure is a circular feature about 100 km northeast of Wiluna, Western Australia, at the junction of the Archaean Yilgarn Block and the Early Proterozoic Nabberu Basin (Fig. 1). The circular structure consists of a core, 10 km in diameter, of granitic and syenitic rocks surrounded by Early Proterozoic sedimentary rocks which form a ring syncline between 18 and 20 km across. It was first described by Butler (1974), who suggested it was due to either the intrusion of a granitoid plug, or the eroded remnant of a giant meteorite impact scar (astrobleme). He compared the structure with the Vredefort Dome of South Africa, which Dietz (1961) regarded as an impact structure. Horwitz (1975) suggested that the structure may be due to the interference of mild folds, and therefore related to the regional stress pattern. Bunting and others (1977) proposed an origin by cold re-emplacement of a plug of syenite, possibly at high strain rates, by localized compressive stresses related to the regional fold trend. In this paper, we present another hypothesis—that the structure formed as a result of an explosion of volatiles related to alkaline magmatism.

A major problem in the interpretation of the Teague Ring Structure has been the age of the granitic and syenitic rocks in the core. In an attempt to solve this, samples from the core, along with two samples of quartz syenite from outside the structure, were submitted for Rb-Sr age determination as part of the joint Geological Survey of Western Australia—Western Australian Institute of Technology geochronology programme. The purpose of this paper is to present the geochronological data, to describe the structure, to discuss previous theories, and to present evidence for a cryptoexplosive origin.

REGIONAL SETTING

The structure lies along the exposed line of unconformity between the Archaean Yilgarn Block and the Early Proterozoic Nabberu Basin (Fig. 1). The Archaean rocks of the Yilgarn Block are predominantly granitoid intruding poorly exposed remnants of greenstone belts (metamorphosed mafic and felsic volcanic rocks and associated metasediments). The regional granitoid in the vicinity of the Teague structure is medium- to coarse-grained adamellite, displaying a strong gneissic fabric where it is marginal to the greenstone belts. Deformational fabrics in both granitoid and greenstone trend north-northwest, and major strike faults in this direction can be followed for many hundreds of kilometres (Elias and Bunting, 1978). Two elliptical plutons of hornblende-quartz monzonite (containing less than 20 per cent quartz) and a small body of quartz syenite intrude the adamellite immediately southwest of the Teague structure.

The overlying Early Proterozoic sediments form the Earaheedy Group of the Nabberu Basin (Hall and others, 1977). A basal clastic unit with minor carbonate (Yelma Formation) is overlain by the Frere Formation which consists of interbedded granular iron-formation and shale. This is overlain by the Wandiwarra Formation (ferruginous sandstone, fine-grained lithic sandstone and shale) and the Princess Ranges Quartzite (interbedded quartz arenite and kaolinitic siltstone).

Outside the area affected by the ring structure the sediments dip gently northeast at between 5° and 10°. Regional deformation in the vicinity of the structure is slight, but increases northwards into the Stanley Fold Belt. The dominant fold trend is west-northwest, and axial surfaces dip steeply to the north. A second generation of scattered medium-scale folds trends northeast.

Figure 2 is an outcrop map of the structure. The non-exposed areas are covered with superficial sediments, mainly sand and pebble colluvium, salt-lake deposits, valley calcrete and alluvium, and eolian sand related to the salt lakes.

THE RING STRUCTURE

THE CORE

Outcrop is restricted to the northeast side of the core, which is about 10 km in diameter. Two main rock types are present—quartz syenite and leucogranite.

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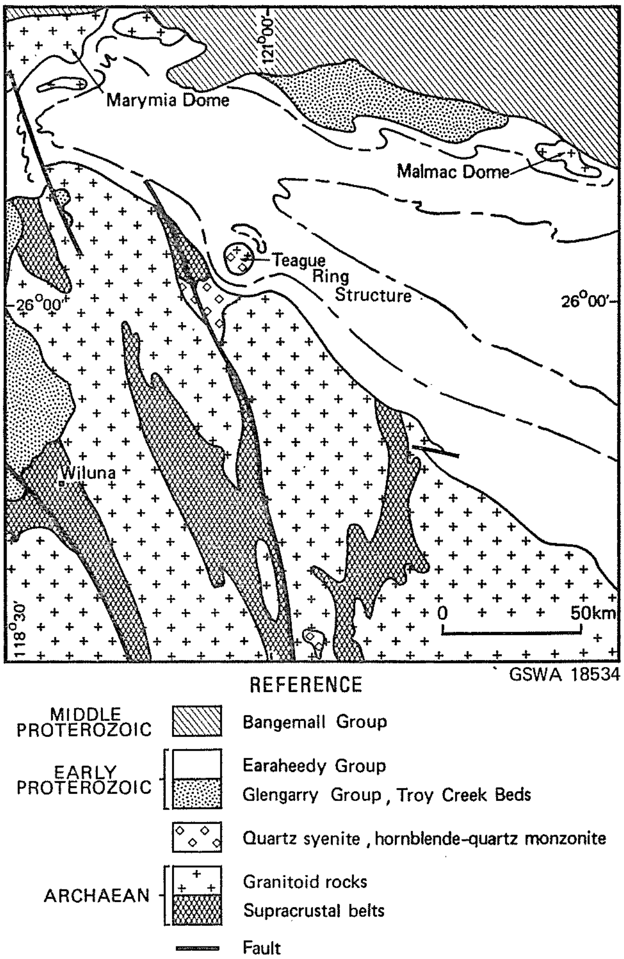

Figure 1 Regional setting of the Teague Ring Structure.

The leucogranite is medium grained and is probably unconformable beneath the Yelma Formation. It contains about 30 per cent quartz, which in some samples displays a weak gneissic foliation and slight strain extinction. Albite usually constitutes about 40 per cent of the rock, and alkali feldspar, which is invariably severely kaolinized, makes up about 30 per cent. A small amount of weathered biotite is the only mafic mineral present.

The quartz syenite is much more variable, both in grain size (from medium to very coarse) and mineral composition. Quartz ranges in abundance from about 30 per cent to 5 per cent. Perthitic microcline is usually coarser than quartz and plagioclase, and is always dominant over plagioclase, the ratio ranging from 3:2 to 3:1. The mafic mineral is a bright-green sodic pyroxene, which commonly has a greyish-blue or pale-green amphibole in the core. Accessories include sphene, apatite and rare zircon. Fluorite is common along fractures in sample 46513, and less abundant in 46515.

Field relationships between these two granitoid types and the cover sequence are not clear. The leucogranite is seen to within 1 m of the basal Yelma Formation, and a lack of intrusive phenomena, plus the continuity of the basal beds and weak gneissic foliation in the granitoid, indicate that the contact is an unconformity. The quartz syenite probably intrudes the leucogranite, but was not observed within 1 km of the cover sequence.

THE RING SYNCLINE

The ring syncline is between 18 and 20 km across and shows a marked asymmetry about a northwest-southeast plane. Sub-vertical, locally overturned dips on the northeast rim become gentler to the southwest, and folding becomes more open. Normal, steeply dipping faults form a polygonal pattern around the northeastern side of the structure (Fig. 3), but are lacking in the less-deformed southwestern side. The faults indicate an overall upward movement of the core. Small-scale faulting and fracturing are common in laminated shales of the Frere Formation.

The preservation of a much thicker stratigraphic sequence on the northeast side (4 000 m from Yelma Formation to Wongawol Formation) compared with the southwest side (about 1 000 m of Yelma Formation and Frere Formation(is a function of the regional tilt of the sequence, and is not necessarily related to any genetic asymmetry of the structure.

GEOCHRONOLOGY

GEOLOGICAL EVIDENCE

Geological constraints on the age of the structure are few. It obviously post-dates the formation of the Earaheedy Group sediments, and hence is probably younger than about 1 700–1 800 m.y. (Bunting and others, 1977). There is no geological evidence to provide a minimum age limit.

The structure is within a belt of alkalic granitoids (similar to quartz syenites within the structure) extending in a south-southeasterly direction across the Eastern Goldfields (Libby, 1978). The only geochronological data previously available for this suite (from Fitzgerald Peaks) gives an age of 2 360 m.y. (de Laeter and Lewis, 1978).

GEOCHRONOLOGICAL SAMPLING

The freshest samples possible were obtained from surface exposures, and all but two are from within the core of the structure. The samples range from moderately fresh to fresh in megascopic appearance but in thin section all are at least slightly altered, presumably by weathering (see Table 1).

TABLE 1. ROCK TYPE AND ALTERATION

Sample	Rock type	Alteration
40397	Pyroxene-quartz syenite	Slight
46301	Alkali granite....	Severe
46302	Pyroxene-quartz syenite	Moderate
46303	Pyroxene-quartz syenite	Slight
46304	Amphibole-quartz syenite	Slight
46511	Granite, possibly alkalic	Severe
46512	Albite-rich granite	Moderate to severe
46513	Pyroxene-quartz syenite	Moderate
46514	Pyroxene-quartz syenite	Moderate
46515	Pyroxene-quartz syenite	Moderate
46518	Pyroxene syenite	Moderate
	Not included in geochronological analysis:	
46516	Albite-rich granite	Severe
46517	Albite-rich granite	Severe
46519	Albite-rich granite	Severe

Sampling localities are shown on Figure 2. All localities are within the Teague Ring Structure except 46304 which is about 5 km south of the structure, and 40397 which is about 185 km south of the structure near Yandal on the Sir Samuel 1:250 000 sheet (Bunting and Williams, 1979).

EXPERIMENTAL PROCEDURE

The experimental procedures for Rb/Sr analyses used in this laboratory are essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project is 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).

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios are given in Table 2. Errors accompanying the data are at the 95 per cent confidence level. The Rb and Sr concentrations in each sample are also listed. However, these concentrations are only accurate to ±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.

TABLE 2. ANALYTICAL DATA—TEAGUE RING STRUCTURE GEOCHRONOLOGY

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
46301	290	150	1·945±0·02	5·67±0·06	0·807 91±0·000 29
46302	320	200	1·58 ±0·02	4·6 ±0·05	0·792 44±0·000 30
46303	200	315	0·65 ±0·01	1·87±0·02	0·756 85±0·000 12
46511	170	300	0·572±0·01	1·66±0·02	0·736 34±0·000 12
46512	180	300	0·60 ±0·01	1·74±0·02	0·753 81±0·000 15
46513	275	190	1·45 ±0·02	4·23±0·05	0·811 37±0·000 23
46514	220	430	0·52 ±0·01	1·51±0·02	0·746 91±0·000 28
46515	225	190	1·19 ±0·02	3·46±0·04	0·794 28±0·000 22
46518	170	180	0·925±0·01	2·68±0·03	0·754 04±0·000 25
46304	55	500	0·110±0·002	0·32±0·005	0·712 95±0·000 18
40397	195	380	0·510±0·005	1·48±0·02	0·754 96±0·000 21

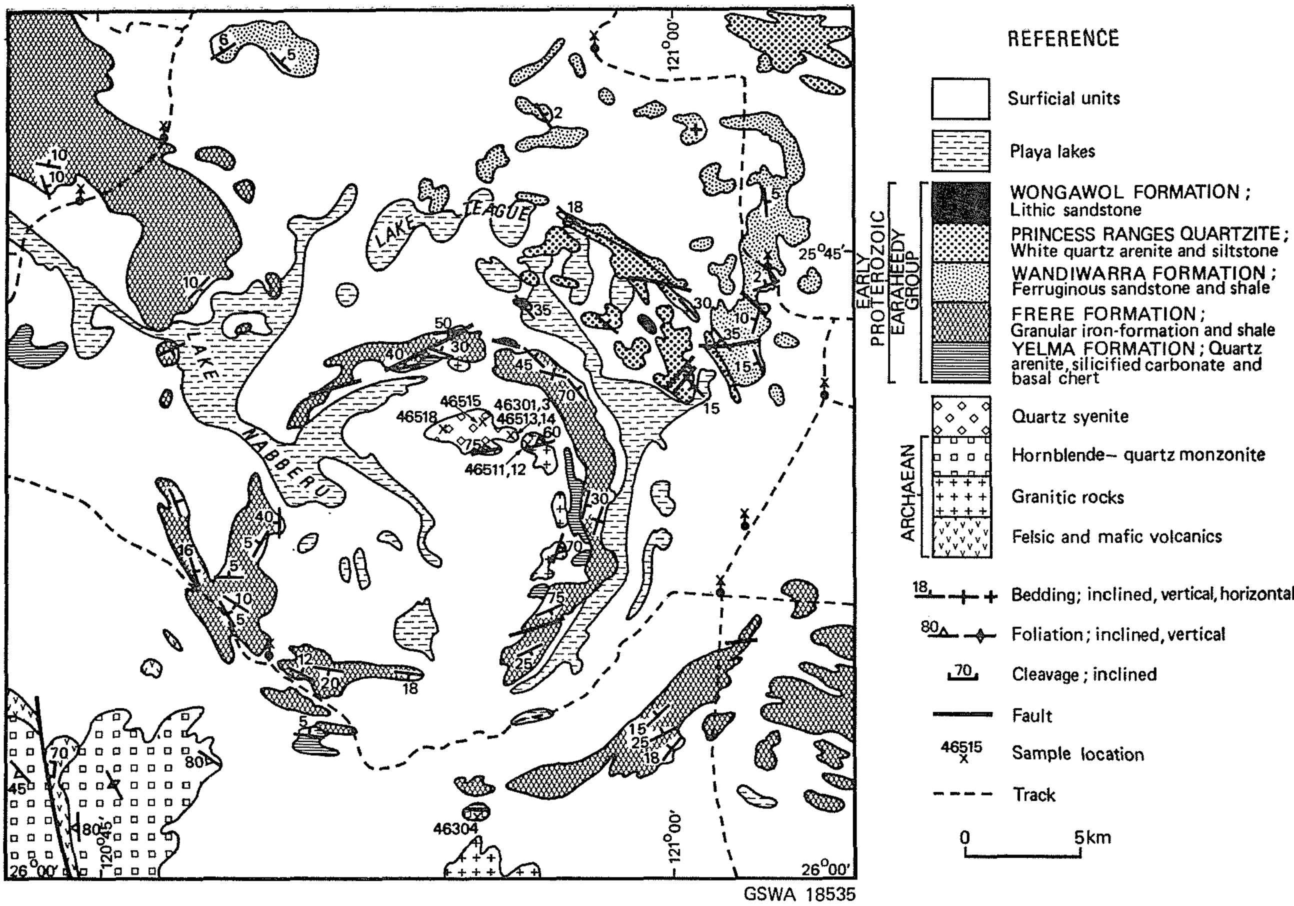

Figure 2 Geology and sample locations.

RESULTS

The geochronological results are presented in Figure 4 and Table 2.

The data fail to define a simple isochron, but rather fall into three groups:

(a) the two samples outside the structure;

(b) a group of five samples which plot near a 1 630 m.y. reference isochron; and

(c) a group of four samples which plot near a 1 260 m.y. reference isochron.

DISCUSSION

The samples from outside the structure were included for comparison of the alkaline granitoids of the Teague Ring Structure with the alkaline suite of the Eastern Goldfields (Libby, 1978). The only reliable age for this suite is 2 360 m.y. (R_i = 0·704 36 for the Fitzgerald Peaks Syenite (de Laeter and Lewis, 1978) in the southern Eastern Goldfields. Using the initial ratio from Fitzgerald Peaks and sample 40397 the age is 2 367 m.y., almost identical to the results from the Fitzgerald Peaks. This supports the supposition that the alkaline suite in the northern Eastern Goldfields is late Archaean.

Data from samples within the ring structure plot roughly along two reference isochrons, one at 1 630 m.y., the other at 1 260 m.y., both clearly Proterozoic.

These results can be interpreted as random points shifted various amounts to the right of an Archaean isochron by preferential loss of radiogenic strontium relative to rubidium during weathering (Bottino and Fullagar, 1968; Dasch, 1969). Alternatively, the disposition of points along the two reference isochrons may have geochronological significance. A simple re-equilibration of 1 630 m.y. rocks at 1 260 m.y. seems unacceptable as the two isochrons fail to cross. The suites are unlikely to have had different initial $^{87}Sr/^{86}Sr$ ratios as they are of similar lithology and are geographically intermixed. They differ systematically only in degree of alteration.

A more likely model accepts the 1 630 m.y. age as approximately the age of a real event, either the original emplacement of the alkali granitoid or its remobilization or metamorphism, but considers the 1 260 m.y. alignment to be fortuitous, arising from the increase in Rb:Sr ratio upon weathering due to preferential loss of Sr (Bottino and Fullagar, 1968; Dasch, 1969). This model would be more convincing if the points on the lower 'isochron' were less well aligned.

A possible explanation for alignment of points along the lower isochron is the preferential leaching of radiogenic strontium relative to primary strontium, as has been observed in micas (Faure and Powell, 1972, p. 103). Radiogenic strontium, metastably situated in weathered K-feldspar may have been leached in preference to strontium stably situated in less-weathered plagioclase.

If all secondary radiogenic strontium were removed during weathering about 1 260 m.y. ago the strontium isotope ratio could be reduced to the level of the original, perhaps Archaean, emplacement. Under sedimentary cover since that time, the system evolved, generating a distribution resembling an isochron. Thus the apparent date may approximate the date of a period of weathering, with an initial ratio below that of the parent rocks.

Of the two isochrons, the older is by far the more reliable, as it contains the freshest samples of quartz syenite. The age of 1 630 m.y. is in broad agreement with radiometric ages of granitic rocks from the Gascoyne Province (Williams and others, 1978; de Laeter, 1976). The age is slightly younger than the indicated age of the Earaheedy Group sediments (1 700–1 800 m.y.), and of K–Ar ages on glauconite from the Earaheedy Group of 1 690–1 680 m.y. (Preiss and others, 1975; Butt and others, 1977), and could represent the age of formation of the ring structure.

ORIGIN OF THE STRUCTURE

EVIDENCE OF SHOCK METAMORPHISM

Several lines of evidence indicate that rocks within the core and the ring syncline were subjected to shock metamorphism, and hence the structure probably formed as the result of cryptoexplosive activity.

Shatter cones (Fig. 5A) are sparsely scattered through the granular iron-formation within a few hundred metres of the granitic core, but only rarely are they well developed. They

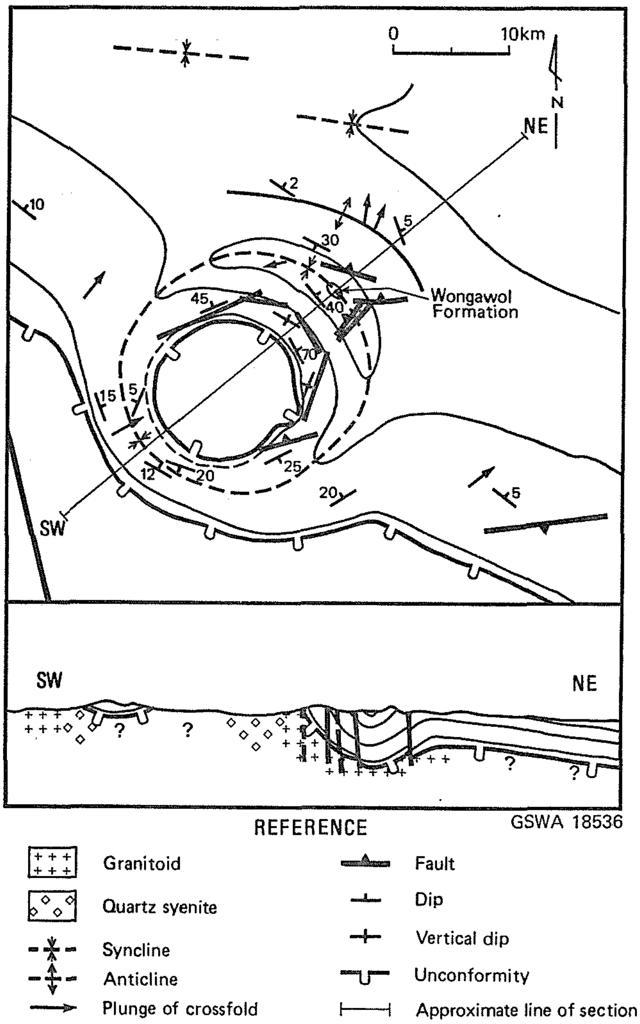

Figure 3 Structural sketch and diagrammatic cross section.

