GEOLOGICAL SURVEY
of
WESTERN AUSTRALIA

ANNUAL REPORT 1975

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1975

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

By Authority: WILLIAM C. BROWN, Government Printer

1976

54809/7/76

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1975

CONTENTS

REPORTS

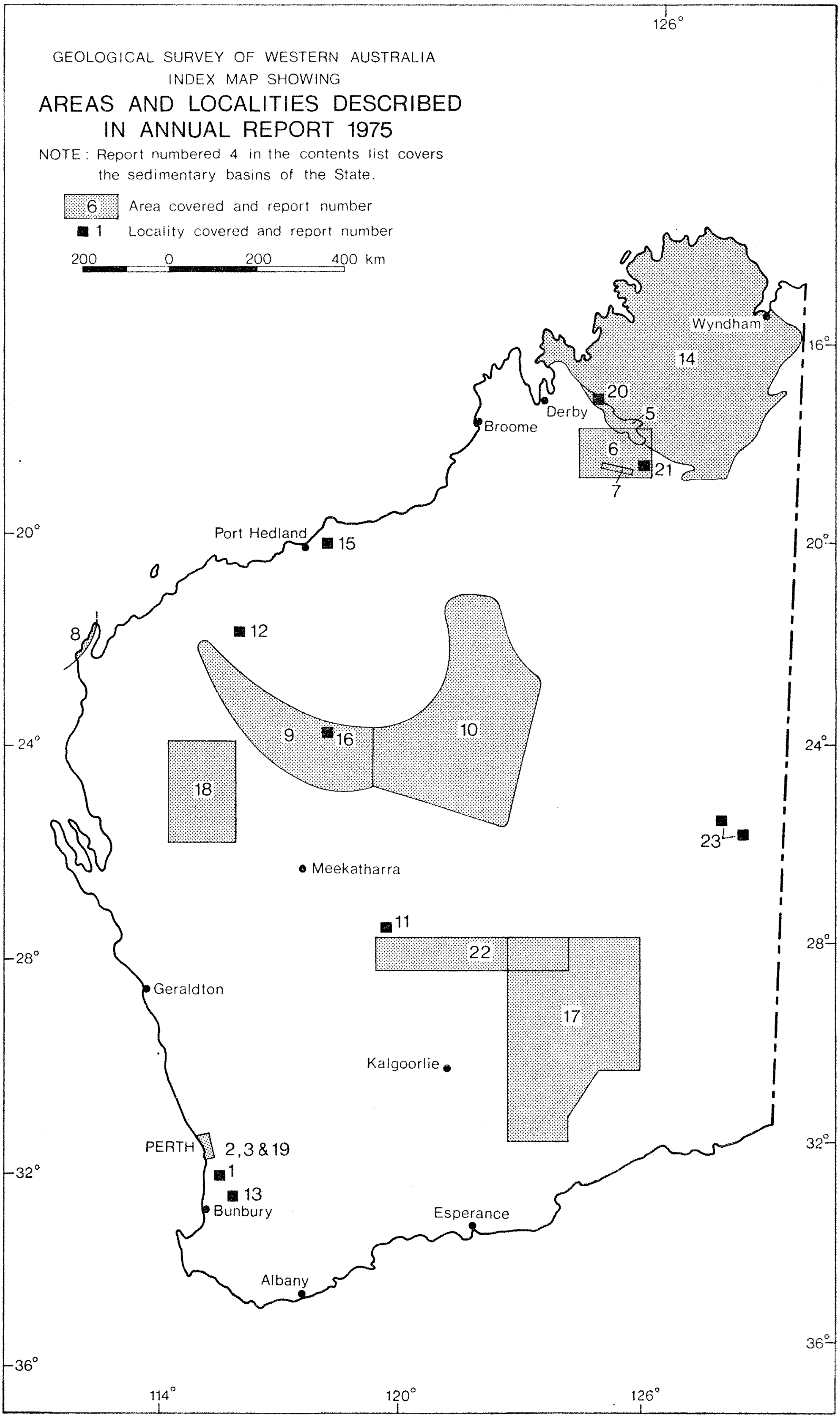


Figure 1. Index map showing areas and localities described in Annual Report for 1975.

LIST OF FIGURES

DIVISION IV

•

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1975

•

Under Secretary for Mines:

My report for 1975 on the activities of the Geological Survey of Western Australia, together with selected reports on investigations and studies made for departmental purposes, are submitted for the information of the Honourable Minister for Mines.

INTRODUCTION

The downward trend in exploration which was so evident during the two previous years, continued in 1975 due to the lack of an encouraging minerals policy from the Commonwealth Government. The amount of general exploratory work done by companies still interested has been on a greatly reduced scale, while the rate of work on promising prospects has been on a restricted scale.

Financial statistics do not show the full extent of this decline in expenditure on exploration as they are not adjusted for the high inflation rate which in itself has seriously affected exploration. A better assessment of the marked decrease in activity can be obtained from the amount of land taken up for exploration and the amount of work reported.

In exploration for minerals, other than iron ore and gold, the granting of new temporary reserves in the last three years shows the run down of activity.

1973	182 granted
1974	47 granted
1975	20 granted

Reports on the results of exploration, submitted to the Department under requirements of the Mining Act, decreased from 1 188 in 1974 to 685 in 1975.

A similar situation prevails for oil exploration both on and offshore, where the number and total depth of wells drilled and the length of seismic work continued to decline substantially.

	Total wells drilled	Total metreage	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	2 737

While exploration has been greatly reduced there have been several new interesting finds of mineralization but these require more investigation before any announcement regarding their potential can be made.

Iron ore exploration has continued without any new major finds being reported. Test parcels of Marra Mamba-type iron ore have been shipped to Japan from Mining Area C and Marandoo, but neither company concerned has yet received a contract. The Broken Hill Pty. Co. Ltd. announced that it would proceed to develop the Deepdale deposits.

Bauxite exploration remains dormant. Alwest has satisfactorily concluded an agreement with the Commonwealth Government on environmental problems. Pacminex, the operator, has withdrawn from a consortium which had planned to develop bauxite deposits in the Chittering area north of Perth. No activity has been reported on the Mitchell Plateau deposit.

Nickel exploration has continued throughout the State in a dilatory manner. The companies concerned with the Forrestania area continue to report promising drill intersections. The mine at Carr Boyd closed as the deposit proved to be uneconomic.

At Eneabba, Jennings Mining Ltd. and Allied Minerals are producing heavy minerals, and Western Titanium is establishing a plant. A plant is also being constructed by W.M.C. Mineral Sands Pty. Ltd. at Jurien Bay. Very little exploration for new deposits is being undertaken.

Some exploration for uranium has continued, despite the fact that the Yeelirrie deposit remains undeveloped while waiting for Commonwealth Government approval to develop the prospect.

Drilling at Golden Grove continues and 13.5 million tonnes of ore averaging 3.95 per cent copper and some zinc have been delineated. Some interesting copper/gold mineralization has been reported from drilling near Kundip.

Exploration is continuing on the lead occurrences located in Devonian limestone in the Kimberley.

While the established gold mines are experiencing operational difficulties under the present economic conditions, several smaller mines are operating in the Yilgarn.

The rapid decline in exploration for oil and gas is shown in the table above. The total length of holes drilled decreased by 65 per cent and there was a 74 per cent decrease in total length of land and marine seismic surveys.

There were two discoveries of significance. The first was the follow-up hole to Barrow Deep No. 1 drilled by Wapet on Barrow Island. This hole, Biggada No. 1, located several gas sands similar to those in the original hole, which await production testing.

The second was at Tidepole No. 1 well, drilled on an untested structure close to the Goodwyn field. In Triassic sands a net pay zone of 102 m, indicating 17 m of oil, was discovered and the well was completed as a gas/condensate/oil discovery.

There is an urgent need, as stated last year, for a change to a policy which will encourage further oil exploration.

A lecture evening was given at Laverton followed by a three-day excursion onto the Duketon and Sir Samuel 1 : 250 000 Sheet areas. Despite the general run down in exploration, approximately 63 persons attended.

A helicopter was used for regional mapping by the Survey for the first time. As a result of good planning and dedicated work by the field geologists, a large area of desert country was mapped, which included the Precambrian rocks on the Tabletop, Runton, Gunanya, Trainor, and portion of the Buller Sheet areas.

This Branch has pioneered microfilming of geological information in Australia. Priority has been given to microfilming of data on surrendered oil exploration permits to facilitate release of this information to interested parties, who are able to purchase relinquishment information packages on 35 mm positive film. Technical difficulties, firstly with the process camera operation and secondly with production of subsequent copies, as well as the inconvenience of camera location remote from Mineral House, have delayed release in some cases. A further large body of information contained in company reports on mineral exploration will also be microfilmed to reduce storage problems.