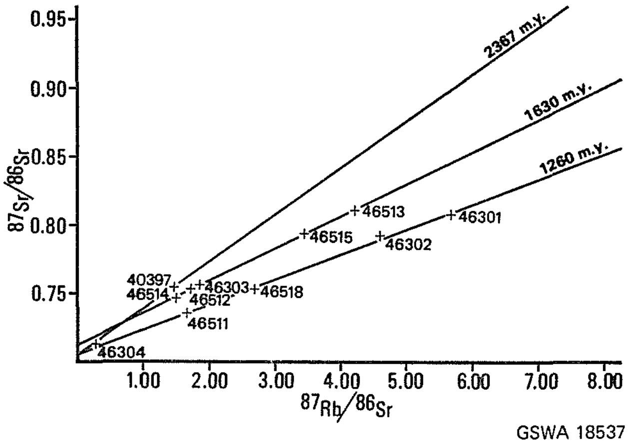

Figure 4 Isotopic data and reference isochrons, Teague Ring Structure.

range in length from a few centimetres to 150 mm and have apical angles of between 30° and 50°. A single shatter cone has been found in the quartz syenite (J. Ferguson, pers. comm.).

Deformation lamellae in quartz occur only in the granitic rocks of the core, not the quartz syenite. The lamellae show characteristics of the 'decorated' type (Carter, 1968) and are formed by lines of small fluid-filled inclusions. Commonly at least two sets are present, and these either overlap or form a chevron pattern (Fig. 5B and C).

Very small (less than 1 mm thick) pseudotachylite veins cut the granite and syenite. The veins consist of brecciated quartz and feldspar fragments in a devitrified glassy matrix. In the same thin sections plagioclase crystals are shattered and twin lamellae disrupted.

TERRESTRIAL OR EXTRATERRESTRIAL ORIGIN?

The features described in the previous section are generally taken as evidence of shock metamorphism produced by a cryptoexplosion. Circular structures produced by such events have been described from numerous parts of the world, and the Teague Ring Structure has features in common with many of them, particularly those in Precambrian terrains, for example the Vredefort Dome, South Africa (Dietz, 1961) and the Carswell Structure, Canada (Currie, 1969). For summaries see Robertson and Grieve (1975), and French and Short (1968).

The origin of such structures has been the subject of much debate. In its most basic terms, this debate centres around whether the structures formed as the result of meteorite impact (extraterrestrial) or an explosive event within the crust (terrestrial). The proponents of meteorite impact point to experimental evidence which suggests that the high strain rates of shock metamorphism cannot be produced by known processes within the crust. Their opponents rely on the empirical observations that many of the so-called impact structures lie on pre-existing structures, or contain features such as thermal metamorphism or igneous intrusions which are related to the origin of the structure but which predate the shock event; thus the event is not random, as required by the impact theory (Currie, 1969; Snyder and Gederman, 1965; Bucher, 1963; Sage, 1978).

In this context it is noted that the Teague Ring Structure does not appear to have been a random event. It lies astride the presently exposed line of unconformity at the base of the Earaheedy Group—which may form a hingeline related to the formation of the Wiluna Arch (Bunting and others, 1977). The plane of symmetry of the structure is perpendicular to the dominant fold direction and regional strike (and hence parallel to the major stress direction). The core contains quartz syenite (an unusual rock type in the Yilgarn Block) that pre-dated the shock metamorphism. Finally, the structure lies on a prominent aeromagnetic lineament which trends 060° and which coincides with a second possible shock metamorphic structure some 260 km to the southwest. Although this evidence is not conclusive, taken in conjunction with similar evidence for other structures elsewhere in the world, there is sufficient doubt about the viability of the impact theory to suggest that a terrestrial mechanism may be involved.

The nature of a terrestrial mechanism for cryptoexplosive features remains a problem. Numerous workers have shown that volcanic, tectonic or diapiric activities by themselves cannot produce the strain rates required for shock metamorphism. However, many of the Precambrian examples show a coincidence between the formation of a circular shock structure and alkaline magmatic activity (Currie, 1971; Sage, 1978), and it seems feasible that volatile pressures during alkaline magmatism could be sufficiently high to create the required explosion. Schreyer (1978, unpubl.) has suggested that an explosion of a dry, carbon dioxide-rich volatile phase in an alkaline magma caused the Vredefort Dome in South Africa. With this in mind, it is interesting to note that the syenitic rocks in the core of the Teague Ring Structure contain fresh pyroxene, and only minor primary hydrated minerals.

CONCLUSIONS AND SUMMARY

The Teague Ring Structure has many features that are characteristic of cryptoexplosive circular structures elsewhere in the world, but as in many of these structures the evidence for the nature and cause of the explosion is inconclusive. The presence of shatter cones, deformation lamellae and pseudotachylite veins could be taken as evidence of a meteorite impact, whereas the sketchy empirical evidence for a non-random origin would require the invocation of a terrestrial cause, such as a volatile explosion in an alkaline magma. The question of origin remains open, and indeed may remain open for many years; however, there are some significant observations on the Teague structure which are either pertinent to, or put constraints on, its origin. They are as follows:

1. In common with many other Precambrian circular structures, the core contains alkaline rocks, in this case pyroxene-quartz syenite.
2. The quartz syenite intrudes granitoid rocks which are in turn unconformable beneath Early Proterozoic rocks of the Nabberu Basin.
3. Of the two possible isochrons obtained from the quartz syenite, the older at 1 630 m.y. is most likely to have geological significance, though it may not represent the age of original emplacement of the

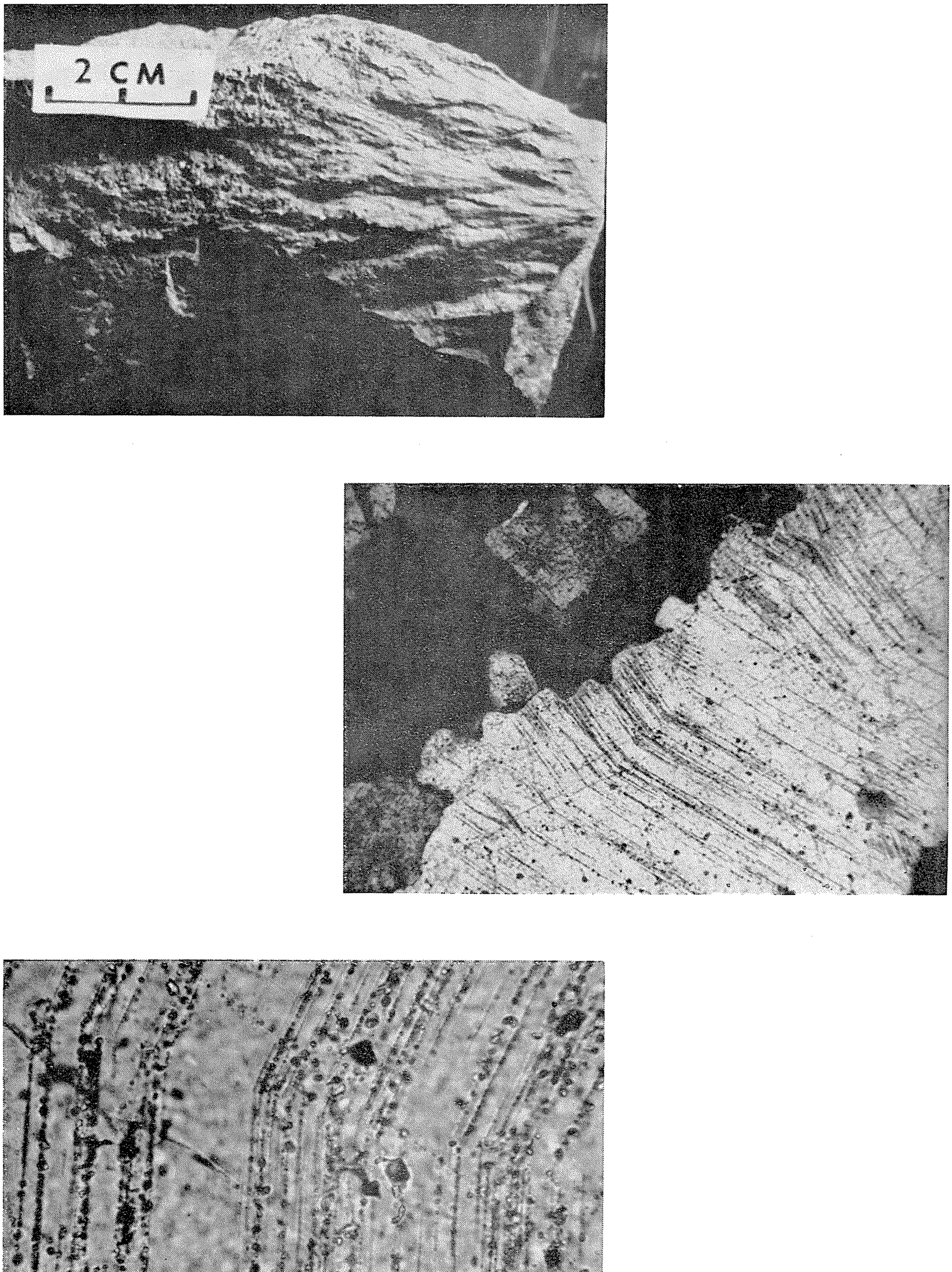

Figure 5 Shock metamorphic features:

(A) Shatter cones in granular iron-formation.

(B) Decorated deformation lamellae in quartz in leucogranite from the core of the structure. Field of view is about 1 mm.

(C) Detail from B showing fluid inclusions.

pluton. This date is younger than the presumed age of the overlying sediments and could conceivably be the time of formation of the structure.

4. As neither circular structures nor syenitic rocks are common in the northeastern Yilgarn Block, their association in the Teague Ring Structure suggests that they may be genetically related. Pseudotachylite veins and a shatter cone in the quartz syenite indicate that the quartz syenite was in place prior to shock metamorphism, and therefore could not be a result of the shock. Thus the structure seems likely to have been formed by a series of terrestrial events culminating in an explosion.
5. The physical meaning of the younger possible isochron at 1 260 m.y. is not clear, but it may record a period of alteration or weathering.

ACKNOWLEDGEMENTS

A structure such as this has produced much debate, and we are indebted to the large number of people with whom we have discussed the problem. In particular, John Bunting would like to thank D. C. Gellatly, W. Schreyer, J. Ferguson, C. Arndt, P. Dunn and numerous colleagues in the Geological Survey of Western Australia. D. C. Gellatly brought to our attention the existence of shatter cones in the iron-formation. The authors are also grateful to Mr D. J. Hosie of the Department of Physics, Western Australian Institute of Technology, for technical assistance during the project.

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SUMMARY OF THE PRECAMBRIAN STRATIGRAPHY OF WESTERN AUSTRALIA

by R. D. Gee

ABSTRACT

An updated stratigraphic table is presented which places lithostratigraphic units for each tectonic unit of Western Australia in a chronometric time scale. The Archaean-Proterozoic boundary should be revised to 2·5 b.y. from the figure of 2·4 b.y. previously adopted by the Geological Survey. Some geochronological control now exists on all major Proterozoic sedimentary sequences, and some inter-regional correlations are indicated by the tabulation. A major sedimentary cycle commenced 1·1 b.y. ago. Stratigraphic continuity before 1·1 b.y. is obscured by orogenic activity, but these older sequences are inherently of restricted extent.

INTRODUCTION

At appropriate times, this survey publishes summaries of the Precambrian stratigraphy of Western Australia, incorporating recent advances in geology and geochronology (Horwitz, 1968; Gee, 1974). This report is another in this series, and comes at a time when initial geological mapping of the State at a scale of 1:250 000 has just been completed. It also follows closely a period of accelerated geochronological enquiry into the Precambrian, much of which has been specifically directed at the broad stratigraphic framework of the State.

Most of the major sedimentary sequences have now been identified, and some geochronological data exist on most of

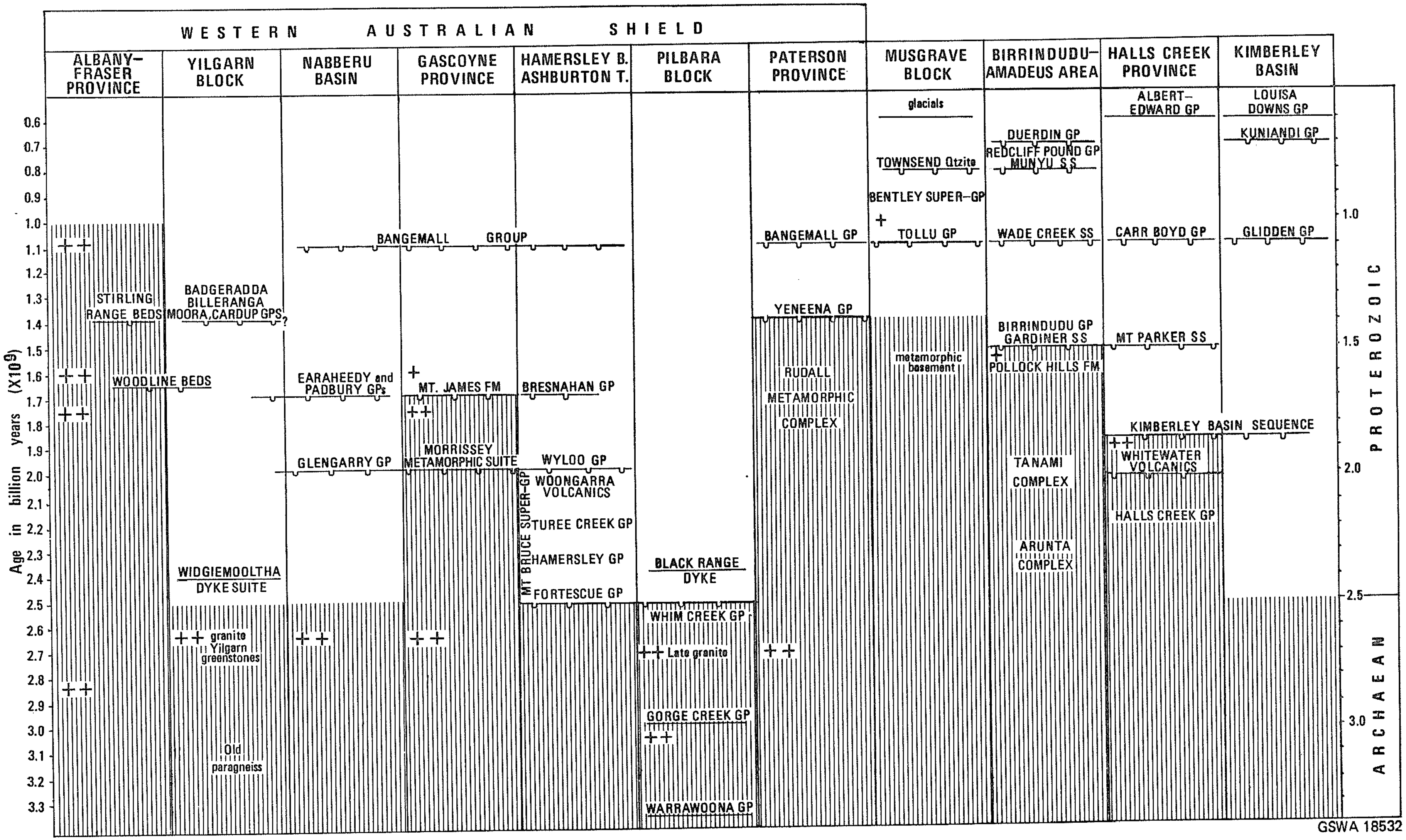

Figure 1 Summary chart of the Precambrian stratigraphy of Western Australia. Unconformities shown in conventional manner. Crosses indicate granite emplacement. Shaded area represents metamorphic/plutonic terrains that form basement to overlying cover sequences.

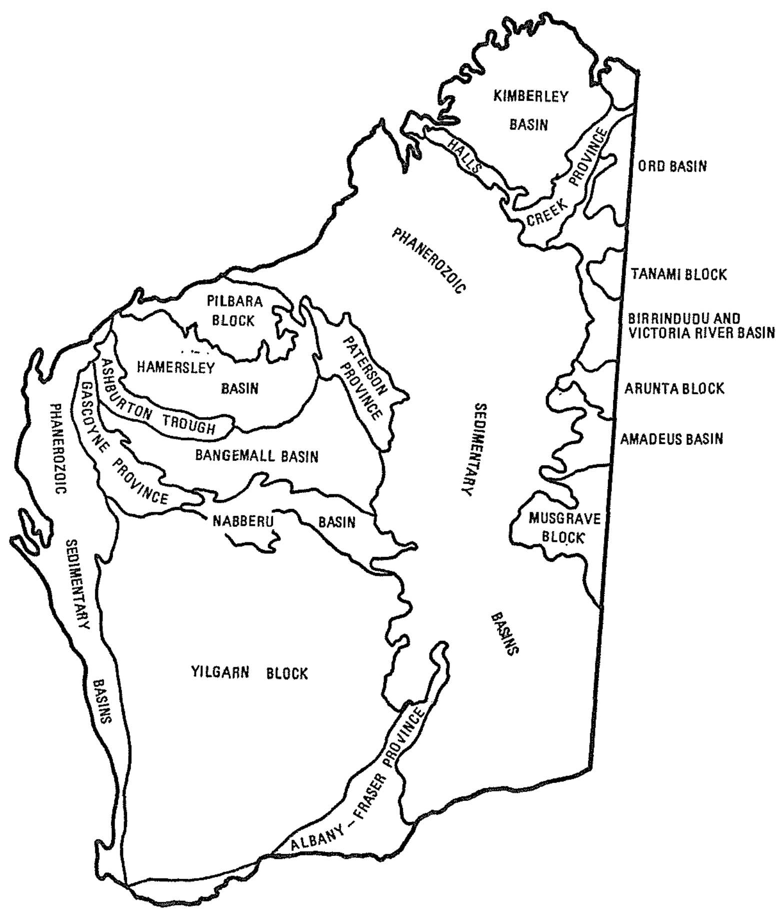

Figure 2 Distribution of Precambrian tectonic units referred to in Figure 1.

the major tectonic units. Consequently it is now possible to present a synthesis which is more solidly based than those of previous years. On the accompanying chart (Fig. 1) the major lithostratigraphic units (e.g. supergroup, group, etc.) that occur within the main tectonic units (Fig. 2) are arranged in a time scale of billions of years. For most rock sequences, the positions in the time scale are set by the relationships they hold to magmatic or metamorphic events for which geochronological data exist. This chart summarises the stratigraphy as it is presently understood, and only the more stratigraphically significant controls are referred to in the text. A more comprehensive review of the contribution of geochronology to the geology of Western Australia has been given by de Laeter and Trendall (1979).

The chart is based on a collation by the Australian Working Group (K. A. Plumb, R. D. Gee and B. R. Thomson) of the Subcommission on Precambrian Stratigraphy. The Australia-wide correlation chart, which will be presented elsewhere, is part of an international enquiry into establishing a widely acceptable global subdivision of the Precambrian.

In 1977 a new decay constant of $1 \cdot 42 \times 10^{-11}$ year $^{-1}$ for ^{87}Rb came into general use in place of the previously accepted figure of 1·39. For precise comparative purposes all Rb–Sr dates should be multiplied by a factor of 1·39/1·42 or 0·979. Whereas this change is significant in that it brings the Rb–Sr dates more closely into correspondence with other systems, and may also be important in resolving relationships in detailed studies, it has no effect on the broad-scale stratigraphy described here. As this paper is not intended to be a summary of geochronology of the State, Rb–Sr determinations prior to 1977 (which represent the vast bulk of the data) have not been corrected to the new constant. Furthermore, as a convention actual ages are quoted in millions of years, without showing the errors at the 95% confidence level, and where ages are used in a broad stratigraphic context, they are quoted in billions of years, rounded to one decimal place. In the compilation of Plumb and others which attempts to examine more precisely the field and geochronological relationships, the Rb–Sr ages will be corrected to the new constant.

SUBDIVISION OF THE PRECAMBRIAN

In Western Australia (Trendall, 1975), the approach to Proterozoic stratigraphy is the integration of isotopic dating and regional geology, rather than the use of chronostratigraphic (time-rock) terms tied to the geological record. This Survey has used a subdivision of the Precambrian time into Archaean and Proterozoic eons, the latter being subdivided into three eras called Lower, Middle and Upper Proterozoic, with time boundaries of 1 640 and 860 m.y. The concept of division of geological time, rather than of the geological record is consistent with the recent recommendations (James, 1978) of the Subcommission on Precambrian Stratigraphy, and the subdivisions of the Proterozoic have found use in broad-scale descriptions, especially where geochronological control has been lacking. But as more such data have become available the subdivisions have been found to have progressively less correspondence with the actual geological record, and have consequently declined in usefulness.

THE ARCHAEAN-PROTEROZOIC BOUNDARY

Since 1967, this Survey has used 2 400 m.y. as a convenient figure that separates the Archaean and Proterozoic rocks. This figure corresponds closely to the indicated age of dolerite dykes in both Archaean cratons. Moreover, this time plane was consistent with the belief that the age of the Mount Bruce Supergroup, which overlies the Archaean Pilbara Block, was in the range of 2 200 to 2 000 m.y. However, with the recognition that the Woongarra Volcanics (ca. 2 000 m.y., Compston and Arriens, 1968) are intrusive rather than extrusive (de Laeter and others, 1974, p. 91), there ceased to be any firm control on the age of the Hamersley Group. The only evidence bearing on its age became a poorly fitted Rb-Sr isochron of about 2 200 m.y. on a dolerite sill possibly contaminated by its wall rock (de Laeter and others, 1974), and an age of 2 329 m.y. on the Black Range dyke (Lewis and others, 1975), for which no field relationship with the Proterozoic rocks has been demonstrated.

Some suggestion for an appreciably older age of the Hamersley Basin sequence is suggested by an isochron of ca. 2 600 m.y. (Hickman and de Laeter, 1977) on sediments at the base of the sequence. More recently W. Compston and A. F. Trendall (pers. comm.) have obtained a U-Pb age of 2 496 m.y. on volcanogenic zircon from a stratigraphic position near the middle of the Hamersley Group, which is underlain by at least 2 km of sediment and volcanics. Therefore, it seems that the Archaean-Proterozoic boundary would be better placed at an older date.

Coincidentally, and independently from these developments, the Subcommission on Precambrian Stratigraphy in 1978 recommended 2 500 m.y. as the time plane that best separates the contrasting Archaean and Proterozoic terrains in most regions of the world. As an interim measure, this Survey now endorses this time boundary, as it is compatible with current knowledge in Western Australia, although it needs to be stressed that this boundary could be further adjusted in the light of continuing studies in the circum-Pilbara region.

Not surprisingly, the 2 500 m.y. boundary is inconsistent with some data. Rb-Sr dates in the range 2 330 to 2 366 m.y. have been obtained (de Laeter and Sylvester, pers. comm.) from volcanic and intrusive material in the Whim Creek Group which is unconformably overlain by the basal units of the Fortescue Group, which according to evidence present in this paper, could be about 2 500 m.y. old. Temporal and spatial relationships between these two rock sequences need to be resolved before any further refinement of the Archaean-Proterozoic boundary can be contemplated.

ARCHAEAN STRATIGRAPHY

PILBARA BLOCK

Hickman (in prep.) has erected a regionally extensive stratigraphy for the Pilbara Block, consisting of the Warrawoona and Gorge Creek Groups. An important U-Pb age of 3 450 m.y. on zircon extracted from dacite (Pidgeon, 1978) is the only direct date for the Warrawoona Group, and makes these rocks the oldest in Australia.

A lower limit on the Gorge Creek Group is given by granite ages of about 3·0–2·9 b.y. (Compston and Arriens, 1968; de Laeter and others, 1975; and Oversby, 1976), some of which were emplaced into the Warrawoona Group before the overlying Gorge Creek Group sedimentation.

As previously mentioned, the more localised late Archaean volcanic sequence (Whim Creek Group) in the West Pilbara gives ages as young as 2·3 b.y. These ages are problematical and contribute to the present uncertainties on the age of the Archaean-Proterozoic boundary.

YILGARN BLOCK

Paragneiss and high-grade schist interfoliated with granitic gneiss that give ages around 3·0 b.y. (Arriens, 1971), are the oldest rocks in the Yilgarn Block. Gee, (1979a) considered that these metasediments are part of an ancient marine-shelf-type sequence that pre-dates the volcanogenic rocks in the greenstone belts.

At present, there is a lack of direct data on the age of the Yilgarn Block greenstones. Most are older than a widespread granite emplacement event at 2·6–2·7 b.y. (Arriens, 1971), and geological evidence (Gee, 1979a) suggests they evolved over a short period of time (ca. ?100 m.y.) which overlapped the period of granite emplacement. It is tentatively concluded that the greenstones are about 2·8–2·7 b.y. old, an age supported by a Rb-Sr date of 2 718 m.y. (Cooper and others, 1978) on gabbro that is probably co-magmatic with stratigraphically low mafic volcanics.

PROTEROZOIC STRATIGRAPHY

HAMERSLEY BASIN—MOUNT BRUCE SUPERGROUP

Trendall (1979) revised the Mount Bruce Supergroup to include the Fortescue, Hamersley and Turee Creek Groups and to exclude the Wyloo Group. Reference to the uncertainty of the age of the Mount Bruce Supergroup has previously been made, but it is probably between 2·6 and 2·0 b.y. The older limit is provisionally accepted as the age of younger granite in the Pilbara Block (de Laeter and others, 1975), the emplacement of which is probably the last craton-forming event in the basement. The younger limit is the age of the Woongarra Volcanics (Compston and Arriens, 1968; Arriens, 1975).

ASHBURTON TROUGH

The Wyloo Group, at its base, contains clasts that can be matched with the Woongarra Volcanics (Trendall, 1979), and the group is affected by granite plutonism and regional metamorphism which produced an orogenic climax at about 1·7–1·8 b.y. (de Laeter, 1976; Williams and others, 1978; Leggo and others, 1965).

NABBERU BASIN

The Glengarry Group in the western part of the Nabberu Basin is a thick geosynclinal sequence occurring in a trough along the northern margin of the Yilgarn Block (Gee, 1979b). It unconformably overlies the Archaean (2.5 b.y.) and participated in the orogeny in the Gascoyne Province (1·7–1·8 b.y.). A broad lithological similarity exists with the Wyloo Group, and Gee (1979a) has proposed that together these two thick trough sequences form the Capricorn Orogen, the oldest recognizable geosyncline in the Western Australian Shield.

In the eastern part and in synclines in the western part of the Nabberu Basin, the Glengarry Group is unconformably overlain by the Earaheedy and Padbury Groups respectively. Both these younger sequences contain granular iron-formation, which is a basis for their correlation. Bunting and others (1977) discussed the age constraints of the Earaheedy Group, and favoured an age of about 1·7 b.y., based on regional considerations and available K-Ar and Rb-Sr isotopic dates on glauconite (Preiss and others, 1975; Horwitz, 1975).

PATERSON PROVINCE—YENEENA GROUP

The Yeneena Group unconformably overlies the Rudall Metamorphic Complex, and is unconformably overlain by the Bangemall Group. Provisional Rb-Sr data (R. J. Chin and J. R. de Laeter, pers. comm.) indicate an age of about 1·4 b.y. for the metamorphic basement. Sedimentation is placed between 1·4 b.y. and the age of the Bangemall Group, of 1·1 b.y.

Some stratigraphic revision in this area (P. C. Muhling and A. T. Brakel, pers. comm.) has incorporated units of the "Manganese Group" into the Yeneena Group, the remainder being incorporated into the Bangemall Group. Likewise, the Waltha Woora Beds in the Robertson area are now variably apportioned either to the Yeneena Group or to the Bangemall Group.

BANGEMALL BASIN—BANGEMALL GROUP

The Bangemall Group is an extensive intracratonic sedimentary sequence which overlies with striking unconformity all the Proterozoic sequences referred to previously. It now incorporates much of the "Manganese Group", and some strata previously assigned to the Waltha Woora Beds. P. C. Muhling and A. T. Brakel (pers. comm.) correlate the Uaroo Group (van de Graaff and others, 1977) with the Bangemall Group.

Rb-Sr data on shale and felsite (Compston and Arriens, 1968) give an age of about 1 080 m.y., and an extrusive rhyolite (Gee and others, 1976) gives an age of 1 096 m.y. The unconformity below the Bangemall Group is placed at 1·1 b.y.

SEDIMENTARY SEQUENCES OF UNCERTAIN AGE

A number of isolated sequences occur in a stratigraphic position unconformably between the Wyloo Group (or the Morrissey Metamorphic Suite, its metamorphic equivalent) and the Bangemall Group. These include the Mount Minnie and Bresnahan Groups (Daniels, 1975), the Mount James Formation (Williams and others, 1979), various basement inliers in the Bangemall Basin (Muhling and others, 1978), and the Mount Leake Sandstone (Gee, 1979b). These sequences are located in the time scale according to the known broad geological constraints.

No recent work has been undertaken on dating the outliers of Proterozoic rocks scattered around the periphery of the Yilgarn Block. Allocation of these sequences (Cardup, Moora, Billeranga and Badgeradda Groups, and Mount Barren, Stirling Range and Woodline Beds) in the time scale is based mainly on the review of Low (1975).

MUSGRAVE BLOCK

A metamorphic basement recording ages around 1·4 b.y. is overlain by a felsic volcanic complex with related subvolcanic granites (Tollu Group) registering an age of 1 060 m.y. (Compston and Nesbitt, 1967). This is overlain by a marine shelf sequence called the Bentley Supergroup, which probably has a comparable age to that of the Bangemall Group.

Unconformably overlying all these rocks is a prominent orthoquartzite marker called the Townsend Quartzite, which is now generally correlated with the Heavitree Quartzite at the base of the Amadeus Basin sequence. It is therefore considered to be about 0·8 b.y. old.

AMADEUS—VICTORIA RIVER—BIRRINDUDU BASINS

Considerable remapping has been undertaken in this area by BMR and joint BMR-GSWA parties, and has resulted in a revised stratigraphy which is embodied in the bulletin by Blake and others (1980). Most of the previous stratigraphic problems stem from difficulties in correlating sandstone formations at the base of major sequences that rest unconformably on metamorphic basement blocks.

The basis for stratigraphic synthesis is now the correlation of the Heavitree Quartzite (correlated with the Townsend Quartzite) with the Munyu Sandstone at the base of the Redcliffe Pound Group. This correlation identifies an extensive sequence, including that of the Amadeus Basin, as a major platform cover anologous to, but marginally younger than, the Bangemall Group in the Western Australian Shield.

Below this major cover sequence, and lying unconformably above the metamorphic basement, is the Birrindudu Group and related sequences in the Birrindudu Basin. The basal sandstone (Gardiner Sandstone) of the Birrindudu Group records K-Ar glauconite ages of around 1 500 m.y. (Page and others, 1976). The Gardiner Sandstone is correlated with the Mount Parker Sandstone, which lies unconformably above metamorphic rocks along the eastern flank of the Halls Creek Province.

KIMBERLEY BASIN AND HALLS CREEK PROVINCE

Recent advances in the understanding of the Precambrian stratigraphy of the Kimberley region are outlined in Plumb and Gemuts (1976). Most significant is the revision of the age of the Whitewater Volcanics from 1 788 m.y. (Dow and Gemuts, 1969) to at least 1 850–1 880 m.y. (contemporaneous with porphyries and granites of this age), and possibly to as old as 1 940 m.y. (Bennett and Gellatly, 1970).

This revision would make the age of the overlying Kimberley Basin sequence consistent with Bofinger's (1967) dates of 1 800 m.y. on the Hart Dolerite, and 1 807 m.y. on the Carson Volcanics.

Another change is the plausible reinterpretation by Page (1976) of the Bofinger (1967) data on the Halls Creek Group. Page considered these basement rocks to be between 2 200 and 1 960 m.y. old, and, therefore, not Archaean.

CONCLUDING REMARKS

Some evidence for inter-regional correlations emerges from the chart (Fig. 1). Also shown, by grey shading on the chart is the extent of the metamorphic terrains. These areas act as stable cratonic basement upon which the sedimentary cover sequences were deposited. It is evident that the younger sequences are far more extensive than the older, and they seem to offer the best possibility of stratigraphically based correlations.

Most conspicuous are the widespread cover sequences of about 1·1 b.y., seen both in the Western Australian Shield and the Precambrian areas east of the Phanerozoic divide. In this latter area it marks the beginning of a period of long-continued stable-shelf-type sedimentation persisting up to the Cambrian, without the interruption of major orogenies.

The older Proterozoic sequences are of a more basinal or trough nature. Correlation of these older, more restricted sequences is made difficult by their partial involvement in orogenic belts, such as the Capricorn Orogen and the Paterson Province. The degree of actual contemporaneity of sedimentation in the Western Australian Shield at about 1·6–1·7 b.y. is uncertain, but the alignment of stratigraphic units at this level, as shown on the chart, offers the possibility of future correlation at this and lower stratigraphic levels in the complex Capricorn Orogen between the two Archaean cratons.

The oldest and most restricted sequence in the Western Australian Shield is the unique Mount Bruce Supergroup, which does not appear to have any correlation outside the Hamersley Basin. Its depositional extent seems to be confined to a basement which is the oldest and most thoroughly stabilised part of the Shield, the outcropping part of which is represented by the Pilbara Block. One of the more interesting problems in the Proterozoic geology of Western Australia is the palaeogeographic reconstruction in the interval 2·5–2·0 b.y., particularly as to what geological processes operated away from the Hamersley Basin while the Mount Bruce Supergroup was being deposited. At present there is no evidence bearing on this question.

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THE DARLING FAULT: DIAMOND DRILLING RESULTS AT HARRISONS COPPER PROSPECT

by J. L. Baxter and J. L. Harris*

ABSTRACT

Diamond drilling of a geochemical anomaly for copper at Harrisons Prospect, 25 km northeast of Mingenew, (lat. 29°05'S, long. 115°37'E) by Amoco Minerals Australia Company indicates that:

(a) the Darling Fault plane is curved, and the dip ranges from 80° west near the surface to 52° west at a depth of less than 100 m;

(b) the mineralization is sub-economic with intersections averaging 0·2% Cu over a drilled distance of 30 m;

(c) mylonites in the Archaean gneissic rocks east of the fault predate development of the Darling Fault;

(d) the Darling Fault was a locus for brittle fracture in Permian and possibly Proterozoic times.

INTRODUCTION

The Darling Fault, a major structural feature in the earth's crust, was intersected in core drilling at Harrisons copper prospect (lat. 29°05'S, long. 115°37'E) by Amoco Minerals Australia Company (Amoco). The prospect is 25 km north-east of Mingenew, and 320 km north of Perth (Fig. 1).

Malachite in a silicified breccia in Archaean rocks cropping out in a steep-flowing tributary of the Lockier River, was first reported by Mr. G. W. Harrison in 1961. In 1976 the Harrison Syndicate conducted a limited exploration programme including percussion drilling. Chalcopyrite mineralization (maximum 2·3% Cu) over a drilled width of 65 m was intersected in one hole. Amoco, under a joint-venture agreement, carried out a systematic programme of exploration on the prospect during 1977. Work included: low-level colour aerial photography; airborne magnetometry and spectrometry; gridding; geological mapping; stream-sediment, soil, and rock-chip geochemistry; ground magnetics; gradient-array I.P.; and percussion-diamond drilling. Amoco's exploration programme culminated in the drilling of six combined percussion and diamond drill-holes at three locations to test a coincident soil, stream-sediment and rock-chip geochemical anomaly related to brecciated Archaean rocks immediately east of the Darling Fault. Although the mineralization encountered is sub-economic, (intersections averaged only 0·2% Cu over 30 m) the drilling provided a rare opportunity to study the Darling Fault.

* Amoco Minerals Australia Company

TECTONIC SETTING OF THE DARLING FAULT

The Darling Fault is a normal fault, which can be traced at the surface and by geophysical methods for about 1 000 km along the western side of the Yilgarn Block. The fault forms the eastern limit of a more extensive fracture system in the Perth Basin.

Playford and others (1976) have described all data previously collected on the fault. The early history of the fault is uncertain. However, from evidence outside this area Playford and others (1976) postulated that a transcurrent fault developed along or close to the line of the present Darling Fault during the Proterozoic or early Palaeozoic and that normal faulting began later, possibly during the Silurian. In the Three Springs-Mingenew area, Proterozoic sediments have been deposited on either side of the fault. East of the fault plane, less than 1 km thickness of sediment is preserved; whereas, on the western or down-thrown side, in the Irwin Sub-basin, more than 5 km is preserved. Baxter and Lipple (in press), suggest that the fault may have acted as a growth fault during the Proterozoic. Playford and others (1976) and Hocking (1979) suggest similar activity on the fault during the Silurian, when more than 3 km of Tumblagooda Sandstone was deposited in the Coolcalalaya Sub-basin. There is no evidence of thick sedimentation in the Irwin Sub-basin after the close of the Permian, and it is probable that major movement along the fault ceased in this area during the early Mesozoic. The most prominent phase of the Darling Fault's history is seen further south. It took place between the Middle Triassic and Early Cretaceous, when movement on the Darling and Urella Faults created deep troughs during development of the Perth Basin, into which up to 15 km of sediments were deposited. Major movement on the fault ceased in the Neocomian (Early Cretaceous) (Playford and others, 1976).

Mylonite zones occur throughout the Yilgarn Block; several are located near its western and northern margins. Elias and Williams, (1977), Wilde and Low, (1978a), Wilson (1958) and Wilde and Low (1978b) interpret the mylonitization along the western margin of the Yilgarn Block as being due to a Precambrian event which may have been a forerunner of the Darling Fault, and Wilde and Low (1978b) suggest that the present position of the fault is controlled by this Precambrian event. Lister and Price (1978) in a study of the mylonite fabrics, and Wilson (1958) in a regional analysis of the south-western Yilgarn Block, conclude that compression, represented

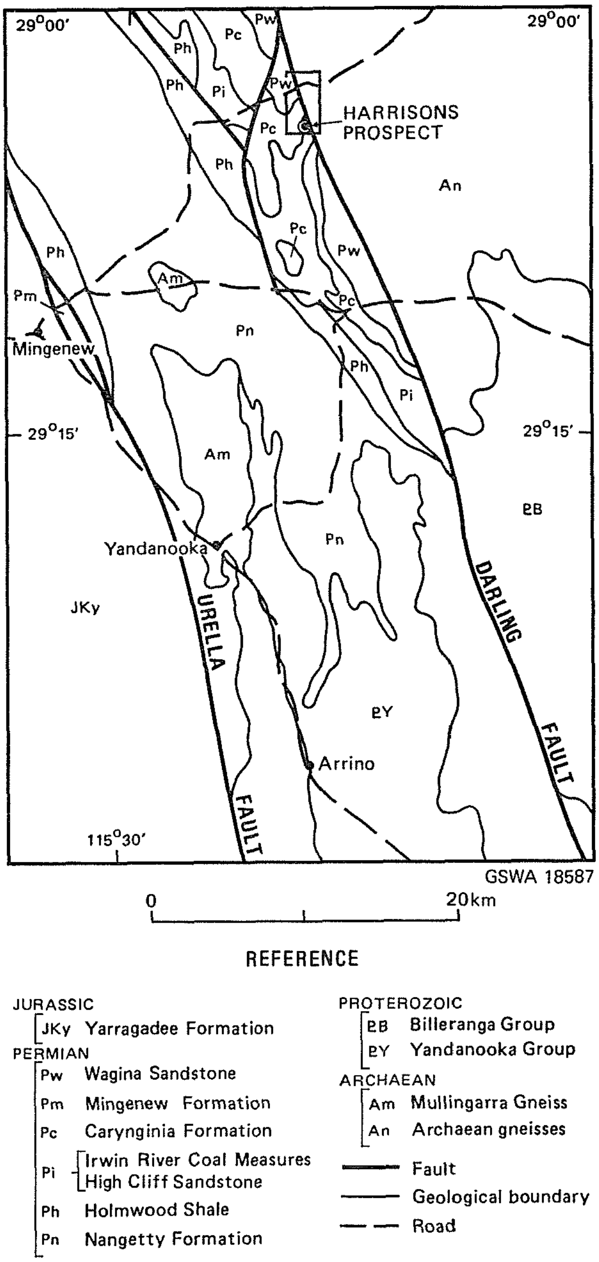

Figure 1 Regional geology and locality of Harrisons prospect, Mingenew.