STAFF

It is with regret that the death of two senior officers is recorded.

Mr. George H. Low, who had devoted the whole of his working geological life to this Survey, collapsed and died suddenly on 1st April, 1975. During his 25 years service he had worked in many parts of the State and his major works on coal, gypsum, iron ore, and copper are recorded in the Survey's publications. Latterly he was involved in oil geology and is co-author of a bulletin on the Perth Basin at present in press. The Survey lost a loyal and sincere officer.

Mr. Alan A. Gibson joined the Survey at the beginning of 1972 as a senior geologist. Unfortunately he suffered ill health soon afterwards and retired because of this in June 1975 and passed away on 3rd October, 1975. During his relatively short time with the Branch he demonstrated his sincerity and dedication by his continual perseverance in his position. It was a pity that he was not with us longer in order to pass on to younger geologists more of his wealth of experience.

While vacancies have occurred in the professional positions, they have been filled satisfactorily. There is still considerable movement amongst sub-professional officers of the General Division.

Lionel Fimmell, who joined the Survey in 1946 as a laboratory assistant, retired in September 1975. For the whole of his service he has been in charge of the Laboratory which has expanded to include many new techniques. He made a major contribution to the Survey during his 29 years of service with his ability and willingness to assist with all problems.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Butcher, B. P., B.Sc. (Hons.) Dip.Ed.	Geologist L1	18/2/75
Hirschberg, K. J. B., Ph.D. (Germany)	Geologist L1	21/2/75
Lewis, I. H., B.Sc. (Hons.)	Geologist L1	7/4/75
Denman, P. D., B.A. (Hons.) M.A.Geol.	Geologist L2	21/4/75
Crank, K. A., B.Sc.	Geologist L3	15/7/75

Promotions

Backhouse, J.	Geologist L2	6/1/75
Barnett, J. C.	Geologist L2	6/1/75
Hill, W. B.	Geologist L2	6/1/75
Williams, S. J.	Geologist L1	25/4/75
Hirschberg, K. J. B.	Geologist L2	17/9/75
Harley, A. S.	Geologist L2	26/9/75

Retirement (ill health)

Gibson, A. A.	Geologist L3	4/6/75

Transfer Out

Sanders, C. C.	Geologist L2	2/7/75

Deceased

Low, G. H.	Geologist L3	1/4/75

CLERICAL AND GENERAL

Appointments

Pettigrew, D. C.	Geological Assistant	16/5/75
Walker, I. W., B.Sc. (Hons.)	Geological Assistant	16/5/75
Maczurad, M. N.	Technical Assistant	22/5/75
Wells, R. W.	Core Librarian	18/8/75
Graham-Sutton, P. B.	Geological Assistant	20/8/75
Hind, P.	Assistant Librarian	1/9/75
McManus, C. H.	Clerk	24/10/75
Emery, L. S.	Technical Assistant	1/12/75
Whiskin, M. K.	Laboratory Assistant	1/12/75

Promotions

Williams, G. T.	Technical Officer	22/8/75
Williams, G. T.	Laboratory Technician	10/10/75

Resignations

Dawson, H. G.	Technical Assistant	21/2/75
Bontemps, T. H.	Geological Assistant	14/3/75
Rankin, P. J.	Geological Assistant	1/5/75
Rettig, H. F.	Core Librarian	6/6/75
Wakeham, J. I.	Assistant Librarian	22/8/75
Dowling, N. R.	Technical Assistant	22/8/75
Blundell, C. D.	Geological Assistant	10/10/75

Transfers Out

Veitch, R. J.	Clerk	24/10/75

Retirement

Fimmell, L. H.	Laboratory Technician	2/9/75

ACCOMMODATION

Although the Branch has had very good accommodation in Mineral House since 1971, the area allocated has gradually become inadequate. This is due to additional staff, growth in library, additional storage required for company exploration reports, and the establishment of a microfilm library with the necessary readers and printers.

There being no area available within Mineral House, it has been necessary to obtain additional office accommodation some 800 m west of Mineral House in Adelaide Terrace. Some 20 geologists are to be housed in this new office but it will be inconvenient as they will have to commute to Mineral House for administrative, library, and laboratory services.

OPERATIONS

HYDROGEOLOGY AND ENGINEERING GEOLOGY DIVISION

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

Hydrogeology

The aggregate depth drilled throughout the State for groundwater resource exploration during the year was just over 18 000 m. This is in excess of any previous annual figure since the inception of Commonwealth financial assistance for the purpose.

Twenty bores were drilled in the Canning Basin to a maximum depth of 965 m. The bores were designed to study separately both the confined and unconfined aquifers, and complete the present programme of exploration. Although the final evaluation of groundwater resources awaits the collection of hydrographic and further hydraulic data from test pumping, there is no doubt that a large water resource has been proved to exist in this area.

Studies have continued in the Millstream area of the Fortescue River to define the extent and storage characteristics of the calcrete used for the West Pilbara water supply. There have been five special core holes and 18 exploration bores drilled as far east as Weelumurra. The continued expansion of Port Hedland water supply has necessitated further drilling along the De Grey River. The eight bores drilled will aid the layout design of a production field to be drilled in 1976.

Deep drilling in the Perth Basin has continued on the new Moora-Grey cross section where the total depth drilled was 2 367 m.

A major part of the exploratory drilling programme of the Metropolitan Water Board has again been directed to the evaluation of the shallow unconfined aquifers both to the north of Perth at Pinjar and Mirrabooka, and also to the south at Lake Thompson and Jandakot. In all, 116 bores have been drilled to an aggregate depth of over 5 329 m. Two sites at Woodmans Point have also been drilled to explore the deep pressure water aquifers and a further two bores at Whitfords were drilled into the shallow pressure water aquifers to provide stratigraphic and hydrological information. A network of bores has been left available for long-term operation.

Investigation of the Perth Basin shallow aquifers has continued at Joondalup, where eight bores complete that programme.

A new project has been started near Bunbury. Twenty-two bores have been drilled to a maximum depth of 120 m to test the aquifers from which the town water supply is drawn.

A major regional hydrogeological survey of the Albany area has been completed as an aid to future water supply planning both for Albany and other townships in the region. Reports are being prepared.

Further drilling has been completed for interdepartmental studies of the hydrological effects of bauxite mining and the woodchip industry, by Alcoa and the Mines Department respectively. A substantial body of hydrographic, water salinity, and salt storage data has been collected as a result of this work.

Members of the public and other government departments continue to make substantial use of the advisory facilities available to satisfy the increasing demands of small townships, stations, farms, and small holdings. Considerable progress has been made with the preliminary studies required for setting up a state-wide network of monitoring bores required for the Commonwealth-sponsored water quality monitoring programme.

Engineering Geology

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

Department of Public Works:

(a) Yule River proposed dam site—geological mapping, geophysics, and drilling as a preliminary investigation.

(b) Dogger and Gregory Gorges, Fortescue River—continued comparative study of these sites—preliminary reports being prepared.

(c) Port Denison breakwater—geological mapping and drilling of proposed quarry sites.

Metropolitan Water Board:

(a) Wungong Dam—this is now under construction, and geological mapping in the foundation area is continuing.

(b) North Dandalup River proposed dam site —geological mapping, geophysics, and exploratory drilling and report written.

(c) South Canning proposed dam site, Canning River—additional geological mapping, geophysics, and exploratory drilling.

(d) Beenyup Tunnel—geological mapping, experimental refraction seismic work and drilling along the tunnel line, and preparation of a report.

(e) Wungong proposed tunnel—preliminary geological mapping as an aid to selection of the most satisfactory route for the tunnel. Report prepared.

W.A. Government Railways: Geological advice given to aid the selection and development of quarry sites in the Walkaway and the Worsley areas.

SEDIMENTARY (OIL) DIVISION

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

The evaluation and collation of data submitted by petroleum companies continued. Although exploration reached its lowest level for some 12 years during 1975, the amount of petroleum administrative work by the Division increased considerably because of the large volume of information to be processed in data packages submitted by companies on the expiry or surrender of permits. A majority of permits held in the State reached the end of their initial terms during the year and many were renewed over reduced areas.

Mapping of the Carnarvon Basin began during the year, and the Onslow, Yanrey, and Ningaloo 1:250 000 Sheets were completed. Compilation of seismic maps covering the land area of the basin and the continental shelf between 23° and 29°S is in progress.

The Canning Basin mapping project was continued in conjunction with the Bureau of Mineral Resources. The Sahara, Percival, Rudall, Tabletop, Ural, Wilson, Runton, Morris, and Ryan 1:250 000 Sheets were mapped during the year.