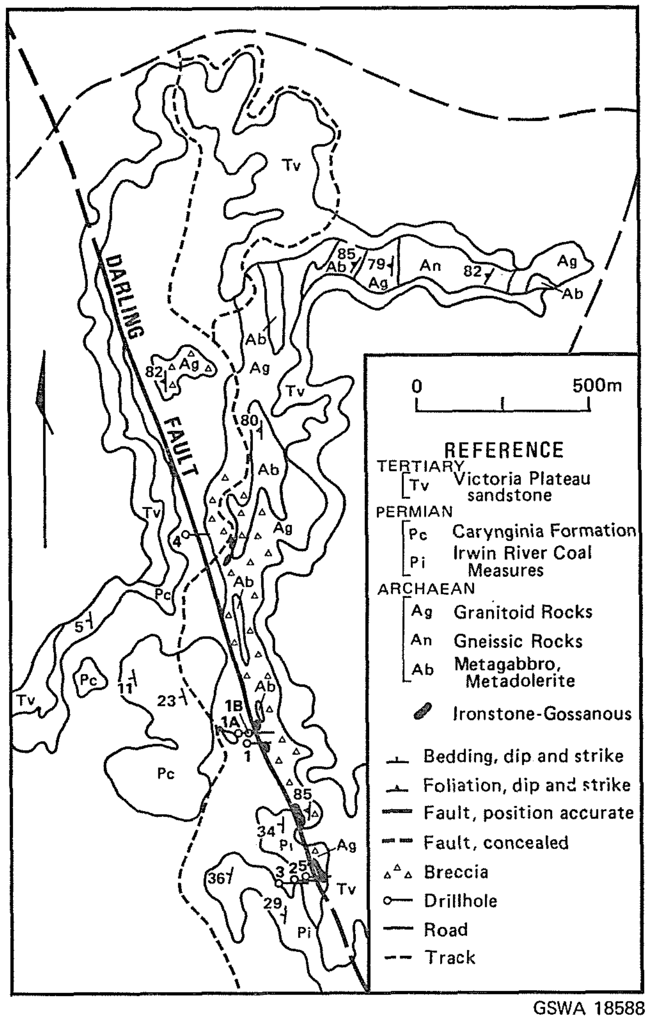

Figure 2 Surface geology at Harrisons prospect (see Fig. 1 for location).

by either transcurrent or reverse faulting, pre-dated the development of the Darling Fault. The transcurrent movement must precede the normal faulting in the Irwin Sub-basin.

GEOLOGICAL SETTING OF HARRISONS PROSPECT

Harrisons Prospect is located on the Darling Fault where the Irwin Sub-basin is faulted against the Yilgarn Block. Locally the Irwin Sub-basin contains Permian and ?Eocene sediments. The Permian sequence is restricted to the west side of the Darling Fault; whereas, the flat-lying ?Eocene Victoria Plateau Sandstone unconformably overlies both the Archaean gneisses and granitoids east of the fault, and the Permian succession west of the fault (Fig. 2). All the rock units are weathered and lateritized at the top of the breakaway exposures, but fresh rock is exposed in most of the creeks.

Archaean rocks

Diverse lithologies characterize the Archaean rock suite east of the fault. Medium- to coarse-grained granitoid and pegmatite underlie approximately half of the area investigated. The granitoids have intruded a gneissic suite which includes banded iron-formation, chert, meta-argillite, laminated pyritic graphitic schist, medium- to coarse-grained metagabbro and fine-grained mafic to ultramafic rocks. The suite is metamorphosed to lower amphibolite facies. The gneissic rocks have a predominantly north-northeasterly mineral foliation parallel to layering. On a regional scale the granitoids tend to be sub-parallel to the gneissic foliation but locally transgress the gneissosity. Generally, foliation in the granitoids is less intense than in the gneisses.

Mylonites: Laminated mylonitic rocks, characterized by deformation lamellae in quartz, and phyllitic fabric in quartz-mica rocks, occur within the granitoid and gneissic terrain east of the Darling Fault. It is generally accepted that the dominant mechanism for development of mylonites is dynamic recrystallization (Bell and Etheridge, 1973, 1976; White, 1977; Etheridge and Wilkie, 1978), and that most microstructures in the mylonites reflect a combination of dynamic recovery and recrystallization processes. Quartz ribbons, which possibly represent higher pressure deformation zones (Bossiere and Vauchez, 1978) in the granitoid host rocks, (Fig. 4 and 5) commonly have new, generally unstrained grains formed at their boundaries. Quartz-phyllite, with fine-grained mica supporting deformed quartz grains, is associated with the predominantly granitoid mylonite. (Fig. 6, 7 and 8). Passive veins formed after mylonization developed incipiently at first (Fig. 6) but finally replaced the micaceous groundmass of the mylonite, leaving the quartz grains almost intact (Fig. 7). The last stage in development of the mylonites was a spaced solution cleavage reflected in opaque clay trails (Fig. 5, 8). The presence of both crystal-plastic and solution fabrics in the mylonites indicates heterogeneous deformation pre-dating brittle fracture and mineralization.

Permian rocks

The Permian succession includes continental and marine sandstones, carbonaceous beds and siltstones. It appears that the contact between the Caryngimia Formation and the Irwin River Coal Measures occurs within the lease. Exposed on the west side of the breakaway are silty sandstones, siltstones and sandstones, which are correlated with the Caryngimia Formation. South of 5 100E, 50 950N, sandstone and

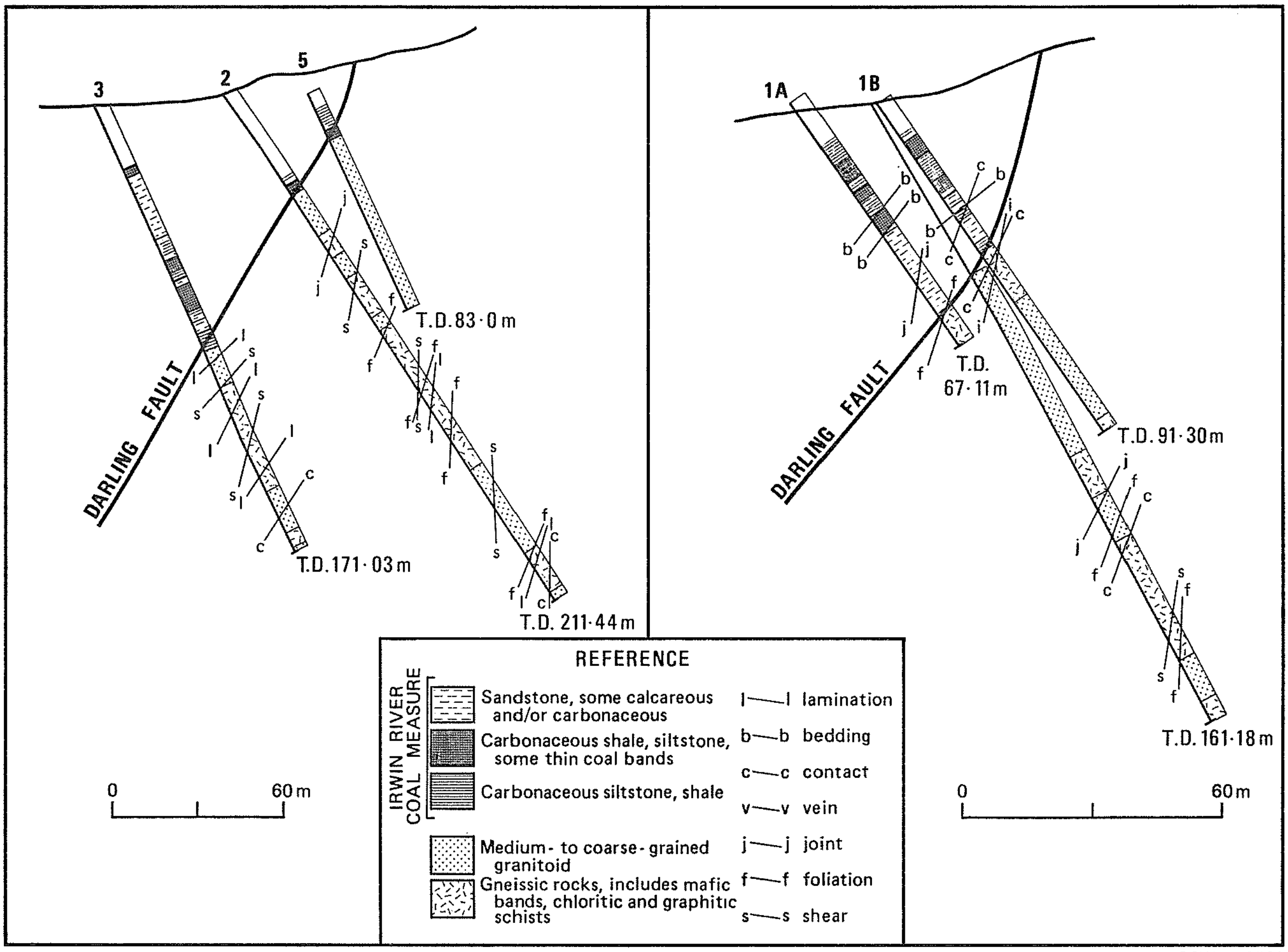

Figure 3 Cross-sections of drilled sections at Harrisons prospect, showing the projected dip of the Darling Fault.

carbonaceous deposits containing an assemblage of palynomorphs that can be assigned to the *Acanthotriletes* assemblage of Segroves (1970) (Backhouse, 1978) probably represent the Early Permian Irwin River Coal Measures. Baryte crystals and small amounts of pyrite have been identified in the Permian sediments. Adjacent to the Darling Fault, calcite-filled joints occur in the Permian rocks.

The Darling Fault at Harrisons prospect

The Archaean rocks adjacent to the Darling Fault are mylonitized, and secondary quartz growth is common in bands throughout most lithologies. Remobilization of this quartz into veins occurs in the gneissic rocks. The mylonitization predates brecciation and gouge associated with the Darling Fault. The breccias extend up to 150 m from the fault plane, and fractures in them have been filled by fine-grained quartz. The gouge is between 0·15 and 0·30 m wide and is restricted to the fault plane. Quartz veins containing chlorite pervade the breccia zone, and are more prominent adjacent to the fault plane.

Unmetamorphosed feldspathic sandstone dykes occur within the breccia zone (Fig. 9). They are up to 0·30 m wide and up to 5 m from the fault plane, but are common within a metre of the plane. The dykes have been emplaced in the brecciated zone. They show no signs of metasomatic effects, post-date brecciation and cementation of the Archaean rocks, and are probably derived from sandstone members of the Permian succession, which they resemble lithologically.

Dip of the fault plane: Playford and others (1976) have reported dips (estimated from seismic data) on the Darling Fault in the southern part of the Perth Basin to be between 50° and 80° and tending to become steeper toward the south. The faulted contact between the Irwin River Coal Measures and the Yilgarn Block was intersected in each of the six holes drilled in this investigation. All holes were drilled on a bearing of 090° with declinations between 55 and 65°E. The contact was cored in two holes, 1A and 1B, with virtually 100% recovery. The dip data are summarized in Figure 3. When allowance is made for the 340° strike of the fault, the true dip of the fault on these two sections is 52° and 62° respectively. In constructing the cross-section care was taken to compensate for slight off-sets in positions of the drill holes in relation to the sections presented.

Exposure of the fault plane at the surface is discontinuous. However, its position at the surface can usually be determined to within a few metres. If the drill intersections of the fault are projected upward the predicted fault would be further east than where it is exposed. From this it is assumed that the fault plane is curved in the manner shown in Figure 3 and has a westerly dip of approximately 80 degrees close to the surface.

Mineralization

Chalcopyrite mineralization, disseminated in late-stage quartz-chlorite veinlets in the breccia zone over a down-hole interval of 30 to 60 m, contains an average of 0·2% copper. The style of mineralization resembles that described by Phillips (1972). Pyrite occurs in the veins, but, except where located in graphitic schist or pink coarse-grained granitoid, it is a minor component of the mineralization. The granitoid contains up to 5% sulphide, mainly as pyrite, and has low copper values.

The average grade of mineralization is independent of rock type. Brecciation and mineralization decrease eastward from the fault contact and are cut off sharply at the fault. Copper contents of the Permian sediments are in the range 20 to 30 ppm whereas the Archaean suite generally contains 1 000 to 3 000 ppm alongside the fault plane.

CONCLUSIONS

The diamond drilling of the Darling Fault has provided an insight into the dip of the fault plane and the development of the fault. It also gave further information on the only known base-metal mineralization within the Darling Fault zone.

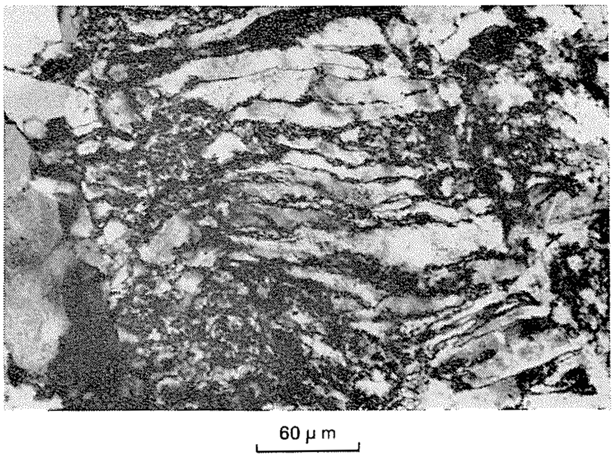

Figure 4 Deformation lamellae with flattened quartz ribbons having new grains developed at the ribbon boundaries (crossed nicols). 44402A.

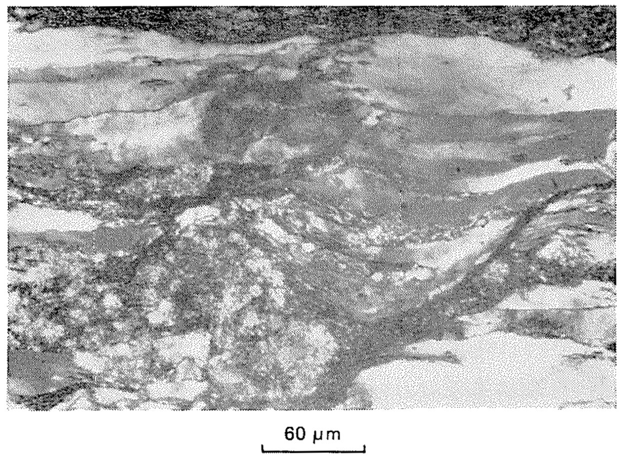

Figure 5 Necking of quartz ribbons with new subgrains at the ribbon boundaries (crossed nicols). 44402E.

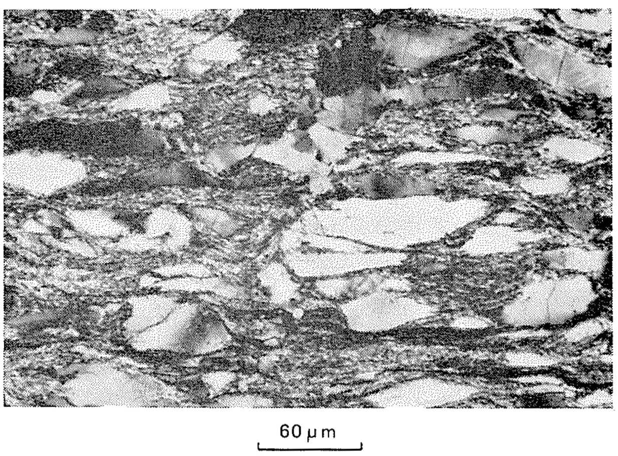

Figure 6 Initial development of passive quartz veins in a quartz phyllite (crossed nicols). 44402A.

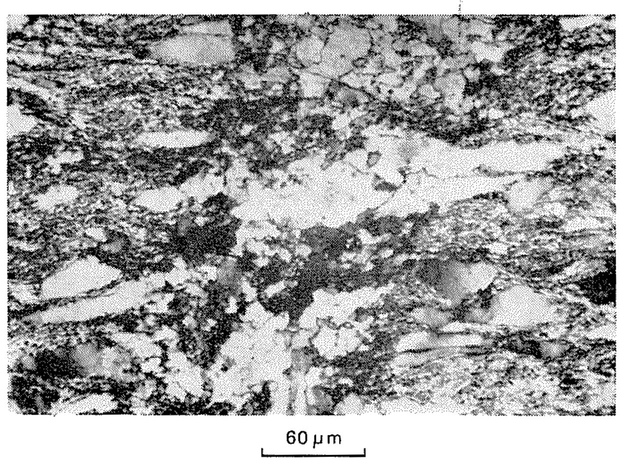

Figure 7 Final development of passive quartz veins in a quartz phyllite (crossed nicols). 44402B.

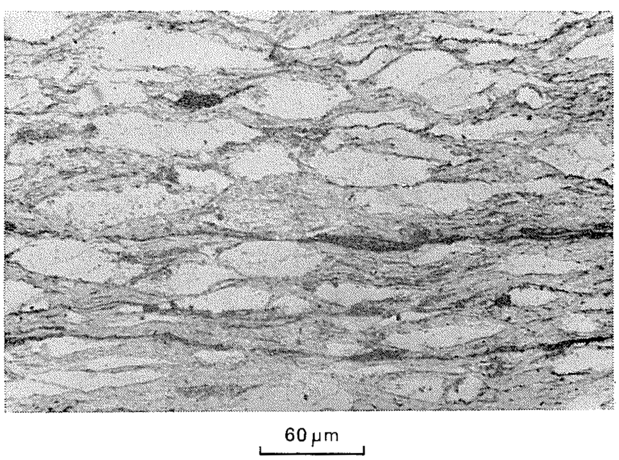

Figure 8 Quartz phyllite with solution effects parallel to mylonite fabric (plane-polarized light). 44402B.

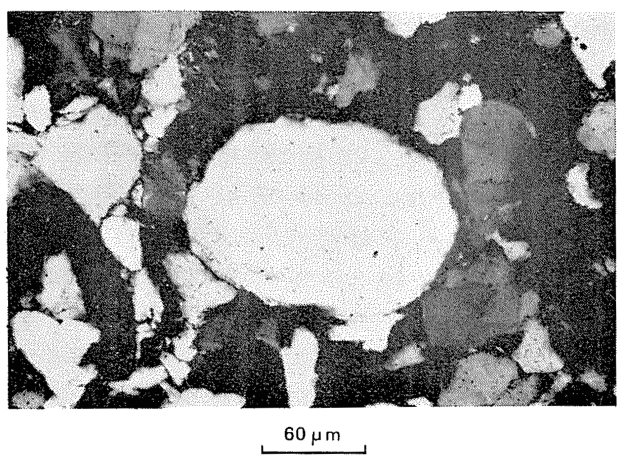

Figure 9 Rounded unstrained quartz grain in a sandstone dyke (crossed nicols). 44403A.

It has been demonstrated that the fault plane has a relatively shallow dip at shallow depth, 52° to 62°, and is curviplanar with dips of about 80° near the surface in this area.

The Darling Fault plane contains a gouge which has been developed by grain-size reduction and mechanical reorientation of chloritic footwall material.

Mylonitization of the Archaean rocks east of the fault predates brecciation and mineralization. The mylonites have developed in a variety of rocks and contain well-developed crystal-plastic deformation and solution fabrics.

The hydrothermal fluids which introduced copper, silica and sulphur into the breccia to the east of the fault also chloritized the host rock. In view of the lack of mineralization in the sandstone dykes the process must pre-date their development. A likely source for the solutions is the Proterozoic Yandanooka Group, which underlies the Permian succession in the Irwin Sub-basin. Activity on the Darling Fault deposition of the volcanogenic wackes of the Yandanooka Group may have induced hydraulic fracturing and metasomatism of the relatively brittle mylonite zone adjacent to the fault plane. This requires a tensional stress regime.

It is apparent from these drilling results that the Darling Fault was initiated as a normal fault, developed under tension. It seems possible that movement was related to development of an asymmetric basin against the Darling Fault during deposition of the Yandanooka Group. Subsequent to the Proterozoic Era there is no record of deposition or deformation until the Permian Period. However, north of this area up to 3 000 m of Silurian sediments, (the Tumblagooda Sandstone) were deposited into a trough, bounded on the east by the Darling Fault. Permian activity on the fault is suggested by sandstone dykes of probable Permian age adjacent to the fault. There is no evidence of movement of fault bounded sedimentation in the area since the displacement of the Late Permian Wagina Sandstone.