REGIONAL GEOLOGY DIVISION

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

Regional mapping of the Precambrian portion of the State for publication on a scale of 1:250 000 continued. Progress is shown on Figure 2.

Field mapping of the Gunanya, Trainor, Buller, Robinson Range, and the Precambrian of Tabletop and Runton Sheets was completed.

Mapping on the following sheets is progressing towards completion in 1976: Rudall (80 per cent), Stanley (10 per cent), Kingston (90 per cent), and Southern Cross (60 per cent).

Work continues on the bulletin on the area covered by the Kalgoorlie and Esperance 1:1 000 000 Sheets.

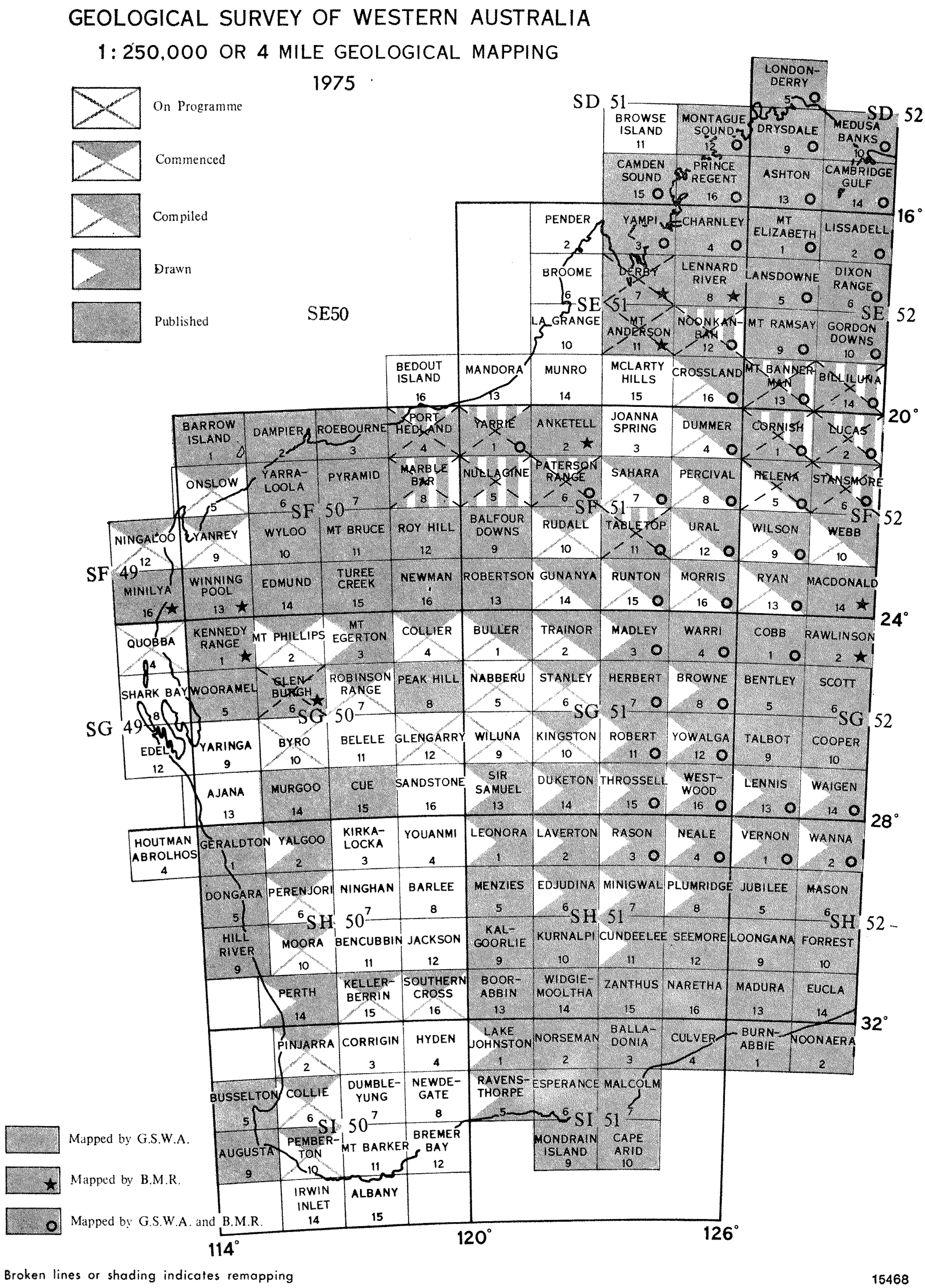


Figure 2. Progress of 1 : 250 000 or 4-mile geological mapping at end of 1975.

MINERAL RESOURCES DIVISION

J. G. Blockley (Supervising Geologist), J. D. Carter (Senior Geologist), J. L. Baxter, A. H. Hickman, S. L. Lipple, S. A. Wilde, and W. B. Hill.

The Precambrian portion of the Port Hedland Sheet was remapped and some time was spent examining the geology of the West Pilbara for a bulletin on the Pilbara Block. The Precambrian portions of the Paterson Range and Yarri Sheets were compiled.

A Ministerial Reserve was created over a new discovery of barite in the Pilbara and some preliminary sampling carried out.

Manuscripts for Mineral Resources Bulletins on chromium, vanadium, tungsten, and molybdenum have been completed. The writing of a bulletin on the State's tin deposits continues while the proposed copper bulletin has been temporarily suspended.

Sundry work included inspections of deposits of limestone, moulding sand, kaolin, copper, tiger-eye, and fluorite.

Some 140 general inquiries from the public were answered and 115 requests for company data handled. An additional 685 assessions were added to the collection of mineral exploration data, a decrease of 503 as compared with 1974.

COMMON SERVICES DIVISION

Petrology (W. G. Libby, J. D. Lewis, J. R. Drake)

The demand for petrological services stabilized during 1975. Eighty-eight reports were written on 1 383 samples, including 1 330 thin sections. About 2 000 further thin sections were examined in order to classify samples already in the collections for incorporation into the computerized rock and mineral data system.

Special studies included syenitic rock at the Fitzgerald Peaks, small ultramafic bodies from the Canning Tunnel, garnet from Heaney's Find, and felsic volcanic rocks from the Bangemall Basin. A study of the granitic and felsic volcanic rocks of the Eastern Goldfields was completed.

Twelve projects in the co-operative geochronological programme with the Western Australian Institute of Technology were active during 1975 and three were added for 1976. The results of three projects were published in 1975 and several others should be ready for publication in 1976.

The laboratory prepared 2 065 thin sections of which 1 474 were petrological; 235 polished slabs were cut, 38 heavy mineral samples were separated, 22 sieve analyses performed, 54 samples crushed for analysis, and 11 mounts polished.

The Government Chemical Laboratories continued to provide valuable chemical analyses and mineral determinations.

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

The 155 file reports written this year reflect the increasing demand for palaeontological information by the Hydrogeology and Engineering Geology Division. A new feature this year was the preparation of an illustrated guide to Mesozoic and Tertiary fossils for use by the Carnarvon Basin mapping party. The main fields covered by the reports are shown in the table below.

Report requested by	Field of palaeontology		
	Palynology	Micro-palaeontology	Macro-palaeontology
Hydrogeology and Engineering Geology Division	132	1	2
Sedimentary Division	2	....	7
Regional Mapping and Mineral Resources Divisions	2	....	2
Other Survey requests	....	4	1
Other organisations	1	1	....

The major effort in palynology has been devoted to further detailed studies on the biostratigraphy of Cretaceous rocks in the Perth Basin. Work continued on the Devonian fauna from the Canning Basin and included studies of stromatoporoids, ostracods, tentaculitids, brachiopods, bivalves, and gastropods. New projects include a study of aspects of the Tertiary fauna of the Carnarvon Basin, and a study of the Proterozoic stromatolites of the Bangemall Basin.

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

Geophysical water-bore logging reached a new, and probably all-time, peak during 1975; 258 bores were logged with an aggregate depth of some 29 900 m. Total chart recordings for all parameters measured were equivalent to about 58 000 m of hole. The unprecedented increase from 133 bores in 1974 was due mainly to exploratory drilling of the unconfined aquifer systems in the northern and southern Perth areas by the Metropolitan Water Board. Operations also included logging as far afield as the Fortescue Valley and West Canning Basin.

Several seismic refraction surveys were undertaken on groundwater and engineering projects. At Weelumurra Creek in the Fortescue Valley about 40 km of section were shot and at Albany in the extreme south another 10 km of profiling and several depth probes were carried out. Dam and reservoir sites investigated included North Dandalup, Forrestfield, and Kangan on the Yule. Seismic sections were also obtained in paired catchments for the woodchip industry monitoring near Manjimup.

Normal laboratory servicing and calibration of geophysical, hydrological, and communications equipment were maintained. Conductivity measurements were made on some 800 bore water samples.

Geochemistry (R. Davy)

Analyses of samples submitted to the Government Chemical Laboratories in connection with the regional rock geochemistry survey of the Laverton, Leonora, and Rason 1:250 000 Sheets were finally completed in August. A report on the Laverton Sheet is on file, and reports on the Rason and Leonora Sheets are in preparation. A paper on regional changes in the granitoids of the three sheets is included later in this report.

Samples from *in situ* laterite and bauxite profiles have been submitted to the Government Chemical Laboratories for chemical and X-ray diffraction analysis. Investigations of this material by the Geological Survey have been completed.

Samples of groundwater from observation bores at and adjacent to the Del Park Mine Site have been monitored periodically to determine the labile elements and their concentrations at different seasons of the year. The results are being related to the weathering pattern, and the nature of the bauxite profiles.

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

The first two preliminary sheets of a series of 1:50 000 Urban Geology maps were issued during the year, entailing detailed geological mapping and correlation with the hydrology, engineering geology, and mineral resources of the area. Field mapping has been completed on a third sheet and initial photogeological interpretation done for a fourth. Other appropriate Divisions contributed to these sheets.

The study into supply and demand of clays near Metropolitan Perth was completed and the results issued as a Record. A similar study on dimension stone and aggregates is substantially complete.

The appraisal of mineral tenements applications continues with a view to protecting the environment while encouraging mining.

The geology was recorded from several score temporary excavations in and around Perth, expanding the knowledge of geological strata within the urban area.

Liaison with and supplying geological information to other departments, instrumentalities, and companies continues to occupy a large part of the section's activities and has included the compilation of appraisals of the geology of the proposed Perth Urban Corridors, heavy mineral examination of samples from Hardy Inlet and compilation of palaeogeological environment of Port Gregory area.

Technical Information (K. H. Green, M. M. Harley, M. E. Wenham, and S. M. Fawcett).

The number of enquiries from the general public including requests for rock identification directed to the section has been smaller during the year than in past years, reflecting the lapse in exploration activity and consequent lack of mining publicity. Two Bulletins were edited and sent to the press, sixteen Records were edited and eight Explanatory Notes published. The collection of Survey photograph negatives and prints has been up-dated

Requisitions raised on the Surveys and Mapping Branch for drafting services and photography for the Survey totalled 1 043. Photocopying for the public of out-of-print publications numbered 800 requisitions, many of these contained several items.

During the year 1 657 members of the public visited the library for research purposes. Book loans to the staff totalled 4 649, and loans to other libraries 547.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

Geological and geophysical projects carried out by the Bureau of Mineral Resources in Western Australia included the following:—

(i) Compilation of two bulletins on the Kimberley Division as a joint project with the Survey, whose portion was completed some years ago. (As it is some 10 years since the field work was completed, it appears as if this project will never be completed, so it will be omitted from the programme in future unless the B.M.R. becomes active again.)

(ii) Preparation of a bulletin on the Officer Basin joint project. The Survey has completed its contribution and is keen to see this work finalized and not have the sad history of (i) above.

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

(iv) Joint collection of rock specimens from the Pilbara area to test for trace element characteristics in selected type sections.

(v) Aeromagnetic survey of the Officer Basin commenced.

PROGRAMME FOR 1976

HYDROGEOLOGY AND ENGINEERING DIVISION

A. Hydrogeology

1. Continuation of the hydrogeological survey of the Perth Basin, including deep drilling on the Moora and Quindalup lines, and pump testing on the Eneabba line.
2. Hydrogeological investigation and/or exploratory drilling for groundwater in the following areas:—
   (a) West Canning Basin
   (b) Fortescue River including coastal district, East Millstream and Weelumurra
   (c) Re-assessment of De Grey, Yule, and Gascoyne River areas
   (d) Stirling Range area for farm water supply.
3. Town water supply investigations and/or drilling for the following:—
   Albany district, Bunbury district, Hopetoun, Horrocks Beach, Halls Creek, Geraldton.
4. Hydrogeological investigations for Metropolitan Water Supply Board:—
   (a) Regional studies
   (b) Shallow drilling at Lake Thompson, Mirrabooka extension area, Salvado
   (c) Studies of certain areas for pollution control
   (d) Study of water balance in coastal lakes.
5. Inter-departmental studies concerning groundwater salinity problems in the Darling Range area.
6. Continuation of bore census of selected areas.
7. Kimberley Division—hydrogeological assistance to pastoralists as required.
8. Miscellaneous investigations and inspections as requested by Government Departments and the public.

B. Engineering

1. Pilbara area—further investigation of proposed dam sites on the Forescue River, at Cooya Pooya and Kangan on Yule.
2. Darling Range area—continuation of investigations at South Canning and North Dandalup dam sites, Wungong Dam, Wungong tunnel, and a safety review of existing dams.
3. Investigation, including drilling of proposed Bibra Lake sewerage tunnel.
4. Miscellaneous investigations by Government Departments as requested.

SEDIMENTARY (OIL) DIVISION

1. Maintain an active interest in the progress and assessment of oil exploration in Western Australia.
2. Continuation of the surface and subsurface study of the Carnarvon Basin including Quobba, and the Phanerozoic portions of the Mount Phillips, Glenburgh, and Byro 1.250 000 Sheets.
3. Continuation of the geological mapping of the Canning Basin in conjunction with the Bureau of Mineral Resources on the Mount Anderson and Derby 1:250 000 Sheets.
4. The commencement of a Bulletin on further studies of the Devonian reef complexes of the Lennard Shelf, Canning Basin.

REGIONAL GEOLOGY DIVISION

1. Completion of mapping of the Bangemall Basin mainly on the Stanley and Nabberu 1:250 000 Sheets and commencement of Bulletin.
2. Completion of mapping of the Nabberu Basin on the Stanley and Nabberu 1:250 000 Sheets.
3. Mapping of the Archaean on the Kingston 1:250 000 Sheet and continuing onto Wiluna and Glengarry Sheets.
4. Commencement of the Gascoyne Province mapping on the Mount Phillips, Glenburgh, and Byro 1:250 000 Sheets.
5. Completion of mapping on the Rudall and Southern Cross 1:250 000 Sheets.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral exploration in Western Australia.
2. Completion of Mineral Resources Bulletins on tin, copper, vanadium, and chromium.
3. Reassessment of the regional and economic geology and commencement of Bulletin on the Pilbara Block.
4. Continuation of regional mapping of the Darling Range on the Collie, Pemberton, Moora, and Perenjori 1:250 000 Sheets and a study of the bauxite occurrence.
5. Geological investigation of Cooke Bluff barite prospect.

COMMON SERVICES DIVISION

Petrology

1. Carry out petrological investigations as required by other Divisions.
2. Completion of the petrological project on Eastern Goldfields granites and acid rocks.
3. A study of the regional petrology of the Pilbara granites.
4. A study of the low-grade metamorphism of the Talbot and Yowalga 1:250 000 Sheets.

Palaeontology

1. Carry out palaeontological investigations as required by other Divisions.
2. Continuing a study of the Devonian stromatoporoids, Lennard Shelf, Canning Basin.
3. A study of ostracod fauna from the same region.
4. A study of the stratigraphic palynology of the Cretaceous Yarragadee Formation.
5. Completion of study of Devonian Atrypids.
6. A study of stromatolites from the Bangemall Basin.

Geophysics

1. Well logging as required on groundwater drilling projects.
2. Seismic surveys for groundwater on the Fortescue River and near Albany.
3. Seismic surveys for dam sites in West Pilbara, South Canning, and of existing dam sites and foundations in the Metropolitan area.
4. Seismic survey for portals and sections of proposed Wungong Tunnel.

Geochemistry

1. Completion of regional geochemistry project on Leonora-Laverton-Rason and a study on laterite profiles in the Darling Range.
2. Examine the nature of the anomalous lead/zinc in the parts of the Bangemall Basin.
3. An assessment of the SO_2 prospecting technique in Western Australia.
4. A geochemical examination of laterites, Mount Saddleback area.

Environmental Geology

1. Continuation of urban geology studies on the Mandurah, Pinjarra, Dampier, and Port Hedland 1:50 000 Sheets.
2. A study of the sand resources in the urban area of Perth.
3. Attend to environmental geological problems as required.

PUBLICATIONS AND RECORDS

Issued during 1975

Annual Report, 1974.

Memoir No. 2: The Geology of Western Australia.

Report 3: An annotated bibliography of the palaeontology of Western Australia 1814-1974.