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TWO "ANOMALOUS" ISOCHRONS FROM THE VICINITY OF NEWMAN

by J. G. Blockley, A. F. Trendall, J. R. de Laeter* and W. G. Libby

ABSTRACT

Two isochrons from the Newman area, one obtained on pillow lava from the Jeerinah Formation, and the other on granite unconformably underlying the Jeerinah Formation, give ages younger than those that could be expected from other geochronological evidence from the Mount Bruce Supergroup.

The age of 1 487 ± 305 m.y. obtained from the Jeerinah Formation lava is interpreted as reflecting a metamorphic event. The age of 2 235 ± 54 m.y. from the granite sample is considered to possibly reflect the time of uplift of the Sylvania Dome.

INTRODUCTION

In recent years the continuing Rb-Sr geochronology programme being conducted jointly by the Geological Survey of Western Australia and the Western Australian Institute of Technology has included studies of material collected from two sites near the iron-ore mining town of Newman, in the north west of Western Australia.

The first study was an attempt to date the Proterozoic Fortescue Group by determining the age of pillow basalt occurring in the Jeerinah Formation at the top of the group. The second was aimed at obtaining the age of a granite from the Sylvania Dome and thereby determining also a maximum age for the unconformably overlying Jeerinah Formation.

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Both studies produced well-aligned isochrons. However, neither the age indicated for the basalt, nor that indicated for the granite are consistent with other geochronological evidence, if they are interpreted simply as the ages of extrusion and emplacement respectively.

Both are therefore regarded as being anomalous. The purpose of this paper is to record the analytical results and to suggest possible explanations for them. At present, no single hypothesis to account for either "age" is completely satisfactory.

REGIONAL GEOLOGICAL SETTING

Newman is situated near the southeastern edge of the Proterozoic Hamersley Basin, close to the northern edge of the Sylvania Dome, an inlier of presumed Archaean rocks (Fig. 1). The Jeerinah Formation is part of the Hamersley Basin succession. It constitutes the uppermost unit of the Fortescue Group, which in turn is the lowermost group in the Mount Bruce Supergroup (MacLeod and others, 1962; Trendall, 1979). A column showing formal stratigraphic units mentioned in this paper appears in Figure 2.

The lower part of the Fortescue Group is missing near Newman—shale of the Jeerinah Formation rests unconformably on granitic rocks of the Sylvania Dome. The granitic rocks have not been mapped in detail, but near Newman consist of strongly foliated biotite adamellite and massive to weakly foliated alkali granite. By analogy with the geologically similar Pilbara Block we would expect these to represent older and younger periods of granite emplacement respectively.

The structure near Newman is complex. Rocks of the Mount Bruce Supergroup form a series of asymmetric folds overturned to the north, so that the south limb of each syncline is near vertical and the north limb subhorizontal (Kneeshaw, 1975). The whole structure is cut by major faults. The Sylvannia Dome is affected by the faults and reticulated by dolerite dykes of several ages.

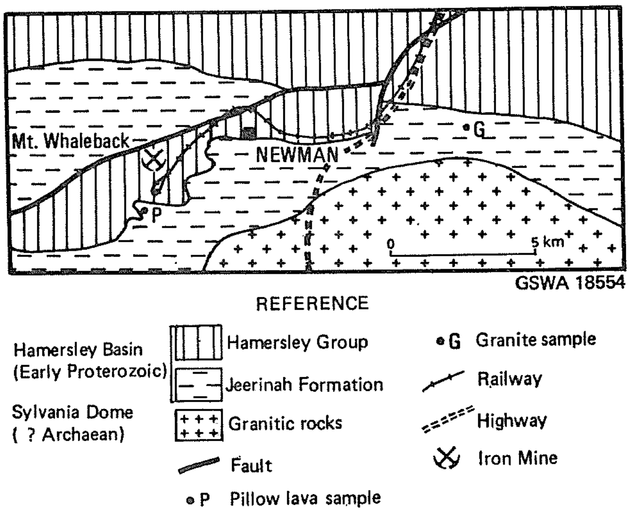


Figure 1 Plan of Newman area showing main geological units and sample localities.

MATERIAL ANALYZED

JEERINAH FORMATION BASALT

Field relationships

Samples of pillow basalt (30596 A–E) were collected from a ballast quarry 9 km southwest of Newman (Fig. 1). The quarry lies in the south limb of a syncline, so that the basalt, of which some 20 m stratigraphic thickness is exposed, is subhorizontal and not evidently deformed. The pillows range in exposed cross-sectional diameter between about 0·4 and 1·3 m, and their shapes clearly indicate that the sequence is right-way-up (Fig. 3A). Just south of the quarry the basal part of the Marra Mamba Iron Formation is exposed, dipping south-southwest at about 20°. There is thus little doubt that the basalt lies in the upper part of the Jeerinah Formation. It evidently represents part of the mafic material mapped and described by Daniels and MacLeod (1965) (who did not have the benefit of excavated exposures) as thick, persistent and concordant sills of dolerite

Petrography

Although the samples collected were the freshest available, all appeared bleached, aphanitic and structureless. The generally close spacing of joints made it impossible to obtain evidently fresh material. In spite of their unpromising macroscopic appearance the samples show no sign of recent weathering when observed in thin section. A close mesh of albite platelets up to 0·5 mm long is intimately intergrown with finer felted fibres of almost colourless amphibole, locally and patchily clouded with a dust of scattered sphene. A lesser proportion of pale chlorite also contributes to the groundmass, and subhedral grains of clinozoisite up to 1 mm across are evenly distributed through the rock.

GRANITE

Field relationships

Samples 54917A–G come from a bulldozed costean in a small inlier of the alkali granite exposed about 15 km east of Newman, apparently at a local high point in the basement relative to the surrounding Jeerinah Formation. Except for 54917F, which is of a cross-cutting aplite dyke, the samples are all of coarse-grained alkali granite. A prominent bed of podded chert a few metres above the granite/Jeerinah Formation contact has been identified elsewhere in the eastern Hamersley Basin at a position some 400 to 500 m below the top of the formation.

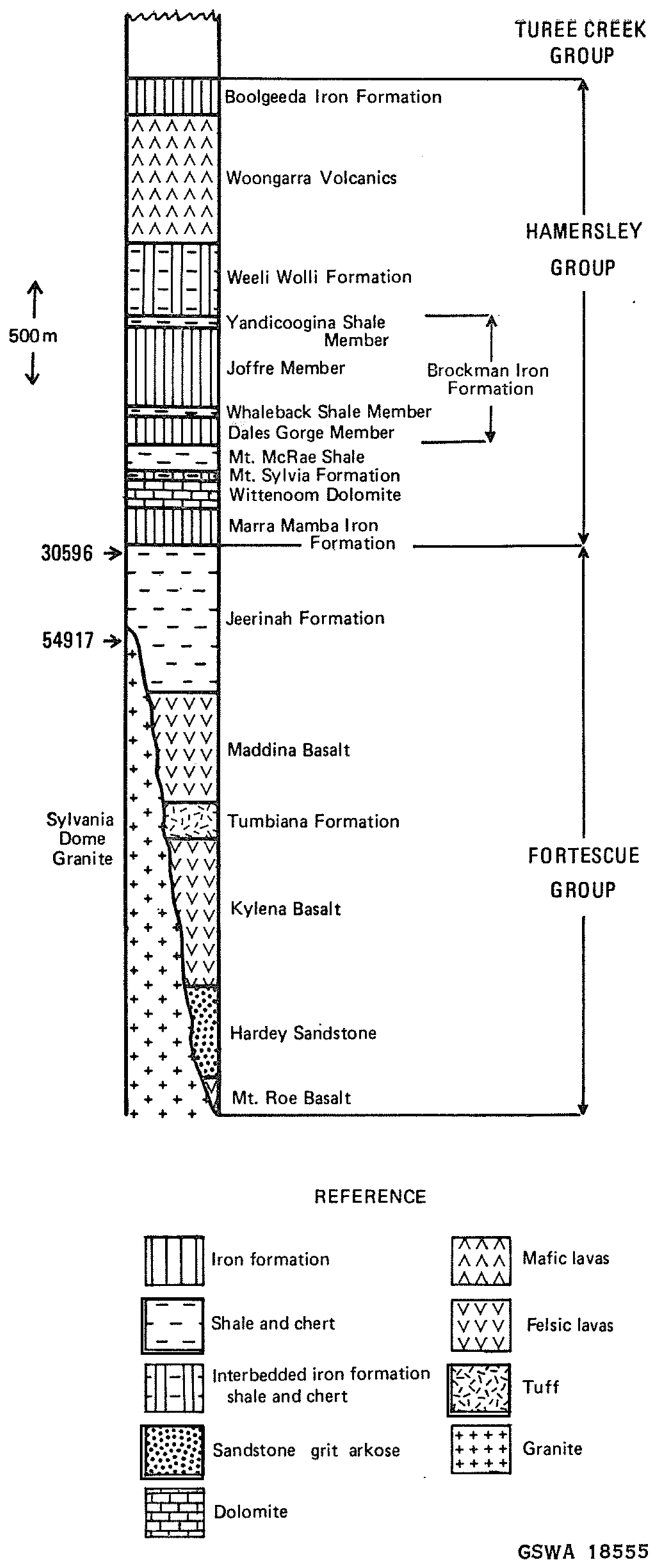


Figure 2 Stratigraphic column of Mount Bruce Supergroup (as redefined by Trendall, 1979) showing formations and members referred to in text. Principal lithologies only of each unit are indicated in the legend.

Near the granite, the shale, chert, and tuff beds of the Jeerinah Formation strike easterly and dip 30 to 40 degrees south. Converging chert beds indicate that there is a general thinning of the units towards the granite. However, the podded chert mentioned above is appreciably thickened and contorted near the granite, suggesting that it has slumped, or has been involved in local folding.

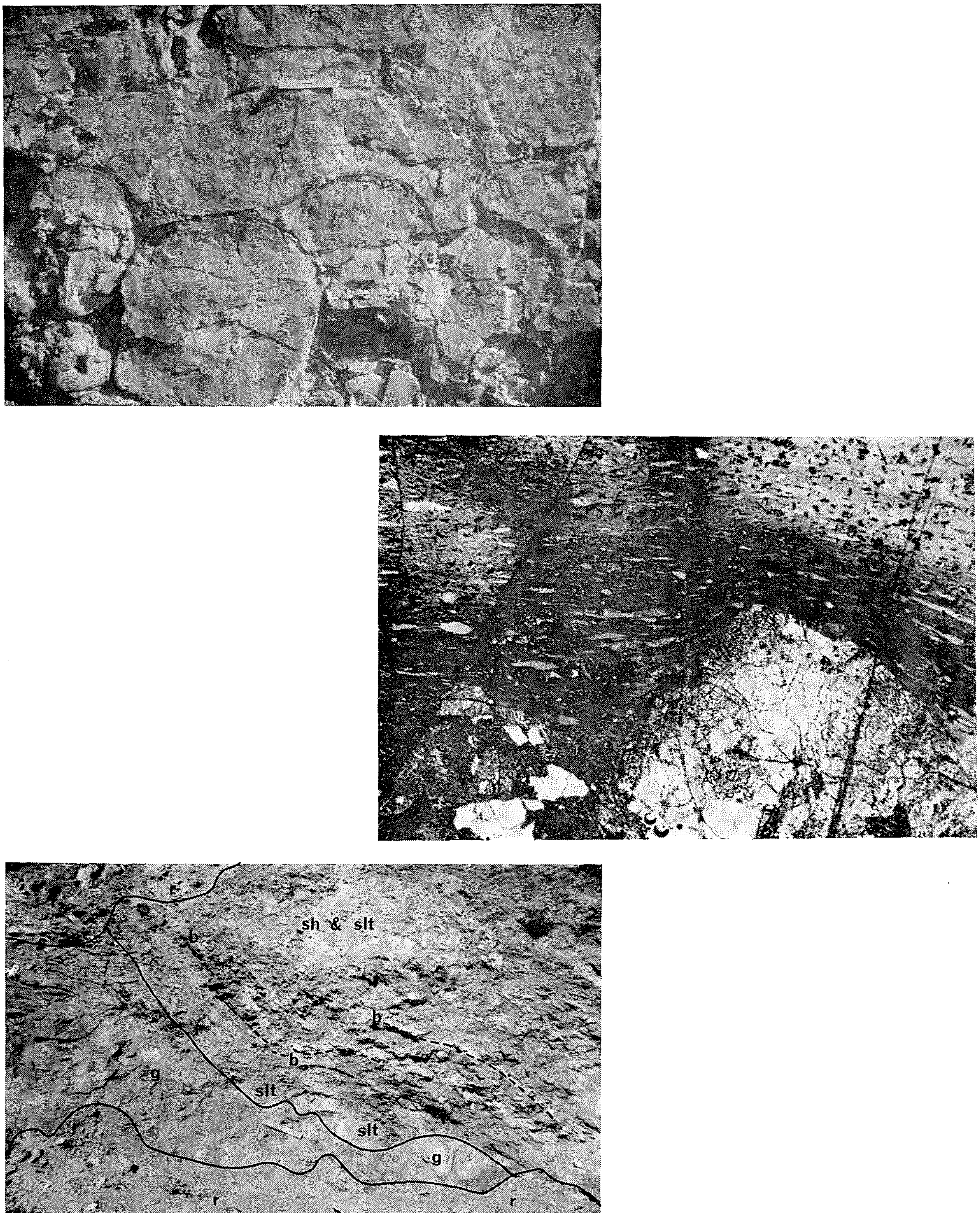


Figure 3 (A) Photograph of pillows in ballast quarry 9 km southwest of Newman. This pillow lava, in the upper part of the Jeerinah Formation, gives an anomalous Rb-Sr age of 1 487 m.y. The scale is 250 mm long.

(B) Photomicrograph of part of the shale/granite contact (see Fig. 3C) 15 km east of Newman. The shale laminations show compaction over a protruding phenocryst in the granite. The dark colour near the contact and along fractures is due to iron staining. The black rods of leucoxene after ilmenite are prominent in the upper right-hand corner. Lenticular clear patches, probably representing original mud pellets, show progressive deformation towards the contact. The prominent line near the right hand edge is a scratch on the slide (plane polarized light). GSWA 51757A x16·5.

(C) Photograph showing shale/granite contact at the site of sample 54917. Generally the bedding of the shale is parallel to the contact, but there are some irregularities in the granite surface. Hollows in this surface are filled with poorly bedded siltstone. The scale is 250 mm long. Letter symbols are as follows: r = rubble; g = granite; slt = siltstone; sh = shale; and b = bedding.

The shale/granite contact

The contact between the granite and Jeerinah Formation shale is well exposed in the costean. Apart from minor irregularities in the surface of the granite, the contact is parallel to the bedding of the shale (Fig. 3C). There is no decrease in grain size of the granite at the contact and no apparent contact metamorphic effects in the shale. No veins of granitic material cut the shale and there are no xenoliths of shale in the granite. Hollows in the granite contain slightly coarser silty material, but no well-defined basal arkose or conglomerate is present.

From this mainly negative field evidence it was concluded that the contact is an unconformity. However, as a further check for possible contact metamorphic effects in the shale, a number of thin sections were cut from across the contact and at varying distances from the granite. Sections cut through the contact show that the granite has been considerably altered, with much of the feldspar being destroyed; however, there is no suggestion of fine-grained chilling effects, and bedding seems to be draped over projecting grains in the granite (Fig. 3B). These factors confirm that the shale is in depositional contact with the granite.

Shale in contact with the granite is an almost cryptocrystalline mixture of phyllosilicates (probably sericite), dusty limonite, and presumed quartzofeldspathic minerals. Elongate pods, defined by their relative freedom from dusty iron-oxide, range from 0·15 mm to 1·0 mm long and are strongly oriented parallel to the contact with the granite. The pods probably represent clasts in the primary sediment. Within a few centimetres of the contact the degree of flattening of the pods increases with proximity to the contact.

Ilmenite, replaced largely by leucoxene, occurring as fine-grained stubby rods much coarser than the matrix, is very abundant in samples within a few centimetres of the contact with the granite, and in some samples at a greater distance. The rods have a weak preferred orientation parallel to the granite contact. Very fine phyllosilicates wrap around the ends of ilmenite grains. As the orientation of the ilmenite is much weaker than the orientation of the clasts, the ilmenite probably post-dates the clasts but predates the final deformation of the rock.

The possibility of the ilmenite being a contact-metamorphic mineral is discounted both on the textural evidence cited above, and the low metamorphic grade of the rock as a whole. Data presented by Best and Weiss (1964) indicated that in pelitic rocks contact-metamorphic ilmenite is associated with sillimanite and cordierite. Neither of these minerals was observed in the shale.

Petrography of the granite

The granite is a quartz-albite-microcline rock with microcline rather more abundant than quartz and albite. Mafic minerals have been replaced by very fine aggregates of chlorite and/or biotite. Relict shapes of the mafic aggregates indicate that amphibole as well as biotite was present. Apatite and zircon are the primary accessories, apatite being particularly prominent. Opaque and quasi-opaque minerals are mainly or wholly secondary and probably have replaced sphene.

The rock is coarse, hypidiomorphic inequigranular. Feldspars range from coarse to very coarse. Albite and, less perfectly, microcline, are euhedral against coarsely recrystallized quartz. Rarely, euhedral microcline forms sheaths around a euhedral core of albite. More commonly, euhedral albite grains are scattered in the larger microperthitic microcline grains. All feldspars are clouded with minute inclusions, perhaps in part chlorite. Epidote was not identified. Deformation and recrystallization are mild, limited mainly to quartz, though there are a few healed fractures in most samples, and feldspar has been substantially fragmented and recrystallized in one sample. Amphibole in a rock of this composition together with abundant apatite suggests that the granite has alkaline affinities.

A medium-grained, even-textured granophyric aplite cuts the granite. Much of the aplite is a vermicular intergrowth of quartz and feldspar around plagioclase and microcline grains. Mafic material present as biotite is rare.

EXPERIMENTAL PROCEDURES

The experimental procedures for Rb/Sr analyses used in this study were essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0·710 2 $\pm$ 0·000 1, normalized to a $^{88}Sr/^{86}Sr$ value of 9·375 2. The value of 1·42 x 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, was well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 1. Errors accompanying the data are at the 95 per cent confidence level. The Rb and Sr concentrations in each sample are also listed. However, these concentrations are only accurate to $\pm$7 per cent and the Rb/Sr ratios may not correspond exactly with the ratios which would be derived from the separate Rb and Sr values listed.

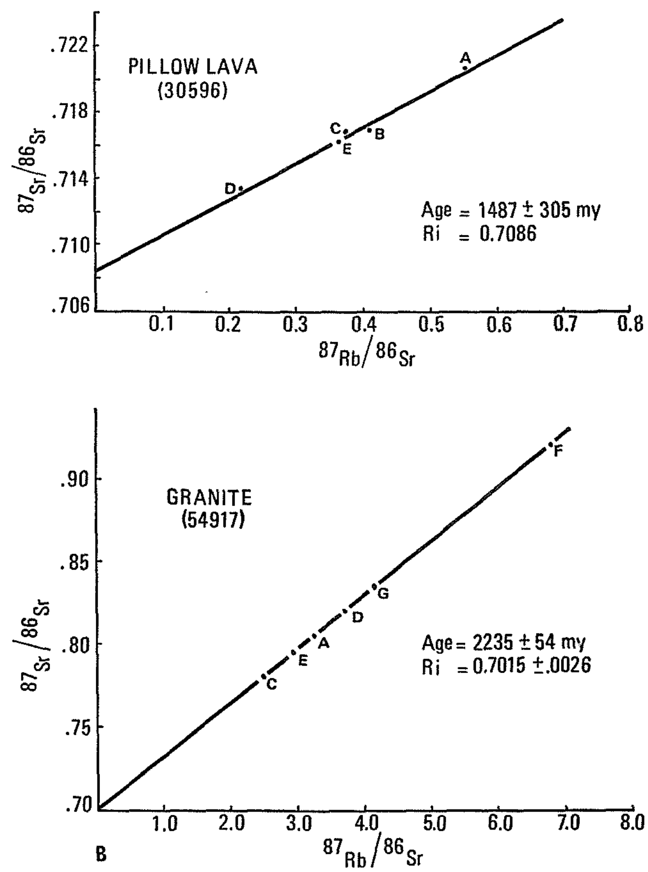
The data listed in Table 1 have been regressed using the least-squares programme of McIntyre and others (1966). The age and initial ratio of the alkali granite are 2 235 $\pm$ 54 m.y. and 0·701 5 $\pm$ 0·002 6 respectively. The mean square of the weighted deviates (MSWD) is 0·45, which indicates that the variations are within the range of experimental errors. The age and initial ratio of the Jeerinah lava are 1 487 $\pm$ 305 m.y. and 0·708 6 $\pm$ 0·001 7 respectively. The MSWD is 0·66, which is again within the range of experimental errors, the large range of possible error in age being due to the fact that only five samples with a limited range in Rb/Sr were available for analysis.