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

Geological map of Dongara-Hill River 1:250 000 Sheet (SH/50-5 and 9 International Grid) with explanatory notes.

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

Geological map of Malcolm-Cape Arid 1:250 000 Sheet (SH/51-7 and 10 International Grid) with explanatory notes.

Geological map of Mason 1:250 000 Sheet (SH/52-6 International Grid) with explanatory notes.

Geological map of Murgoo 1:250 000 Sheet (SG/50-14 International Grid) with explanatory notes.

Geological map of Seemore 1:250 000 Sheet (SH/51-12 International Grid) with explanatory notes.

Geological map of Warri 1:250 000 Sheet (SG/51-4 International Grid) with explanatory notes.

Reprints

Geological map of Mount Bruce 1:250 000 Sheet (SF/50-11 International Grid).

Geological map of Yarraloola 1:250 000 Sheet (SF/50-6 International Grid).

In press

Bulletin 124: The geology of the Perth Basin.

Mineral Resources Bulletin 11: Heavy mineral sands of Western Australia.

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

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

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

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

Geological map of Neale 1:250 000 Sheet (SH/51-4 International Grid) with explanatory notes.

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

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

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

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

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

In preparation

Bulletin 125: The geology of the Eastern Goldfields.

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

Geological maps 1:250 000 with explanatory notes, the field work having been completed: Billiluna, Crossland, Cundeelee, Duketon, Dummer, Helena, Laverton, Lennis, Leonora, Marble Bar, Minigwal, Mount Bannerman, Mount Egerton, Nullagine, Paterson Range, Perth, Robert, Sir Samuel Stansmore, Throssell, Waigen, Wanna, Webb, Westwood, Yarrie, Yowalga.

Geological maps 1:1 000 000 Kalgoorlie, Esperance.

Records produced

1975/1 Wells drilled for petroleum exploration in W.A. to the end of 1974, by G. H. Low.

1975/2 A system for storage and retrieval of rock and mineral data, by W. G. Libby.

1975/3 Hydrogeology of the Mandurah-Pinjarra area, by D. P. Commander.

1975/4 Clay resources of the Perth region, by R. H. Archer.

1975/5 Explanatory notes on the Nullagine 1:250 000 geological sheet, W.A., by A. H. Hickman.

1975/6 Explanatory notes on the Perth 1:250 000 geological sheet, W.A., by S. A. Wilde and G. H. Low.

1975/7 Explanatory notes on the Duketon 1:250 000 geological sheet, W.A., by J. A. Bunting and R. J. Chin.

1975/8 North Dandalup proposed dam site: seismic refraction survey, by I. R. Nowak.

1975/9 Explanatory notes on the Throssell 1:250 000 geological sheet, W.A., by J. A. Bunting, M. J. Jackson, and R. J. Chin.

1975/10 Beenyup outfall tunnel and outlet: geological report, by G. Klenowski.

1975/11 Moochalabra Creek dam, Stage II: geological investigation, by G. W. A. Marcos.

1975/12 Hydrogeological reconnaissance of the northwest Pilbara region, by W. A. Davidson.

1975/13 Bullinarwa Pool dam site: geological report, by J. M. Campbell.

1975/14 Wungong proposed tunnel: preliminary geological report, by R. P. Mather.

1975/15 North Dandalup proposed dam site, North Dandalup River: geological investigation progress report, by G. Klenowski.

1975/16 South Dandalup dam: final geological report, by G. W. A. Marcos.

Reports in other publications

Lord, J. H., 1975, Coal deposits of Western Australia *in* Economic Geology of Australia and Papua New Guinea: Australasia Inst. Mining and Metall. Monograph 6, Coal. p. 269-279, 339, 372.

Playford, P. E., 1975, Petroleum in Western Australia—a review of exploration, production and future prospects: Australia Petrol. Expl. Assoc. Jour. v. 15, pt. 2, p. 72-79.

Trendall, A. F., 1975, Iron Formations of the Hamersley Basin: International Geological Correlation Programme, Moscow, 1975 *in* Correlation of the Precambrian, Abstracts, p. 147-148.

Van de Graaff, W. J. E., 1975, Carboniferous deltas in the Pisuerga area, Cantabrian Mountains, Spain *in* Deltas, models for exploration, M. L. Broussard (ed.), Houston Geological Society, p. 451-456.

Yeates, A. N., Crowe, R. W. A., Towner, R. R., Lyborn, L. A. I., and Passmore, V. L., 1975, Notes on the geology of the Gregory Sub-basin and adjacent areas of the Canning Basin, Western Australia: Australia Bur. Mineral Resources Rec. 1975/77 (unpublished).

J. H. Lord,
Director.

2nd February, 1976.

THE EFFECTS OF BAUXITE MINING AT DEL PARK ON GROUNDWATER HYDROLOGY

by T. T. Bestow

ABSTRACT

A study of hydrographic and salinity data collected from a grid of bores drilled through lateritic profiles, both in a rehabilitated mine pit and the adjoining Darling Range forest, indicates that the combined effects of selective felling, Phytopthora cinnamomi and bauxite mining are resulting in an annual discharge of salt of about 1.2 times the accession from rainfall. However, the greater infiltration and the absence of a transpirative draw from the water table below the mine pit, as compared with the forest, has resulted in the creation of a groundwater mound below and downslope of the mine pit. This has a substantially lower salinity than that of groundwater below the adjoining forest. Comparative water balances in the mine pit and forest indicate that the groundwater discharge from the pit area is about twice that from the forest.

The study indicates that bauxite mining in the Del Park area has benefitted the groundwater regime by increasing the volume being discharged and by reducing salinities. It is estimated that the present salt imbalance within the mine pit is expected to return to balance in between 24 and 48 years.

INTRODUCTION

The increase in stream salinity which results from forest clearing in the South West Division, has been recognized for a considerable number of years (Wood, 1924). Research into the underlying physical causes of such increases was slow to start and it was not until salination became a serious problem in the agricultural areas east and northeast of the Darling Range that the first serious studies were commenced (Burvill, 1947). Indeed it was not until about 1964 that detailed studies can be said to have started (Bettenay and others, 1964). Since then the pace of research has quickened, and concern at the environmental risks of land use changes has become more widespread in the community. The West Australian Government has recognized the need for research specific to the hydrologic effects of land use changes related to major developments such as the Manjimup Wood Chip Industry and bauxite mining, and in 1973 set up committees to supervise and carry out research. Several projects were started under the guidance of inter-departmental panels and with the full co-operation of the mining companies concerned. One of them was conducted at Del Park, 13 km almost due east of Pinjarra (Fig. 3).

HISTORY AND OBJECTIVES

The particular objectives of the investigation at Del Park (which forms part of what is known as Project 3) are to assess the changes in the groundwater hydrology which have resulted from mining, by drilling a series of boreholes in the mined and the adjoining unmined area and then observing the salinity and water-table levels.

The Del Park area falls within the Alcoa mining lease (1SA) and at the time when its bauxite potential was initially explored by grid drilling, was entirely covered by jarrah forest. This had been cut over early this century and was already infected with the root fungus Phytopthora cinnamomi which was destroying the jarrah and other susceptible species.

Most of the Del Park mine area was cleared between August and October 1970, but the part presently described was not cleared until the corresponding months of 1971. This clearing included not only the mine pit area but also a surrounding narrow strip of ground. After the felling and burning, the top soil was removed and stockpiled. Then between November and December 1972 bauxite was mined by open-cut methods, and early in 1973 the area was rehabilitated. This involved firstly deep-ripping the pit floor to 1.5 m and replacing the top soil which was contour ploughed. Finally exotic eucalypts were planted to re-establish a forest cover and by February 1974, when the present series of investigation bores were drilled, these trees had grown to between 1 and 2 m in height.

TOPOGRAPHY

The Del Park mine site lies on the north flank of the Boomer Brook, a westward-draining tributary of the South Dandalup River, and is at an elevation of between 300 and 330 m above sea level. The valley form is essentially juvenile although the higher ground tends to have a pateau-like form. Valley slopes in the forest and at the mine site have gradients between 1 in 6.5 and 1 in 13. The removal of bauxite has had the effect of lowering the surface in the rehabilitated mine pit by an average of 3.83 m, to produce a southward-sloping depression. At its southern margin there is an up-slope batter which tends to impound run-off within the mine pit.

RAINFALL

Rainfall records for Del Park are available only from July 1972 (Table 1).