DISCUSSION

SIGNIFICANCE OF GRANITE AGE

The well-fitting isochron obtained from the granite samples would seem to support earlier estimates that deposition of the Mount Bruce Supergroup began at about 2 300 m.y. BP (Geol. Survey of Western Australia, 1975, p. 31). A discussion of the geochronological evidence for this estimate is given by Trendall and de Laeter (1972).

However, there is a body of later evidence which suggests that all components of the Mount Bruce Supergroup (as re-defined by Trendall, 1979) are appreciably older than 2 300 m.y. Such evidence includes: a Rb-Sr age of about 2 600 m.y. for shale from the Hardey Sandstone (Hickman and de



GSWA 18557

Figure 4 Isochrons from the Newman area.

(A) Five samples of pillow lava from near the top of the Jeerinah Formation (Samples 30596 A-D).

(B) Six samples of granite and cross-cutting aplite (F) from granite of the Sylvania Dome unconformably underlying the Jeerinah Formation (Samples 54917 A-F).

As discussed in the text, neither isochron is regarded as giving the primary igneous ages of the samples.

TABLE 1. ANALYTICAL DATA FOR JEERINAH PILLOW LAVA AND SYLVANIA DOME GRANITE

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Jeerinah pillow lava					
30596 D	9	124	0·075 6 ± 0·000 8	0·219 ± 0·002	0·713 37 ± 0·000 21
30596 E	15	112	0·127 ± 0·002	0·367 ± 0·004	0·716 32 ± 0·000 25
30596 C	14	105	0·129 ± 0·002	0·373 ± 0·004	0·716 85 ± 0·000 28
30596 B	14	100	0·142 ± 0·002	0·410 ± 0·005	0·717 07 ± 0·000 24
30596 A	10	52	0·192 ± 0·003	0·555 ± 0·006	0·720 59 ± 0·000 19
Sylvania Dome granite					
54917 C	170	200	0·86 ± 0·01	2·50 ± 0·03	0·782 15 ± 0·000
54917 E	195	195	1·01 ± 0·02	2·94 ± 0·04	0·796 34 ± 0·000
54917 A	190	170	1·12 ± 0·02	3·26 ± 0·04	0·805 96 ± 0·000
54917 D	190	150	1·27 ± 0·02	3·71 ± 0·05	0·821 68 ± 0·000
54917 G	190	135	1·42 ± 0·02	4·15 ± 0·05	0·835 29 ± 0·000
54917 F	170	75	2·30 ± 0·03	6·78 ± 0·09	0·919 98 ± 0·000

Laeter, 1977); a model lead age of about 2 700 m.y. from galena in a vein cutting the Kylena Basalt (Richards, 1977); a U-Pb age of 2 490 m.y. on zircons from the Dales Gorge Member of the Brockman Iron Formation (Compston and others, in prep.); an age of about 2 350 m.y. for intrusive dolerite within the Weeli Wolli Formation (Trendall and de Laeter, in prep.); and a minimum age of 2 400 m.y. for the Woongarra Volcanics (Compston and others, in prep.).

If this more recent geochronology is accepted, then the isochron obtained from the granite samples cannot be interpreted simply as the age of intrusion, giving the maximum age of the Jeerinah Formation. Other possible explanations for what appears to be a geologically significant isochron are therefore examined in turn.

1. The granite actually intrudes the Jeerinah Formation.

   The field and petrographic evidence described previously makes an intrusive relationship between granite and the Jeerinah Formation very unlikely.

2. The shale resting on the granite is not part of the Jeerinah Formation.

   The distinctive podded chert band forming part of the succession near the contact has been identified elsewhere in the eastern Hamersley Basin, where it is undoubtedly part of the Jeerinah Formation.

3. The isochron gives the age of metamorphism of the granite. Calculations using the relationship defining the $^{87}Sr/^{86}Sr$ ratio (Faure and Powell, 1972, p. 12) and assuming an average $^{87}Rb/^{86}Sr$ ratio of 3·0 for the granite give a crustal residence time of 35 m.y. for $R_i = 0{\cdot}701\,5$, or 95 m.y. for $R_i = 0{\cdot}704\,1$ (i.e. $0{\cdot}701\,5 + 0{\cdot}002\,6$). In either case the original (intrusive) age of the granite is still too young to be compatible with other geochronological results summarized above.

4. Sr isotopes in the granite have equilibrated with Proterozoic water of the Hamersley Basin.

   Although apparently fresh, the granite samples come from only a few metres below the unconformity. They have sufficient granulation of grain boundaries to suggest that they *may* have been permeated by water at the time when the Jeerinah Formation was deposited. It is possible that the Sr isotopes in the granite attained equilibrium with those in the permeating basin water. Veizer (1975) indicated that the $^{87}Sr/^{86}Sr$ ratio at about 2 235 m.y. BP was in the order of 0·702 0 to 0·703 5, figures not inconsistent with the R_i of $0{\cdot}701\,5 \pm 0{\cdot}002\,6$ found in the granite.

   If this hypothesis is correct, then the isochron gives the time at which the uplift of the Sylvania Dome led to final dewatering of the Hamersley Basin sediments in this area, allowing the granite to dry out and the isotopes to lose mobility.

SIGNIFICANCE OF BASALT AGE

For the reasons already given, the isochron age of 1 487 ± 305 m.y. obtained from the basalt samples certainly cannot be accepted as an extrusive age. An extensive regional "event" at about 1 700 m.y., during which Sr isotopes were redistributed, is well established elsewhere in an about the Hamersley Basin (Leggo and others, 1964; Trendall and de Laeter, 1972; Compston and others, in prep.; Trendall and de Laeter, in prep.), and this event has already been reported in the Newman area (Linley, 1975). It presumably corresponds with a period of metamorphism and folding, possibly related to the Ashburton Fold Belt (Gee, 1979). At present we accept the basalt isochron as an expression of this event.

ACKNOWLEDGEMENTS

We are pleased to acknowledge the co-operation of Mr. B. Willis and Mr. M. Kneeshaw of Mount Newman Mining Company Pty Ltd, who drew attention to the two exposures, made available a company bulldozer to assist with the sampling of the granite, and provided maps to help our geological interpretation of the geochronological results.

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Rb-Sr DATING OF GRANITIC ROCKS IN THE PEMBERTON AREA

by K. J. R. Rosman*, S. A. Wilde, W. G. Libby and J. R. de Laeter*

ABSTRACT

Rubidium-strontium isotope analysis of 37 samples from 7 localities in the Manjimup-Northcliffe-Walpole area of south-western Western Australia confirm the westward extension of the Proterozoic Albany-Fraser Province. In the vicinity of Northcliffe, the Proterozoic belt is at least 50 km wide and may extend farther northward. Model dates suggest that the Proterozoic rocks are primitive; that is, they were not derived within the crust from Archaean precursors.

INTRODUCTION

The Albany-Fraser Province is a Proterozoic mobile belt which extends around the southern margin of the Archaean Yilgarn Block. The Fraser Range section of the province, northeast of Ravensthorpe, has been the subject of several regional geochronological studies (Wilson and others, 1960; Arriens and Lambert, 1969; and Bunting and others, 1976). In the Albany area, several studies (Wilson and others, 1960; Turek and Stephenson, 1966; and Stephenson and others, 1977) have established the presence of Proterozoic rocks; however, their extension to the west and north has been in doubt. This doubt prompted the present reconnaissance study of the western sector of the province.

SAMPLES

Collection

A suite of samples was collected from each of seven areas, roughly constituting a north-south traverse of the suspected westward extension of the Albany-Fraser Province (Fig. 1). Each suite was assigned a number, and each sample within the suite was assigned a letter suffix. The location of each suite together with a brief description is shown in Table 1.

Suites 55810 to 55815 are outcrop samples collected by one of the authors (S.A.W.) in 1978. Sample 54161 F consists of a single diamond drill core segment, from Planet Mining Co. Drillhole DDH 14.

Co-ordinates of localities mentioned in the text are based on the 10 000 yard transverse mercator grid and were taken from the Pemberton (SI 50–10) 1:250 000 sheet.

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Description

Suite 55810: This suite of samples was collected from the Gibralter Quartz Monzonite (Walker, 1977; Wilde and Walker, 1979) which forms a discontinuous, curvilinear belt up to 100 km long (Fig. 1). The main sample site was 1·5 km northeast of Grevillea Fire Tower (4327 7916). The rock is variable, consisting chiefly of fine-grained quartz monzonite with scattered amphibolite xenoliths, and diffuse areas of coarse-grained material with scattered megacrysts of hornblende. There are also areas which are more gneissic. Sample 55810 F was collected 4·7 km east of Palgarup (4212 7760) from the south-west continuation of the quartz monzonite. The rock is even-grained with a strong lineation and weaker foliation.

Several samples have deep, dusky-green clinopyroxene, probably aegirine-rich, either as solitary grains or cores in mafic knots. These, together with microcline megacrysts, may antedate a prominent deformation event during which the other major minerals (feldspar, quartz, biotite and hornblende) were recrystallized. Garnet is present in sample 55810 E, which also has abundant clinopyroxene, very coarse sphene and prominent apatite.

Suite 55811: Poorly exposed migmatic rocks extend from Northcliffe northeast toward Quininup. They are inter-developed with granitic gneisses of uncertain affinities, which also outcrop further west.

The sample site was a creek bed, exhumed by the bursting of an earth dam, alongside the Wheatley Coast Road, 12·4 km north-northeast of Northcliffe (4162 7363). The earliest phase present is a fine- to medium-grained augen gneiss that varies from a compositionally layered variety to a more homogeneous variety with a streaky foliation. The gneiss is cut by veins and larger, more irregular, areas of even-grained adamellite. Veins of pegmatite, commonly bearing garnet, cut both the gneiss and the adamellite.

Under the microscope, protomylonitization obscures the distinct contrast between gneissic and isotropic phases observed in the field. Typically, abundant feldspar porphyroclasts are set in crystal-plastically deformed mortar, mainly quartz defining a flaser structure. Garnet, hastingsitic hornblende, together with failure of plagioclase to degrade from andesine, all suggest deformation at elevated temperature.

TABLE 1. LOCATION AND BRIEF DESCRIPTION OF SAMPLES

Sample Number	Locality Name	Location		Grid	Notes on individual samples
		Lat.	Long.		
54161	Yornup diamond corehole	34°05′	116°11′	4212 7760	*GNEISS* Biotite amphibolite
55810	Grevillea Fire Tower	34°04′	116°19′	4327 7916 (4212 7760)	*GIBRALTER QUARTZ MONZONITE* A. Typical fine-grained phase B. Fine-grained, leuco., gneissic variety C. Med. to coarse grained with hbld. megacrysts D. Coarse grained, marginal to gneiss E. Coarse grained, marginal to gneiss
55811	Northcliffe	34°32′	116°09′ 30″	4162 7363	*MIGMATITE* A. Fine-grained. compositionally layered gneiss with feldspar augen B. Mesocratic foliated adamellite with mafic schlieren C. Streaky augen gneiss D. Late pegmatite with clasts of earlier material E. Adamellite, coarser than B F. Late pegmatite
55812	Mount Chudalup	34°45′	116°04′	4076 7089	*ADAMELLITE* A–D & F. Typical E. Slightly weathered
55813	Windy Harbour	34°50′	116°01′	4005 6981	*GRANULITE* A. Melanocratic gneiss with lighter layers B. Ultramafic boudins in lighter material C. Leucrocratic felsic gneiss D. Pyroxene granulite E. Leucocratic granulite F. Leucocratic granulite G. Interlayered leucocratic/melanocratic gneiss
55814	Wainbup	34°47′	116°17′	4267 7007	*ADAMELLITE* A, D. Typical adamellite B, C. Adamellite with leucocratic veins E. Coarser adamellite F. Gneissic adamellite G. Strongly gneissic adamellite
55815	Walpole	34°57′	116°35′	4576 6865	*PORPHYRITIC GRANITE* A, D. Typical deformed porphyritic granite B, E. Mafic-rich variety C. Fine-grained variety

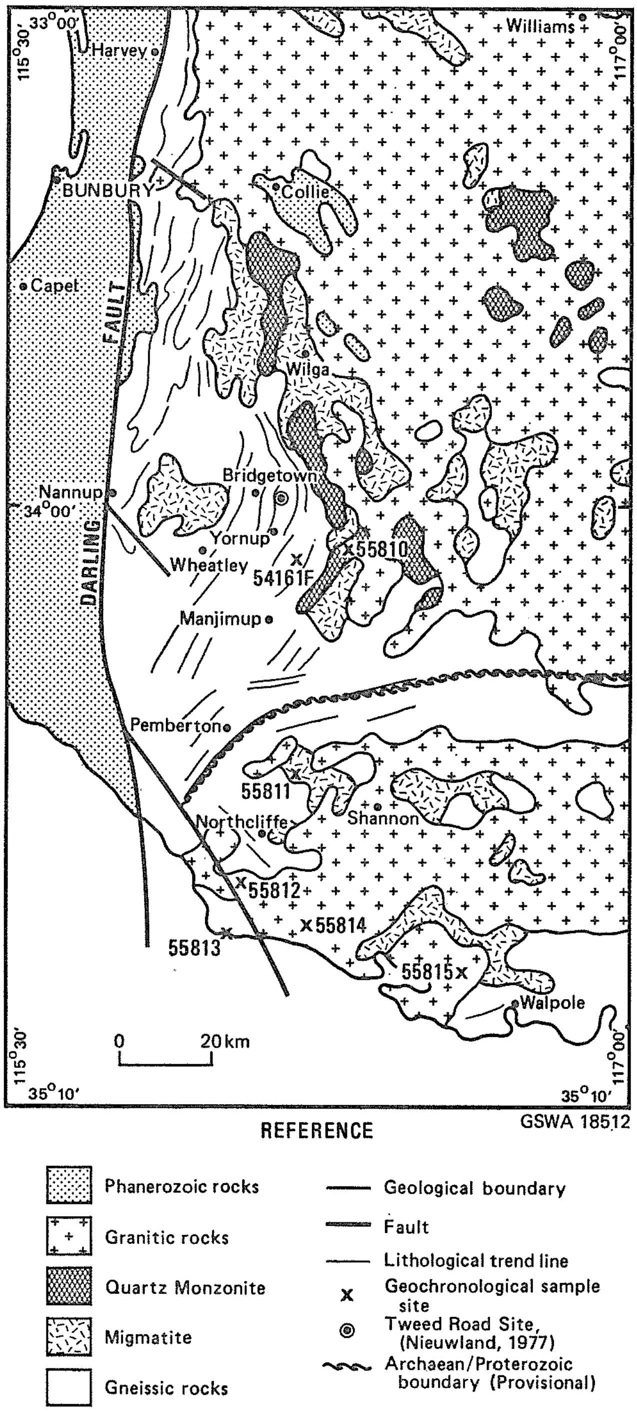

Figure 1 Sample localities and regional geology.

Suite 55812: Irregular areas of even-grained adamellite are associated with high-grade rocks of charnokitic affinity, granulite facies gneisses, and porphyritic granite south of Northcliffe. They are exposed as tree-covered knolls protruding from the coastal plain.

The sample site (4076 7089), where fresh rock had been exposed by blasting, is 1·2 km north-northwest of Mount Chudalup. The rock is a medium-grained, hornblende-bearing adamellite with a moderately strong cataclastic fabric.

Principal minerals are biotite, hornblende, quartz, microcline and calcic oligoclase. Deformed feldspar and mafic minerals are set in a mortar of quartz and shredded biotite.

Suite 55813: Granulite facies rocks are sporadically exposed between Windy Harbour and Mount Chudalup. The samples were collected from the foreshore at Windy Harbour (4005 6981). Units of felsic and mafic granulite are interlayered and there are also lenses and boudins of ultramafic composition, rich in both ortho- and clinopyroxene. Veins of orthopyroxene traverse the units, especially in the eastern parts of the exposure.

The mafic and ultramafic assemblages contain hornblende, clinopyroxene, hypersthene and plagioclase (samples 55813 A, B, and D). The intermediate phases (samples 55813 C and E) have quartz, oligoclase and hypersthene, with less biotite and minor microcline. Sample 55813 C contains quartz, oligoclase and perthite and is free of mafic minerals. Sample 55813 E is composed primarily of oligoclase antiperthite with quartz, about 5% hypersthene and very minor biotite.

Suite 55814: Even-grained adamellite is subordinate to the dominant porphyritic varieties in a large granitic area east of Northcliffe (Figure 1).

The even-grained adamellite was sampled from an exposure 24·5 km east of Windy Harbour (4267 7007) that was blasted during construction of Chesapeake Road.

Porphyroclasts of microcline and subordinate sodic oligoclase are set in a recrystallized, mylonitic, medium-grained matrix of quartz, feldspar, biotite, muscovite, and epidote.

Suite 55815: A body of coarse, even-grained to porphyritic granite forms an isolated area west of Walpole (Fig. 1). The porphyritic granite was sampled from blasted material along the South Coast Highway, 14·8 km west-northwest of Walpole (4576 6865).

All samples show some degree of cataclastic deformation, with slight rounding of microcline megacrysts and thorough recrystallization of quartz. Allanite is conspicuous in some samples and fluorite is abundant in samples 55815A and B.

Sample 54161*F*: The material was obtained from Planet Metals drill hole number DDH Y14 (4212 7760) sunk to test a nickel prospect near Yornup. The core was collected between 132·84 m and 133·22 m (depth from surface).

The rock is a medium-grained biotite amphibolite with minor quartz.

EXPERIMENTAL PROCEDURES

The experimental procedures used in this study were essentially the same as those described by Lewis and others (1975). The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured during this project was 0·710 2 ± 0·000 1, normalized to a $^{88}Sr/^{86}Sr$ value of 8·375 2.

RESULTS

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios as well as the calculated $^{87}Rb/^{86}Sr$ ratios are shown in Table 2. Errors accompanying the data are at the 95% confidence level. The Rb and Sr concentrations in each sample are also listed. However, these concentrations are only accurate to ± 7% 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 2 have been regressed using the least-squares programme of McIntyre and others (1966). The results of regression, based on a decay constant of 1·42 x 10^{-11} yr^{-1} (Steiger and Jäger, 1977), are shown in Table 3 together with model dates for each suite based on an assumed $^{87}Sr/^{86}Sr$ initial ratio of 0·700.

DISCUSSION

The only previous geochronological data directly applicable to this study is a date of 2 838 ± 200 m.y. obtained by Nieuwland (written communication, 1977) from layered gneiss at Tweed Road, 5 km southeast of Bridgetown (Fig. 1).

Five of the seven localities sampled in the present study provide useful geochronological data, although the small range in isotopic ratios creates large uncertainties in results obtained by the isochron "method". The two remaining localities fail to provide data which can be readily interpreted; plotted points from suite 55813 (Windy Harbour) are extremely scattered and 54161 F (Yornup drillcore) is an isolated sample with a low $^{87}Rb/^{86}Sr$ ratio.

Isochrons (Fig. 2) from suites 55811, 55812, 55814, and 55815 yield dates which range from 733 m.y. to 1 289 m.y., with little indication of progressive increase in age across the province (Fig. 1 and Table 3). However, model dates in Table 3 (calculated to mean $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ values for each suite) range less widely and show a systematic decrease from suite 55810 in the north to suite 55815 in the south. This gradient is consistent with southward decreasing dates within the Fraser Range section of the Albany-Fraser Province described by Bunting and others (1976). The assumed initial ratio of 0·700 assures that model dates generated are close to maximum ages if the system is geochemically closed. This analysis of maximum model dates strongly suggests that these rocks were not derived from Archaean precursors. Such a hypothesis would have to involve either the introduction of Rb into, or the selective removal of radiogenic Sr from, an immense volume of crust, or both.