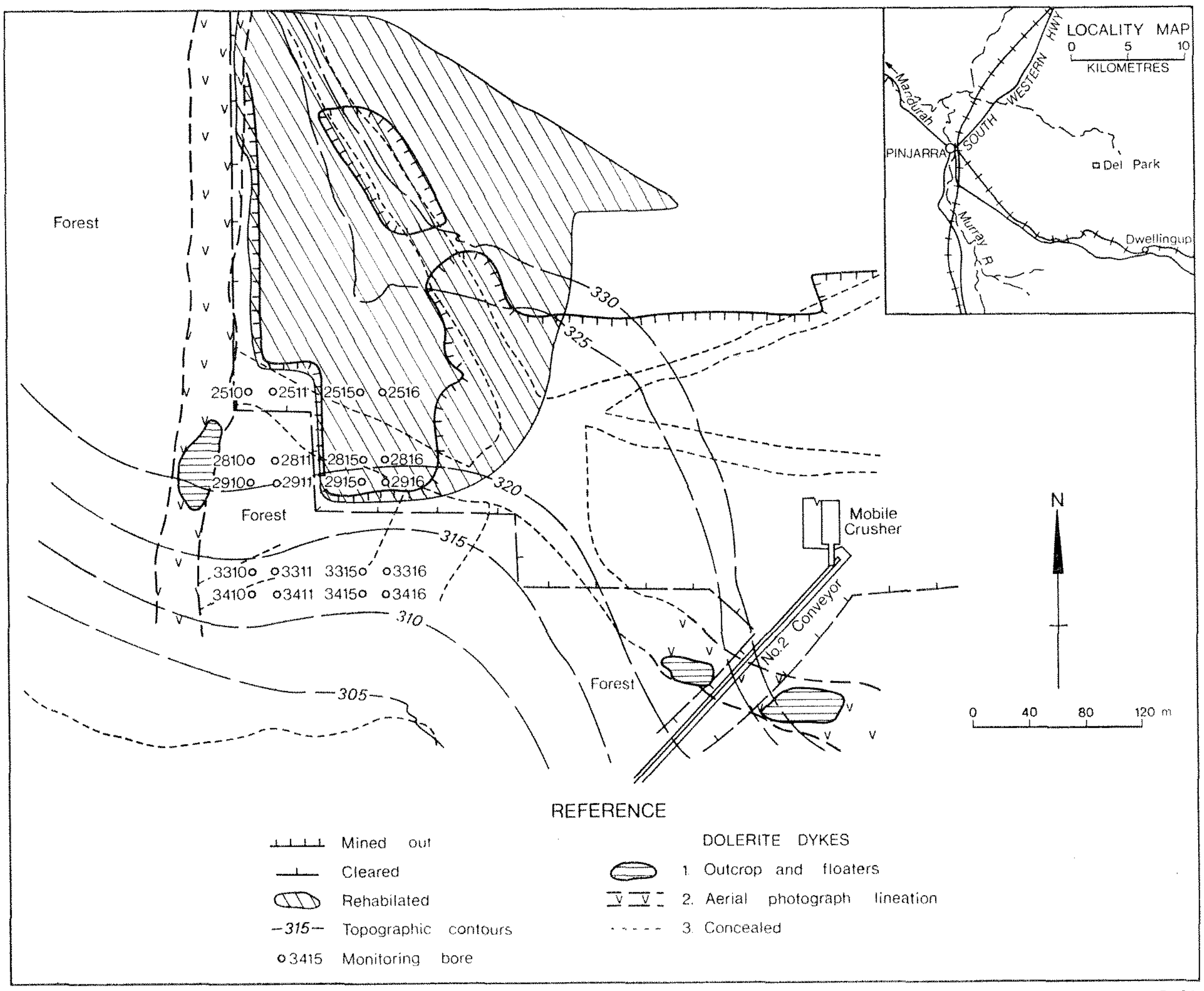


Figure 3. Locations of monitoring bores at Del Park.

TABLE 1. MONTHLY RAINFALLS AT DEL PARK

		mm			mm
1972	July	342·9	1974	January	0
	August	376·9		February	0
	September	81·3		March	0
	October	98·3		April	105·40
	November	10·2		May	343·20
	December	0		June	256·30
				July	532·90
		(909·6)		August	201·90
				September	52·07
1973	January	18·0		October	150·02
	February	0		November	23·37
	March	0		December	0
	April	187·7			
	May	251·0			1 665·16
	June	364·0			
	July	399·0			
	August	173·0	1975	January	0
	September	234·2		February	0
	October	88·4		March	0
	November	16·5		April	16·30
	December	0		May	364·70
		1 731·8			(380·10)

The nearest rainfall station with a long record is at Dwellingup. The season pattern of rainfall is mediterranean, with rain confined to a winter period and dryness between November and March. The long-term mean annual rainfall at Del Park is probably about 1 500 mm but the total rainfalls for the years 1973 and 1974 were above average, being 1 732 and 1 665 mm respectively.

MONITORING BOREHOLES AND DATA COLLECTION

Twenty boreholes were drilled with an auger-type rig without the use of drilling fluids, on a grid consisting of five sites on each of four lines. Six of the bores are in the mined area and the remainder in the relatively undisturbed forest. Four of the bores were cored and a full suite of drill cuttings collected from the remainder. Only three bores reached reasonably unweathered bed-rock.

Each bore was cased with 38 mm I.D. P.V.C. pipe slotted to allow the ingress of groundwater from 2 m below the surface to the full depth of the bore (6.9-44.10 m) (Table 2). The position and elevation of each bore was surveyed and related to the grid of exploration bores drilled by the mining company through part of the profile, and numbered accordingly. The cores were analysed to determine the pH of pellicular moisture, the total soluble salts and the sodium chloride content (Table 3).

The water levels in each bore were measured as soon as possible after drilling was completed, and subsequently each month. As all boreheads have been accurately levelled, it is possible to reduce all standing water level measurements to height above mean sea level (Table 4).

TABLE 2. SUMMARY OF BOREHOLE DATA

Bore No.	Elevation of borehead	Total depth m	Depth cased m	Date completed in 1974	Water cut m	Standing water level on completion	Salinities recorded during drilling (TDS mg/l)	Sample log	Comments
2510	325·27	15·52	15·52	9·2	Dry	....	....	0–12 laterite, 12–14 weathered dolerite, 14–15 dolerite	Auger samples damp from 2m
2511	325·45	21·50	21·50	12·2	16	17·34	200	0–15 laterite, 15–18 clay, 18–21 weathered dolerite, 21–21·5 dolerite	
2515	320·75	23·64	23·64	30·3	15	11·91	....	0–18 clay	No sample recovery below 18 m
2516	320·24	17·18	17·18	4·4	15·13	11·36	....	0–17 clay, 17–17·5 slightly weathered granite	No recovery 15–17 as clay became a slurry
2810	322·13	20·61	20·61	26·2	....	....	....	0–6·5 laterite, 6·5–17·5 kaolin, 17·5–20·6 weathered granite	Cored but no recovery between 8·1–16·2, 19·7–20·6
2811	321·88	19·58	19·58	18·2	....	....	140		
2815	317·63	9·62	9·62	29·3	9·5	9·5	....	0–3 kaolin, 3–9 silt	
2816	317·55	6·90	6·90	5·4	Dry	....	....	0–3 laterite, 3–6·9 weathered dolerite	Cored from 1 to 4·95 m with 80 per cent recovery
2910	320·84	34·00	30·00	28·2	21·0	19·25	120, 130	0–12 laterite, 12–27 kaolin, 27–33 silty clay, 33–34 clay	
2911	320·50	23·50	23·50	19·2	....	....	....	0–6 laterite, 6–22 kaolin	No recovery 22–23·5
2915	315·53	15·13	15·13	28·3	8·0	7·8	115	0–6 laterite, 6–15·1 kaolin, 15·1 weathered granite	
2916	315·04	12·27	12·27	28·3	7·0	7·0	....	0–3 laterite, 3–6 silt, 6–10 silty clay	Cored to 4·95, no sample recovery 10–12·27
3310	314·44	36·28	36·28	18·3	18·0	16·35	....	0–4 laterite, 4–16·8 kaolin, 16·8–20 weathered granite, 20–21·3 kaolin, 21·6–22·3 weathered dolerite	Cored but no recovery 17·5–18·9, 22·3–36·28
3311	314·29	42·12	41·29	14·3	19·0	....	160–220	0–12 laterite, 12–18 kaolin, 18–42 sandy and silty clay	Partially cored, bore completed in puggy clay
3315	312·60	31·29	31·29	25·3	7·0	7·0	....	0–2·8 laterite, 2·8–6·2 kaolin, 6·2–12 deeply weathered dolerite	Cored to 7·8 m
3316	312·13	30·34	30·34	28·3	10·6	10·6	....	0–3 silty clay, 3–6 kaolin, 6–11 silty clay, 11–30·3 clay	
3410	312·83	35·65	35·65	11·3	18·0	14·0	....	0–12 laterite, 12–24 kaolin, 24 clay	No recovery 24–35·6
3411	312·60	34·20	31·37	6·3	16·0	13·6	185–210	0–3 laterite, 3–6 clay, 6–12 sandy clay, 12–15 kaolin, 15–21 weathered granite, 21–24 sand, 24–27 clay	No recovery 27–34
3415	311·08	44·10	38·51	21·3	9·03	7·4	....	0– laterite, 33–42 clay	Partially cored, 0–33 not recorded
3416	311·00	24·00	24·00	26·3	....	6·6	....	0–3 gravel, 3–6 kaolin, 6–9 silty clay, 9–15 clay	No recovery 15–24

All bores were drilled 152 mm diameter and cased with 2 m of 76 mm PVC stand pipe from 180 mm above ground to 1·82 m below. Each bore is also cased with 38 mm ID PVC pipe slotted with hacksaw cuts (20 per metre) from 2 m below ground level to the appropriate depth given above.