TABLE 2. ANALYTICAL DATA FOR WHOLE ROCK SAMPLES FROM THE PEMBERTON SHEET

Sample	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
55810—					
B	79	700	0·113 ± 0·002	0·327 ± 0·004	0·715 15 ± 0·000 42
F	89	712	0·125 ± 0·002	0·362 ± 0·004	0·715 32 ± 0·000 12
E	130	1 000	0·129 ± 0·002	0·373 ± 0·004	0·715 32 ± 0·000 28
A	105	786	0·135 ± 0·002	0·391 ± 0·004	0·714 20 ± 0·000 15
D	127	768	0·166 ± 0·002	0·481 ± 0·005	0·719 43 ± 0·000 56
C	133	785	0·169 ± 0·002	0·489 ± 0·005	0·719 90 ± 0·000 31
55811—					
C	185	170	1·09 ± 0·01	3·17 ± 0·04	0·774 80 ± 0·000 19
B	238	216	1·09 ± 0·01	3·18 ± 0·04	0·765 25 ± 0·000 19
A	210	148	1·42 ± 0·02	4·13 ± 0·05	0·786 00 ± 0·000 19
D	328	205	1·59 ± 0·02	4·64 ± 0·05	0·795 05 ± 0·000 48
E	253	145	1·74 ± 0·02	5·09 ± 0·06	0·800 30 ± 0·000 27
55812—					
E	175	241	0·724 ± 0·008	2·10 ± 0·03	0·745 28 ± 0·000 29
A	180	225	0·796 ± 0·008	2·31 ± 0·03	0·749 96 ± 0·000 19
B	181	216	0·836 ± 0·009	2·43 ± 0·03	0·751 17 ± 0·000 20
F	177	235	0·843 ± 0·009	2·45 ± 0·03	0·751 22 ± 0·000 50
C	187	215	0·871 ± 0·009	2·53 ± 0·03	0·753 27 ± 0·000 25
D	196	217	0·903 ± 0·009	2·62 ± 0·03	0·755 53 ± 0·000 54
55813—					
D	1·5	250	0·006 ± 0·000 1	0·017 4 ± 0·000 5	0·707 86 ± 0·000 28
A	3·4	162	0·019 ± 0·000 2	0·055 ± 0·001	0·726 90 ± 0·000 31
E	33	300	0·108 ± 0·001	0·313 ± 0·004	0·726 17 ± 0 000·80
F	33	292	0·111 ± 0·001	0·322 ± 0·004	0·727 00 ± 0·000 32
G	35	230	0·153 ± 0·002	0·444 ± 0·005	0·744 49 ± 0·000 21
C	120	201	0·599 ± 0·007	1·75 ± 0·02	0·785 35 ± 0·000 80
B	30	36	0·835 ± 0·009	2·43 ± 0·03	0·754 78 ± 0·000 67
55814—					
A	221	166	1·33 ± 0·02	3·87 ± 0·04	0·775 11 ± 0·000 35
D	238	161	1·48 ± 0·02	4·33 ± 0·05	0·782 24 ± 0·000 72
E	226	149	1·52 ± 0·02	4·42 ± 0·05	0·783 74 ± 0·000 20
G	226	148	1·53 ± 0·02	4·45 ± 0·05	0·784 94 ± 0·000 24
B	235	152	1·54 ± 0·02	4·48 ± 0·05	0·782 67 ± 0·000 37
F	229	145	1·59 ± 0·02	4·64 ± 0·05	0·788 27 ± 0·000 33
C	256	152	1·69 ± 0·02	4·93 ± 0·05	0·790 26 ± 0·000 18
55815—					
C	344	148	2·32 ± 0·03	6·78 ± 0·07	0·827 17 ± 0·000 25
A	334	133	2·52 ± 0·03	7·37 ± 0·08	0·833 73 ± 0·000 25
D	361	142	2·55 ± 0·03	7·46 ± 0·08	0·833 79 ± 0·000 25
B	363	137	2·65 ± 0·03	7·77 ± 0·08	0·838 00 ± 0·000 39
E	375	135	2·78 ± 0·03	8·15 ± 0·09	0·840 59 ± 0·000 89
54161—					
F	8·5	410	0·021 ± 0·001	0·061 ± 0·000 8	0·706 50 ± 0·000 24

TABLE 3. PEMBERTON GEOCHRONOLOGY

	Regression age	Ri	Model	Model age	Assumed Ri
54161 F	....	....	....	....	....
55810	2 327 ± 1 624	·703 0 ± ·009 2	3	2 828	·700
55811	944 ± 246	·731 6 ± ·014	3	1 454	·700
55812	1 289 ± 258	·706 6 ± ·008 6	3	1 478	·700
55813	....	....	....	....	....
55814	1 047 ± 266	·717 3 ± ·016	2	1 316	·700
55815	733 ± 107	·756 2 ± ·010	2	1 252	·700

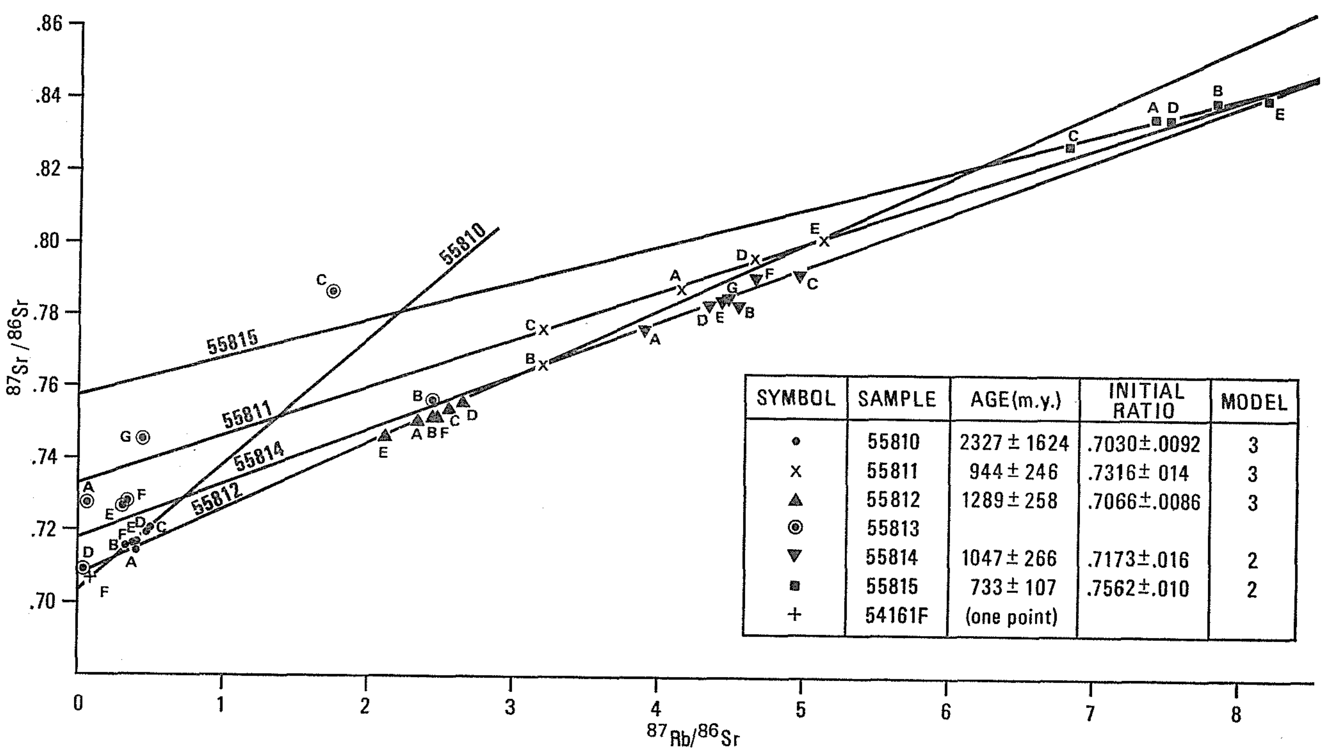

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Figure 2 Isochron plot of 37 whole-rock Rb-Sr analyses from the Pemberton map sheet.

It seems likely that suite 55810 (Gibralter Quartz Monzonite) from near Grevillea Fire Tower is Archaean. The model date is well within the Archaean, the sample site is near the better controlled Archaean site of Nieuwland (written communication, 1977), the site is within the area of north-south regional structural trends characteristic of the Archaean Yilgarn Block, and the isochron regression, though Early Proterozoic, includes Archaean dates well within the error limits.

Even assuming an Archaean age for the rocks at Grevillea Fire Tower, the location of the Archaean-Proterozoic boundary is not closely defined by isotopic dating. The location of the boundary shown on Figure 1 is the best current estimate based on geological and structural controls that are consistent with the Rb-Sr geochronology.

CONCLUSIONS

The reconnaissance Rb-Sr geochronological study in the Manjimup-Northcliffe-Walpole area has demonstrated that the Proterozoic Albany-Fraser Province extends westward from Albany at least to within 20 km of Pemberton and has a north-south extent of more than 50 km.

The lack of evidence for Archaean precursors, combined with the apparent high initial $^{87}Sr/^{86}Sr$ ratios of some rocks suggest that the area had a complex Proterozoic history. This history includes a period of gneissification, formation of migmatite, and emplacement of even-grained and porphyritic granitic rocks.

A fuller evaluation of geochronological and geological data will accompany the report from further studies, now in progress, which are aimed at more precisely defining both the nature and position of the Archaean-Proterozoic boundary.

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PERMIAN AMMONOIDS FROM THE CARNARVON BASIN – A REVIEW

by A. E. Cockbain

ABSTRACT

Permian ammonoids are known from the following units in the Carnarvon Basin (listed in ascending order): Callytharra Formation (*Metalegoceras* n. sp. Glenister and Furnish, *Mescalites* sp., *Svetlanoceras irwinense*); Wooramel Group—Cordalia Sandstone (*Pseudoschistoceras simile*), Billidee Formation (*Neocrimites* sp., *Bamyaniceras* sp.); Byro Group—Coyrie Formation (*P. simile*, *Neocrimites* sp., *Bamyaniceras* n. sp. Glenister and Furnish), Mallens Sandstone (*Bamyaniceras* sp.), Bulgadoo Shale, Quinnanie Shale and Wandagee Formation (*Bamyaniceras australe*), Nalbia Sandstone (*B. australe*, *Paragastrioceras wandageense*, *Daubichites goochi*); Kennedy Group—Coolkilya Sandstone (*D. goochi*, *Agathiceras applanatum Popanoceras* sp. indet. Glenister and Furnish). On the basis of the ammonoids the Callytharra Formation is Sterlitamakian (late Sakmarian), the Wooramel Group and Byro Group up to the Nalbia Sandstone are Baigendzhinian (mid Artinskian), and the Nalbia Sandstone to Coolkilya Sandstone are Roadian (late Artinskian or early Kungurian). All the ammonoid-bearing units are Early Permian in age.

INTRODUCTION

Ammonoids have been accorded a high value in the study of Permian stratigraphical palaeontology. It is unfortunate, therefore, that so few are known from Australia. In the eastern states about 60 specimens belonging to 2 genera are known, while in Western Australia, apart from the several hundred *Juresanites jacksoni* from the Holmwood Shale of the Perth Basin, only about 100 specimens belonging to 12 genera have been reported.

Some 40 specimens in 10 genera occur in the Carnarvon Basin. Nearly all have been described in 3 publications (Teichert, 1942, 1944, Glenister and Furnish, 1961) and their stratigraphical distribution has been documented by (among others) Glenister and Furnish (1961) and Condon (1967). However, because of different interpretations of the stratigraphy, particularly those of Teichert (e.g. 1957) and Condon (e.g. 1954) it is uncertain what formations some of the ammonoids came from. Now that the Geological Survey has completed the remapping of the basin it is an appropriate time to review the stratigraphical distribution of the Permian ammonoids, report some new records, and assess the age of the units in the light of these data. The stratigraphic nomenclature used follows the recent revision of Hocking and others (1980).

PERMIAN STAGE NAMES

There has been little uniformity in naming the major subdivisions of the Permian. Ross and Ross (1979) give a useful outline of Permian stratigraphical palaeontology. The accompanying table (Table 1) is an attempt to summarise and compare several of the more recently proposed schemes. The Geological Survey currently uses the subdivision of McWhae and others (1958). However, a more detailed subdivision for the Lower Permian (the part with which this paper is concerned) is needed and I follow Furnish (1973) with the substitution of Baigendzhinian in place of Leonardian for the middle substage of the Artinskian. The major difference between this scheme and that currently adopted by the Survey (see Table 1) is in the abandonment of the Kungurian Stage; early Kungurian rocks are here called Roadian and placed in the late Artinskian. The status of the Kungurian Stage is the subject of considerable debate (see, for example, Waterhouse, 1976). Ross and Ross (1979) refer to the "Kungurian facies" and point out that many of the Kungurian evaporite beds in the Urals may prove to be Artinskian, Ufimian or Kazanian in age. The few Kungurian ammonoids are similar to those of the Artinskian (Glenister and Furnish, 1961).

TABLE 1. COMPARISON OF VARIOUS SUBDIVISIONS OF THE PERMIAN

McWHAE AND OTHERS 1958 AND CURRENT GSWA USAGE	GLENISTER AND FURNISH, 1961		MOORE, 1965 NORTH AMERICA	MOORE, 1965 EUROPE	NASSICHUK AND OTHERS, 1965		FURNISH, 1973		WATERHOUSE, 1976		DICKENS, 1976	ROSS AND ROSS, 1979
TRIASSIC	TRIASSIC		TRIASSIC	TRIASSIC	TRIASSIC		TRIASSIC			GRIESBACHIAN	TRIASSIC	TRIASSIC
								CHANGHSINGIAN	DORASHAMIAN	OGBINAN		
TATARIAN	DZHULFIAN		OCHOAN	TATARIAN	DZHULFIAN		DZHULFIAN	CHHIDRUAN		VEDIAN	TATARIAN	DZHULFIAN
								ARAKSIAN		BAISALIAN		
								AMARASSIAN	DJULFIAN	URUSHTENIAN		
KAZANIAN		CAPITANIAN		KAZANIAN		CAPITANIAN				CHHIDRUAN	KAZANIAN	
					GUADALUPIAN		GUADALUPIAN	CAPITANIAN	PUNJABIAN	KALABAGHIAN		
	GUADALUPIAN		GUADALUPIAN							SOSNOVIAN		KAZANIAN
KUNGURIAN		WORDIAN		KUNGURIAN		WORDIAN		WORDIAN	KAZANIAN	KALINOVIAN	UFIMIAN	
									KUNGURIAN	IRENIAN		
						Not Named		ROADIAN		FILIPPOVIAN	KUNGURIAN	
		BAIGENDZHINIAN			ARTINSKIAN	BAIGENDZHINIAN				KRASNOUFIMIAN		
ARTINSKIAN	ARTINSKIAN		LEONARDIAN	ARTINSKIAN			ARTINSKIAN	LEONARDIAN	BAIGENDZINIAN	SARGINIAN	ARTINSKIAN	ARTINSKIAN
		AKTASTINIAN				AKTASTINIAN		AKTASTINIAN		AKTASTINIAN		
	SAKMARIAN				SAKMARIAN	STERLITAMAKIAN		STERLITAMAKIAN	SAKMARIAN	STERLITAMAKIAN		SAKMARIAN
						TASTUBIAN		TASTUBIAN		TASTUBIAN		
SAKMARIAN			WOLFCAMPIAN	SAKMARIAN			SAKMARIAN			KURMAIAN	SAKMARIAN	
	ASSELIAN				ASSELIAN			ASSELIAN	ASSELIAN	USKALIKIAN		ASSELIAN
										SURENAN		

Where the columns are vertically subdivided the units shown are stages and substages except in the Furnish, 1973 column where series and stages are shown.
Thick horizontal line marks boundary between Lower and Upper Permian except in the Waterhouse, 1976 column where Lower, Middle and Upper Permian are indicated.

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TABLE 2. STRATIGRAPHIC DISTRIBUTION OF PERMIAN AMMONOIDS OF THE CARNARVON BASIN

STRATIGRAPHIC UNIT		*Mescalites* sp.	*Svetlanoceras irwinense* (Teichert and Glenister), 1952	*Metalegoceras* n.sp. Glenister and Furnish, 1961	*Pseudoschistoceras simile* Teichert, 1944	*Neocrimites* sp.	*Bamyaniceras* sp.	*Bamyaniceras* n.sp. (Glenister and Furnish), 1961	*Bamyaniceras australe* (Teichert), 1942	*Paragastrioceras wandageense* Teichert, 1942	*Daubichites goochi* (Teichert), 1942	*Agathiceras applanatum* Teichert, 1944	*Popanoceras* sp. indet. Glenister and Furnish, 1961	AGE SUBSTAGE
KENNEDY GROUP (PART)	COOLKILYA SANDSTONE										UWA 20504–07 35777	UWA 21451	CPC 1775	
BYRO GROUP	BAKER FORMATION													ROADIAN
	NALBIA SANDSTONE								UWA 20145	UWA 20142	UWA 20507*			
	WANDAGEE FORMATION								CPC 1763 F21628 UWA 20144 a,b 20509,10					
	QUINNANIE SHALE								UWA 23237					
	CUNDLEGO FORMATION													
	BULGADOO SHALE								CPC 1764 F21629 A—D					
	MALLENS SANDSTONE						×							BAIGEND -ZHINIAN
	COYRIE FORMATION				UWA 21326–29 21440 39097,98	CPC 1777		CPC 1765 F21627 GSWA F11077/1						
WOORAMEL GROUP	BILLIDEE FORMATION					CPC 1776	×							
	MOOGOOLOO SANDSTONE													
	CORDALIA SANDSTONE				GSWA F10163									
	CALLYTHARRA FORMATION	×	×	CPC 1770										STERLIT-AMAKIAN

* Teichert (1942) recorded this as *Pseudoschistoceras* sp.

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UWA University of Western Australia Geology Department specimen number
CPC Bureau of Mineral Resources Commonwealth Palaeontological Collection
GSWA Geological Survey of Western Australia specimen number

STRATIGRAPHICAL DISTRIBUTION IN THE CARNARVON BASIN

The stratigraphical distribution of Permian ammonoids in the Carnarvon Basin is summarized in Table 2. Distribution details and remarks on the age significance of the species (where appropriate) are given below. The genera are dealt with in alphabetical order. Specimen numbers are those of the University of Western Australia Geology Department (UWA), the Bureau of Mineral Resources Commonwealth Palaeontological Collection (CPC) and the Geological Survey of Western Australia (GSWA).

Agathiceras applanatum Teichert

1944 *Agathiceras applanatum* Teichert: p. 85, pl. 17 figs. 6, 7, text fig. 1.
1961 *Agathiceras applanatum* Teichert; Glenister and Furnish: p. 696, pl. 80 figs. 6, 7, text fig. 5A.

OCCURRENCE

Coolkilya Sandstone. UWA 21451 (the only known specimen) came from ". . . 300 yards [274 m] east of the mouth of the southeastern gully of Wandagee Hill (23°50½'S, 114°27½'E) . . . about 90 feet [27 m] below the top of the Coolkilya Greywacke (Teichert, 1952, p. 130), where it is associated with *Pseudogastrioceras goochi*" (Glenister and Furnish, 1961, p. 697).

REMARKS

A long ranging genus with limited biostratigraphical value.

Bamyaniceras australe (Teichert)

1942 *Propinacoceras australe* Teichert: p. 224, pl. 35 figs. 2–7, text fig. 3C.
1961 *Propinacoceras australe* Teichert; Glenister and Furnish: p. 691, pl. 78 figs. 6–13, text fig. 3A.

OCCURRENCE

1. Nalbia Sandstone. UWA 20145 (holotype) came from the ". . . same horizon as *Helicoprion davisii* and *Paragastrioceras wandageense* (Teichert, 1952, p. 130), on the west limb of the syncline north of Wandagee Hill, 1 475 yards [1 349 m] north of the Wandagee-Minilya road . . ." (Glenister and Furnish, 1961, p. 693). As discussed under *P. wandageense* this locality is in the Nalbia Sandstone.