TABLE 3. ANALYTICAL DATA FROM CORE SAMPLES

Bore	Depth m	Density kg/m³	H_2O %	pH	E.C. μS	TSS %	NaCl %	Remarks
2810	0	....	4·2	6·2	28	·005	·004	Surface sample
	1	....	4·5	6·1	7	·001	< ·001	DTH-Hammer sample
	2	....	3·2	5·95	9	·001	·003	DTH-Hammer sample
	3	....	16·7	5·35	21	·003	·005	DTH-Hammer sample
	3·487	820	25·5	5·4	31	·005	·008	Complete core ?
	4	....	16·5	5·4	19	·003	·006	DTH-Hammer sample
	5	....	20·2	5·25	22	·003	·006	DTH-Hammer sample
	5·842	....	16·8	5·25	37	·006	·010	Incomplete core
	6·582	....	18·8	4·95	42	·007	·010	Incomplete core
	7·292	....	27·2	4·85	57	·011	·015	Incomplete core
	8·143	....	25·2	4·95	56	·011	·013	Most of sample lost
	16·176	1 530	26·2	5·25	32	·005	....	Complete core ?
	16·724	....	35·2	5·25	47	·009	·005	Incomplete core
	18·252	1 590	20·5	5·1	20	·003	·005	Complete core ?
	18·987	1 650	24·8	5·0	24	·004	·006	Complete core ?
	19·707	....	26·2	5·0	27	·004	·006	Incomplete core
2816	Surface	....	....	5·25	19	·003	·004	
	1·590	....	....	5·15	18	·003	·004	
	2·236	....	....	5·15	19	·003	·004	
	3·010	....	....	4·70	22	·003	·003	
	3·715	....	....	4·70	25	·004	·004	
	4·260	....	....	4·95	24	·004	·004	
	4·950	....	....	5·20	23	·004	·005	
3310	0	....	6·2	6·0	31	·005	·004	Surface
	3	2 520	8·4	5·8	8	·001	·001	Complete core ?
	4·767	....	17·0	5·55	15	·002	·004	Incomplete sample
	5·537	....	....	....	....	....	....	Complete core lost
	6·322	....	15·3	5·45	14	·002	·004	Incomplete core
	7·057	....	15·1	5·35	17	·002	·005	Sample from auger flight
	7·821	....	14·0	5·20	18	·003	·005	Sample from auger flight
	8·572	....	15·8	5·05	24	·004	·006	Sample from auger flight
	9·262	....	17·9	5·05	26	·004	·006	Sample from auger flight
	10·082	....	18·8	5·05	27	·004	·006	Sample from auger flight
	10·817	....	20·0	4·95	31	·005	·006	Sample from auger flight
	11·607	....	18·2	4·95	32	·005	·006	Sample from auger flight
	12·347	....	17·8	4·85	34	·006	·006	Sample from auger flight
	13·132	....	18·7	4·85	34	·006	·005	Sample from auger flight
	13·847	1 270	29·5	4·65	29	·005	·005	Core length 122 mm, ID 48 mm
	14·557	....	19·2	4·6	38	·007	·006	Incomplete core
	15·232	....	....	4·6	75	·015	·016	Complete core lost
	15·552	1 300	36·4	....	....	....	....	Full shoe length 122 mm, ID 48 mm
	15·982	1 310	39·1	4·9	73	·015	·016	Full core
	16·822	....	23·0	4·95	38	·007	·009	Incomplete core
	17·532	....	30·6	4·8	48	·010	·011	Incomplete core
	18·182	....	....	....	....	....	....	Complete core lost
	18·892	....	....	....	....	....	....	Complete core lost
	19·287	1 470	35·2	4·85	55	·011	·013	Complete core ?
	20·082	1 410	36·8	4·9	56	·012	·013	Complete core ?
	20·757	1 400	36·5	4·8	53	·011	·012	Complete core ?
	21·317	1 860	19·9	5·0	31	·005	·006	Complete core ?
	21·550	....	....	....	....	....	....	Blind bit
	22·550	....	17·3	5·3	96	·020	·011	Incomplete core
	23·027	....	....	....	....	....	....	No core
3311	15·982	....	....	4·9	70	·014	·016	
	16·822	....	....	5·0	37	·006	·009	
	17·532	....	....	4·8	46	·009	·011	
3315	....	....	....	5·85	13	·002	< ·001	No cores
	....	....	....	5·8	7	·001	< ·001	
	....	....	....	5·7	11	·001	·003	
	....	....	....	5·15	10	·001	< ·001	
	....	....	....	4·45	21	·003	·003	
	....	....	....	4·3	33	·006	·004	
	....	....	....	4·05	53	·011	·008	
	....	....	....	4·05	66	·013	·011	
	....	....	....	4·35	54	·011	·011	
	....	....	....	4·75	73	·015	·016	
3415	3·657	1 650	19·8	4·95	14	·002	·003	Complete sample
	6·482	1 720	29·8	4·4	48	·010	·010	Complete sample
	9·522	....	34·1	4·75	52	·010	·012	Incomplete sample
	10·607	....	32·5	5·3	53	·011	·012	Incomplete sample
	15·732	....	26·0	5·15	31	·005	·007	Incomplete sample

1. NOTE—TSS % calculated using the new relationship of
$Y = \cdot 0000000483\, x^2 + \cdot 0002175\, x - \cdot 0014$
where Y = TSS % and x = E.C.
TSS % at 25°C.
2. NOTE—NaCl % may be slightly higher than the TSS % in the low range because of the equation used for TSS %.

TABLE 4. MONTHLY REDUCED LEVELS OF THE WATER TABLE (METRES ABOVE MSL)

MONTH	4	5	6	7	8	9	10	11	12	1	2	3	4
						FOREST							
2510	309·62	309·81	310·34	310·94	312·59	316·47	310·64	309·94	....	....	....	....	....
2511	308·11	308·80	310·30	310·91	312·47	311·43	310·49	309·90	309·00	308·93	308·49	....	308·03
2810	....	302·42	304·69	305·74	309·83	307·93	306·26	304·95	302·52	303·30	302·83	....	....
2811*	304·67	305·09	307·45	308·70	311·62	309·51	308·92	307·80	305·72	306·00	305·31	....	304·77
2910*	301·14	301·45	303·44	304·41	308·20	303·37	304·82	303·73	302·21	302·19	301·70	....	301·32
2911*	305·17	304·62	307·48	308·79	311·70	310·00	309·04	307·57	304·79	305·60	304·46	....	304·27
3310*	298·67	298·80	299·34	299·85	301·30	300·43	299·93	299·52	298·39	299·10	298·88	....	298·77
3311*	299·34	299·59	300·35	300·93	303·05	302·09	301·37	300·76	299·32	300·05	299·69	....	299·47
3410*	298·53	298·78	299·25	299·88	301·31	300·50	299·83	299·55	297·89	299·09	298·51	....	298·73
3411*	298·72	299·06	299·23	299·88	301·30	300·59	300·05	299·78	298·67	299·26	298·97	....	298·90
Average (of 7)	300·89	301·06	302·36	303·21	305·51	303·78	303·42	302·67	301·00	301·61	301·07	....	300·89
						PIT							
2515*	308·84	309·75	310·78	311·71	313·41	312·50	311·09	310·53	309·90	309·72	309·27	....	308·88
2516	308·88	310·16	311·14	311·92	313·94	312·89	311·37	310·56	....	309·74	309·23	....	308·74
2815	307·96	308·73	310·51	311·50	313·18	312·23	310·77	309·97	308·88	308·82	308·32	....	....
2816	....	....	310·58	311·59	313·19	312·20	310·77	310·43	....	....	....	....	....
2915*	307·72	308·80	310·42	311·41	313·03	312·14	310·70	310·00	309·01	308·65	308·17	....	307·61
2916*	307·75	308·88	310·44	311·62	313·09	312·24	310·71	310·40	308·97	308·74	308·21	....	307·61
Average (of 3)	308·10	309·14	310·55	311·58	313·18	312·29	310·83	310·31	309·29	309·04	308·55	....	308·03
						FOREST DOWNSLOPE OF MINE PIT							
3315*	305·66	306·60	307·87	309·08	310·29	308·93	308·19	307·53	306·29	306·43	306·03	....	305·70
3316*	306·31	306·93	308·55	309·97	310·55	309·50	308·62	305·48	306·11	306·95	306·57	....	306·28
3415*	304·72	305·49	306·50	310·28	308·98	307·21	306·59	305·38	305·10	304·10	304·92	....	304·25
3416	305·44	305·39	307·10	308·75	309·40	308·56	....	....	305·70	306·13	....	....	....
Average (of 3)	305·56	306·34	307·64	309·78	309·94	308·55	307·80	306·13	305·83	305·83	305·84	....	305·41

* Included in the monthly averages.