2. Wandagee Formation. UWA 20144 a, b, 20509, 20510 from the Wandagee Formation, ". . . east limb of syncline exposed along the Minilya River west of Coolkilya Pool . . . also . . . 1 1/3 miles [2·1 km] south of Coolkilya Pool, just south of an important E.W. fault" (Teichert, 1942, p. 226). CPC 1763, F21628 from "1·5 miles [2·4 km] on a bearing of 52° from Curdamuda Well and 2·6 miles [4·2 km] on a bearing of 278° from Cundlego Well, at 23°44'06"S, 114°24'49"E . . ." respectively ". . . approximately 300 feet [91 m] above the base and . . . 190 feet [58 m] above the base of the Wandagee Formation" (Glenister and Furnish, 1961, p. 693).

3. Quinnanie Shale. UWA 23237 ". . . from the Quinnanie Shale near Coolkilya Pool on the south bank of the Minilya River" (Glenister and Furnish, 1961, p. 693).

4. Bulgadoo Shale. CPC 1764 ". . . from 136 feet [42 m] below the top of the Bulgadoo Shale at a point 2·0 miles [3·2 km] on a bearing of 151° from Donnelly's Well at 24°05'03"S, 115°05'36"E" (Glenister and Furnish, 1961, p. 693). CPC F21629A-D ". . . from near the base of the Bulgadoo Shale . . . 7·6 miles [12·2 km] on a bearing of 231° from Moogooloo Trig (K58), at 23°38'42"S, 114°38'33"E" (Glenister and Furnish, 1961, p. 693).

The species is also known from the Liveringa Formation (Canning Basin).

REMARKS

Glenister and Furnish (1961, p. 693) included the species in the *Propinacoceras knighti* group. According to Glenister (pers. comm. 1979) ". . . true *Propinacoceras* is exclusively Wordian, and . . . the homeomorphic group of *P. knighti* is confined to the Artinskian (through Roadian) . . . All Australian occurrences formerly referred to *Propinacoceras* should now be assigned to *Bamyaniceras*" (Termier and Termier, 1970). *B. australe* is the commonest Permian ammonoid in the Carnarvon Basin.

Bamyaniceras n. sp. (Glenister and Furnish)

1961 *Propinacoceras* n. sp. Glenister and Furnish: p. 694, pl. 78 figs. 14, 15, text fig. 4.

OCCURRENCE

Coyrie Formation. CPC 1765 and F21627 are from the same locality as the Coyrie Formation *Neocrimites* (i.e. 24°06′06″S, 115°08′04″E). GSWA F11077/1 came from float collected below the outcrop of the carbonaceous shale near the base of the Coyrie Formation at 25°06′10″S, 115°08′45″E.

Bamyaniceras sp.

OCCURRENCE

1. Billidee Formation. Condon (1954, p. 62) recorded *Propinacoceras* from a unit labelled "75 feet [23 m] of soft dark-grey laminated coarse-grained siltstone" from what is now the upper part of the type section of the Billidee Formation (see Condon, 1967, fig. 79 wherein the record is repeated). Condon (1967, p. 97) also lists the genus from "4½ miles [7·2 km] west of Moogooree homestead and ½ mile [0·8 km] north of the Moogooree/Donnellys Well road" in the Billidee Formation.

2. Mallens Sandstone. Dickins (1956) identified *Propinoceras* sp. ind. (sic) from the "Bogadi Greywacke" (now called Mallens Sandstone, see Hocking and others (1980)) from "4 3/8 miles [7·0 km] on a bearing of 059° from Keogh Hill, near base". Condon (1967, p. 152) also gave this record and adopted the same erroneous spelling.

Daubichites goochi (Teichert)

1942 *Pseudogastrioceras goochi* Teichert: p. 227, pl. 35 figs. 12–16.
1942 *Pseudogastrioceras* sp. Teichert: p. 229, pl. 35 fig. 8 (see Glenister and Furnish, 1961, p. 721).
?1960 *Pseudogastrioceras fortieri* Harker *in* Harker and Thorsteinsson: p. 75, pl. 24 figs. 3–5, pl. 25 figs. 1–3 (see Nassichuk, 1970, p. 84)
1961 *Pseudogastrioceras goochi* Teichert; Glenister and Furnish: p. 719, pl. 84 figs. 1–4, pl. 85 figs. 1, 2, 5–7, text figs. 14A–C.
1970 *Daubichites goochi* (Teichert); Nassichuk: p. 82.

OCCURRENCE

1. Coolkilya Sandstone. UWA 20504 (holotype) came from "Somewhat above the basal beds (approximately *Thamnopora-Cleiothyridina* zone) of the *Linoproductus* stage of the Wandagee series, near mouth of northeastern gully of Wandagee Hill, on fence dividing Shed and Mundagan Paddocks, Wandagee Station" (Teichert, 1942, p. 228). Glenister and Furnish (1961, p. 721) pointed out that the holotype came from about 107 m above the base of the Coolkilya Sandstone (sensu Teichert, 1952). Other specimens (UWA 20505, 20506, 35777) came from the holotype horizon and higher; the highest specimen occurred about 27 m below the top of the formation and was associated with *Agathiceras applanatum* (Glenister and Furnish, 1961, p. 722).

2. Nalbia Sandstone. Glenister and Furnish (1961, p. 721) assumed that the holotype was the lowest known specimen of *D. goochi*. However, UWA 20507, which is the *Pseudogastrioceras* sp. of Teichert (1942) was placed in *D. goochi* by Glenister and Furnish. The specimen came from the same horizon as *Paragastrioceras wandageense* which is considered to be in the Nalbia Sandstone (see below).

The species is also known from the Lightjack Member of the Liveringa Formation (Canning Basin).

REMARKS

Glenister and Furnish (1961, p. 721) considered this species to be close to *Pseudogastrioceras roadense* from the Guadalupian. However, Nassichuk (1970) placed *goochi* in the genus *Daubichites* and suggested that it is possibly conspecific with *D. fortieri* from the Assistance Formation (Canada) which is Filippovian (i.e. Roadian) in age (see Waterhouse, 1976, p. 126; Nassichuk and others, 1965, p. 3). While *Daubichites* is currently known only from the late Early Permian (Roadian), *Pseudogastrioceras* is Dzhulfian in age (Nassichuk, 1970).

Mescalites sp.

OCCURRENCE

Callytharra Formation. The specimens came from G. A. Thomas' locality S662 from which *Svetlanoceras irwinense* (see below) is also recorded.

REMARKS

W. M. Furnish, who identified the specimens states (in correspondence to G. A. Thomas, 1976) "The second species in S662 is a gonioloboceratid, belonging in a family that characterizes the Upper Pennsylvanian, but is represented in the Permian by a single genus, *Mescalites* (Furnish & Glenister, 1971, Smithsonian Contribution to Paleobiology 3, p. 301–312). Previously, *Mescalites* was known only through the type species *M. discoidale* from the Bursum Formation of New Mexico. We are fairly confident of an Asselian age for the ammonoid bed in the Bursum. However, the Australian specimens differ in several respects from *M. discoidale* and are not conspecific with it: they may even warrant a new genus. Consequently, they cannot be utilized for age refinement".

Metalegoceras n. sp. Glenister and Furnish

1954 cf. *Metalegoceras*: Condon: p. 52.
1954 *Metalegoceras* cf. *M. clarkei* Miller; Thomas and Dickins: p. 219.
1961 *Metalegoceras* n. sp. Glenister and Furnish: p. 709, pl. 83 fig. 9, text fig. 9.
1973 *Metalegoceras* n. sp. Glenister and Furnish; Glenister and others: p. 1040.

OCCURRENCE

Callytharra Formation. The only known specimen (CPC 1770) came from ". . . near the base of the Callytharra Formation . . . (24°31′23″S, 115°18′20″E) approximately 8 miles [13 km] from Lyons River Homestead on a bearing of 344°, and 3·6 miles [5·8 km] from Mead's Bore on a bearing of 112°" (Glenister and Furnish, 1961, p. 709).

REMARKS

Glenister and others (1973) remark that the specimen can be related to the late Sakmarian *Metalegoceras australe* and possibly to the Artinskian genus *Sverdrupites*.

Neocrimites sp. Glenister and Furnish

1961 *Neocrimites* sp. Glenister and Furnish: p. 729, pl. 83 figs. 7, 8, pl. 86 figs, 4, 5, text fig. 16B.

OCCURRENCE

1. Coyrie Formation. CPC 1777 came from ". . . 4·95 miles [8·0 km] on a bearing of 119° from Donnelly's Well and 4·7 miles [7·6 km] on a bearing of 236° from Moogooree Homestead, at 24°06′06″S, 115°08′04″E . . . 485 feet [148 m] above the base of the Coyrie Formation" (Glenister and Furnish, 1961, p. 730). This is the same locality from which *Propinacoceras* n. sp. Glenister and Furnish (1961) was recorded. Coyrie Formation as used by Glenister and Furnish was the unit erected by Condon in 1954, the lower part of which was subsequently separated as the Billidee Formation. A level ". . . 485 feet [148 m] above the base of the Coyrie . . ." corresponds to somewhere within the ". . . 145 feet [44 m] thin-bedded soft dark siltstone . . ." of Condon (1967, fig. 102) which is the unit containing *Propinacoceras* in Condon (1954, p. 61) and is near the base of the Coyrie Formation as presently recognized.

2. Billidee Formation. CPC 1776 came from "2 000 feet [610 m] north of the Mt Sandiman Woolshed (24°23′22″S, 115°16′44″E) . . . Coyrie Formation, at about one-third the outcrop width from the base of the unit" (Glenister and Furnish, 1961, p. 730). This is presumably the same record as Condon's (1967, p. 97) "Ammonoidea (Glenister, 1961): *Neocrinites* sp." (sic) from "Five hundred yards [457 m] north of Mount Sandiman woolshed". This outcrop is now mapped as Billidee Formation (Condon, 1967, p. 97).

REMARKS

Glenister and Furnish (1961, Table 3) show the genus as not being recorded from pre-Baigendzhinian strata.

Paragastrioceras wandageense Teichert

1942 *Paragastrioceras wandageense* Teichert: p. 226, pl. 35 figs. 9, 10.
1961 *Paragastrioceras wandageense* Teichert; Glenister and Furnish: p. 713, pl. 84 figs. 5–7, text fig. 10A.

OCCURRENCE

Nalbia Sandstone. UWA 20142—the holotype and only extant specimen (a second one recorded by Teichert having been subsequently lost according to Glenister and Furnish (1961, p. 714))—came from "Two hundred yards [183 m] north of Wandagee-Minilya Road, west side of syncline, north of Wandagee Hill. In lower part of the *Linoproductus* stage of the Wandagee series, at approximately the same horizon as *Helicoprion davisii*" (Teichert, 1942, p. 227). Glenister and Furnish (1961, p. 714) argued that the holotype came from the lower part of the Coolkilya Sandstone, however, Condon (1954, p. 87) considered the outcrop to belong to the Nalbia Sandstone and recent mapping by the Survey confirms this interpretation. There is no reason to believe that *P. wandageense* occurs in the Baker Formation as implied by Condon (1967, p. 184).

REMARKS

The genus is not known in post-Artinskian strata (Ross and Ross, 1979).

Popanoceras sp. indet. Glenister and Furnish

1961 *Popanoceras* sp. indet. Glenister and Furnish: p. 725, pl. 83 fig. 10.

OCCURRENCE

Coolkilya Sandstone. CPC 1775 came from "0·45 miles [724 m] on a bearing of 103° from Wandagee Hill Trigonometrical Station, at 23°50′02″S, 114°27′05″E . . . 230 feet [70 m] below the top of the Coolkilya Greywacke as this formation is defined by Condon (1954) . . ." (Glenister and Furnish, 1961, p. 725).

REMARKS

The specimen is poorly preserved, although Glenister and Furnish (1961, p. 725) suggest "... relationship with advanced species of *Popanoceras* . . .". The genus is not recorded from post-Artinskian strata (Nassichuk, 1970).

Pseudoschistoceras simile Teichert

1944 *Pseudoschistoceras simile* Teichert: p. 88, pl. 17 figs. 1–5, text fig. 4.
1961 *Pseudoschistoceras simile* Teichert: Glenister and Furnish; p. 711, pl. 83 figs. 1–6, text fig. 8F.

OCCURRENCE

1. Coyrie Formation. UWA 21326 (holotype), 21327, 21328, 21329, 21440, 39097, 39098 all came from ". . . mud flat ¼ to ½ mile [400–800 m] south of Barrabiddy Dam, Wandagee Station" (Teichert, 1944, p. 89); 23°57′S, 114°31′E (Glenister and Furnish, 1961, p. 712). The formation at this locality was considered by Teichert (1944) and Glenister and Furnish (1961) to be the Barrabiddy Member of the Bulgadoo Shale. However, Condon (1967, p. 131) argued that, following the drilling of the nearby Quail 1 well, the unit was more likely to be Coyrie Formation. Recent mapping supports this (R. M. Hocking, pers. comm. 1979).

2. Cordalia Sandstone. GSWA F10163 came from the type section of the Cordalia Sandstone, northeast of Round Hill at 23°21′00″S, 114°39′00″E.

REMARKS

According to Teichert (144, p. 84) "The accompanying fauna gives no definite clue, and deductions as regards the possible age . . . can only be made with great reservations". On the other hand, Glenister and Furnish (1961, p. 687) point out that "The only species of *Pseudoschistoceras* known from outside of Australia is *P. gigas* (Smith), which occurs in the Baigendzhinian Bitauni beds of Timor". They go on to say that *P. simile* has a more advanced suture than the Timor species. It should be noted that Waterhouse (1976) considers the brachiopods from the Bitauni beds to indicate a post-Baigendzhinian age while acknowledging that ammonoid workers prefer a Baigendzhinian age (by contrast, earlier he (Waterhouse, 1970) raised the possibility that the beds could be lower Artinskian). The balance of evidence suggests that *P. simile* is no older than Baigendzhinian.

Svetlanoceras irwinense (Teichert and Glenister)

1952 *Uraloceras irwinense* Teichert and Glenister: p. 21, pl. 4 figs. 2–7.
1961 *Uraloceras irwinense* Teichert and Glenister; Glenister and Furnish: p. 715, pl. 84 figs. 8–11, text figs. 11A, 12.
1976 *Uraloceras* (*Svetlanoceras*) *irwinense* Teichert and Glenister; Thomas: p. 319.

OCCURRENCE

Callytharra Formation. The species came from G. A. Thomas' locality S662 which is 8·2 km on a bearing of 225° from Coondoo Outcamp, Bidgemia station (lat. 23°52′39″S, long. 115°31′20″E). This outcrop is in the lower part of the formation (G. A. Thomas, pers. comm. 1979).

The species was previously known only from the Holmwood Shale in the Perth Basin.

REMARKS

The species was identified by G. A. Thomas. W. M. Furn ish who also examined the material, states (in correspondence to G. A. Thomas, 1976) "By itself, *S. irwinense* indicates only a Sakmarian (Asselian-Sterlitamakian) assignment".

AGE SIGNIFICANCE

The oldest ammonoid-bearing formation in the Carnarvon Basin is the Callytharra Formation, from the lower part of which *Mescalites* sp., *Metalegoceras* n. sp. and *Svetlanoceras irwinense* are recorded. Of these species, *Mescalites* sp. is of unknown significance, *Metalegoceras* n. sp. is ". . . compatible with either a late Sakmarian or an Artinskian age" (Glenister and Furnish, 1961, p. 686) while *S. irwinense* suggests a Sakmarian age for the formation.

Previous workers have taken the abundant brachiopods and molluscs in the Callytharra Formation to indicate a correlation with the Nura Nura Member of the Poole Sandstone (Canning Basin) which Teichert (1942) and Thomas and Dickins (1954) considered to be early Artinskian on the basis of the ammonoids. However, Glenister and Furnish (1961, p. 686) pointed out that the presence of advanced *Propopanoceras* (*P. ruzhencevi*) means that the Nura Nura Member can be no younger than late Sakmarian (Sterlitamakian). Condon (1967) accepted an Artinskian age for the Callytharra Formation following Teichert (1942) and Thomas and Dickins (1954), while more recent authors (e.g. Playford and others, 1975) have followed Glenister and Furnish in considering the unit to be late Sakmarian. Webster (1977) has recently stated that the formation is Artinskian without giving any reasons. The presence of *S. irwinense* and *Metalegoceras* n. sp. in the lower part of the Callytharra Formation now provides direct evidence for a late Sakmarian age for at least part of the unit.

The overlying Cordalia Sandstone, the basal formation of the Wooramel Group, contains *Pseudoschistoceras simile*, which it is argued above, suggests an age no older than Baigendzhinian (mid Artinskian). *Neocrimites* sp. from the Billidee Formation suggests a Baigendzhinian age for this the uppermost formation of the Wooramel Group. Hence the Wooramel Group as a whole is Baigendzhinian. Consequently, the unconformity between the Callytharra Formation and the Wooramel Group (van de Graaff and others, 1977) may represent the Aktastinian (early Artinskian). Contrary to this interpretation, Waterhouse (1976) believes the Wooramel Group itself to be Aktastinian, mainly on the evidence of the brachiopods.

Brachiopod and molluscan faunas in the Wooramel Group are best developed in:

1. The Jimba Jimba Calcarenite Member of the Billidee Formation (Condon, 1967),
2. shelly horizons within the Billidee Formation (R. M. Hocking, pers. comm.; see Cockbain, 1979); and
3. the "basal siltstone member of the One Gum Formation" (Konecki and others, 1958). This unit also occurs in B.M.R.8 (Mount Madeline) borehole (Dickins, *in* Mercer, 1967, p. 17) where Condon (1967) considers it to correlate with the Jimba Jimba Calcarenite Member. Stratigraphically it occurs above a sandstone ("Nunnery") and below a siltstone ("One Gum") and hence is in an equivalent position to the Jimba Jimba Calcarenite Member.

The faunas from all these horizons in the Wooramel Group are essentially the same and are very similar to that of the Callytharra Formation. Although Dickins (1963) established two faunal stages in the Callytharra–Wooramel sequence —Stage B from the Callytharra Formation and Stage C from the Wooramel Group—both Runnegar (1969) and Waterhouse (1970) recognize only one fauna at this level, Runnegar's Fauna II and Waterhouse's *Stepanoviella-Taeniothaerus* fauna. Dickins (1963, p. 20) admitted that his Stage C was "... marked by the absence rather than the presence of a marine fauna". The *Stepanoviella-Taeniothaerus* fauna occurs in the Callytharra Formation, the Wooramel Group, and the Nura Nura Member as well as in the Beckett and Fossil Cliff Members of the Holmwood Shale (Perth Basin). Ammonoids from these units range in age from Tastubian (mid Sakmarian, Beckett Member) to Baigendzhinian (mid Artinskian, Billidee Formation at the top of the Wooramel Group). From this it can be concluded that the *Stepanoviella-Taeniothaerus* fauna has a fairly long time range and occurs at a number of shelly horizons, often of limited extent, and hence cannot be used for detailed biostratigraphic correlation.

Most of the Byro Group, with *Neocrimites* and *Bamyaniceras australe*, is Baigendzhinian (mid Artinskian). The Nalbia Sandstone contains *Daubichites goochi* which suggests a Roadian (late Artinskian) age. The highest ammonoid-bearing unit, the Coolkilya Sandstone, contains *Agathiceras applanatum*, *Popanoceras* sp. indet. and *D. goochi*. Glenister and Furnish (1961, p. 725) considered the horizon from which *Popanoceras* came to be of early Guadalupian (Late Permian) age and they believed their Lower-Upper Permian boundary to lie between the uppermost bed with *Paragastrioceras* and the lowest occurrence of *goochi*. However, with the revision of the ammonoid occurrences presented here and the assignment of *goochi* to the early Permian genus *Daubichites*, it seems that the whole of the Coolkilya Sandstone is Lower Permian—a possibility forseen by Glenister and Furnish (1961, p. 688).

CONCLUSIONS

A reassessment of the stratigraphical distribution of Permian ammonoids in the Carnarvon Basin shows that only Early Permian species are present. The oldest ammonoid-bearing unit, the Callytharra Formation, is Sterlitamakian (late Sakmarian) and the overlying Wooramel Group is Baigendzhinian (mid Artinskian). The unconformity between the two units may represent all or part of the Aktastinian. The Byro Group is Baigendzhinian up to the Nalbia Sandstone which, together with the Coolkilya Sandstone of the Kennedy Group, is Roadian (late Artinskian). The age of the pre-Callytharra and post-Coolkilya beds cannot be established on the basis of ammonoids.

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