Water samples were collected in the course of drilling where this was possible, and after completion at monthly intervals (Table 5). At the same time any variations of salinity with depth were measured *in situ* by means of a down-hole conductivity meter (Table 6).

TABLE 5. MONTHLY WATER SAMPLE ANALYSES—TOTAL DISSOLVED SOLIDS EXPRESSED AS MG/LITRE

Month	4	5	6	7	8	9	10	11	12	1	2	3	4	Average
						FOREST								
2510	280	130	210	221	140	127	145	190	....	....	....	....	....	180
2511*	170	90	150	139	130	98	120	125	135	150	138	150	126	132
2810	....	98	150	141	110	110	140	96	133	115	133	....	....	123
2811*	144	95	150	137	120	71	85	90	148	227	135	130	125	127
2910*	130	90	140	84	80	60	120	110	135	140	120	115	115	111
2911*	125	80	120	103	80	76	115	90	126	131	100	100	104	104
3310*	170	105	170	78	110	140	165	140	170	168	160	170	164	142
3311*	180	130	210	90	130	125	185	165	203	195	205	180	155	166
3410*	205	130	200	76	80	165	120	165	220	280	180	205	245	174
3411*	175	130	210	166	80	104	125	82	155	161	166	158	187	146
Average (of 8)	162	106	169	109	101	105	129	121	161	181	150	151	153	140
									Mean of monthly averages					138
						PIT								
2515*	145	75	190	123	120	143	125	125	152	152	133	115	124	126
2516*	148	98	104	100	80	75	75	90	121	160	128	115	90	106
2815	280	135	135	120	110	98	105	96	132	242	200	....	....	150
2816	....	....	....	90	110	78	100	....	....	....	....	....	....	....
2915*	115	73	115	78	70	73	95	82	121	105	118	98	104	95
2916*	148	75	95	85	70	68	75	76	121	124	133	120	104	104
Average (of 4)	139	80	103	96	85	100	92	93	129	135	128	112	105	115
									Mean of monthly averages					108
						FOREST DOWNSLOPE OF THE MINE PIT								
3315*	245	110	100	50	40	72	95	110	208	260	250	260	245	157
3316*	245	100	120	50	320	255	140	60	100	167	208	152	187	162
3415*	100	100	100	50	50	120	95	140	105	90	205	160	170	114
3416*	238	170	300	166	270	235	195	220	275	270	265	240	228	236
Average (of 4)	207	120	155	77	170	170	131	132	172	197	232	203	207	167
									Mean of monthly averages					168

* Included in the monthly averages.

TABLE 6. VERTICAL VARIATIONS IN SALINITY BASED ON DOWNHOLE CONDUCTIVITY

Bore-hole No.	19–4–75		16–5–74		17–6–74		17–7–74		20–8–74		18–9–74		17–10–74	
	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l
2510	15·65–15·67	280	15·46–15·67	130	14·93–15·67	210	14·33–15·67	221	12·68–15·67	140	13·80–15·67	127	14·63–15·67	145
2511	17·34–21·76	170	16·65–20·00 20·00–21·76	90 95	15·15–20·80 20·80–21·76	150 190	14·54–21·76	139	12·98–21·20 21·20–21·76 21·76	130 120 180	14·02–21·76	98	14·96–20·77 20·77–21·76	120 140
2515	11·91–24·16	145	11·00–24·16	75	9·97–11·00 11·00–24·16	100 150	9·04–24·16	123	7·34– 8·57 8·57–10·60 10·60–24·16	120 140 160	8·25–24·16	143	9·66–14·50 14·50–24·16	125 160
2516	11·36–17·54	148	10·08–17·54	98	9·10–17·54	104	8·32–17·54	100	6·30–17·54	80	7·35–17·54	75	8·87–17·54	75
2810	....	....	19·71–21·09	98	17·44–21·09	150	16·39–21·09	141	12·30–13·40 13·40–21·09	110 100	14·20–21·09	110	15·87–21·09	140
2811	17·21–20·23	144	16·79–20·23	95	14·43–19·00 19·00–20·23	150 95	13·18–20·23	137	10·26–16·60 16·60–20·23	120 100	12·37–20·23	71	12·96–17·12 17·12–20·23	85 135
2815	9·67– 9·85	280	8·90– 9·85 9·85	135 180	7·07– 9·85	135	6·13– 9·85	120	4·45– 4·50 4·50– 9·85	110 120	5·40– 9·85	98	6·86– 9·85	105
2816	....	....	....	....	....	....	5·96– 7·35	90	4·36– 7·35	110	5·35– 7·35	78	6·78– 7·35	100
2910	19·70–34·31	130	19·39–34·31	90	17·40–29·00 29·00–34·31	140 90	16·43–34·31	84	12·64–23·40 23·40–34·31	80 140	17·47–34·31	60	16·02–34·31	120
2911	15·33–23·80	125	15·88–23·80	80	13·02–21·00 21·00–23·80	120 90	11·71–23·80	103	8·80–13·90 13·90–23·80	80 110	10·50–23·80	76	11·46–23·80	115
2915	7·81–15·31	115	6·73–15·31	73	5·11–15·31	115	4·12–15·31	78	2·50–15·31	70	3·39–15·31	73	4·83–15·31	95
2916	7·29–12·48	148	6·16–10·00 10·00–12·48	75 130	4·60–12·48	95	3·42–12·48	85	1·95–12·48	70	2·8–12·48	68	4·33–12·48	75
3310	15·77–36·58	170	15·66–30·00 30·00–36·58	105 115	15·10–16·20 16·20–36·58	170 180	14·59–36·58	78	13·08–20·00	110	14·01–36·58	140	14·51–24·50 24·50–36·58	165 150
3310	....	....	....	....	....	....	....	....	20·00–36·58	165	....	....	....	....
3311	14·95–41·30	180	14·70–41·30	130	13·94–41·30	210	13·36–41·30	90	11·24–41·30	130	12·20–41·30	125	12·92–11·30	185
3315	6·94–31·61	245	6·00–10·00 10·00–31·61	110 180	4·73–26·00 26·00–31·61	100 180	3·52–31·61	50	2·31–31·61	40	3·67–31·61	72	4·41– 7·25 7·25–31·61	95 140
3316	5·82–30·77	245	5·20–30·77	100	3·58–30·77	120	2·16–30·77	50	1·58–30·77	320	2·63–30·77	255	3·51– 6·76 6·76–30·77	140 180
3410	14·30–35·65	205	14·05–25·00 25·00–35·65	130 190	13·58–22·00 22·00–35·65	200 220	12·95–35·65	76	11·52–35·65	80	12·33–35·65	165	13·00–35·65	120
3411	13·88–34·37	175	13·54–34·37	130	13·37–34·37	210	12·72–34·37	166	17·17–34·37	80	12·01–34·37	104	12·55–34·37	125
3415	6·36–44·48	100	5·58–44·48	100	4·58–44·48	100	0·80–44·48	50	2·10–44·48	50	3·87–44·48	120	4·49–44·48	95
3416	5·56–24·19	238	5·61–10·00 10·00–20·00 20·00–24·19	170 180 175	3·90–24·19	300	2·25–24·19	166	1·60–24·19	270	2·44–24·19	235	?	195

Depth measured below top of casing.

20-11-74		23-12-75		23-1-75		24-2-75		15-4-75		19-5-75		Weighted mean
Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	Depth (m)	mg/l	
15·33–15·67	190	dry	....	dry	....	dry	....	dry	....	dry	....	142
15·55–21·76	125	16·45–21·76	135	16·52–20·49 20·49–21·76	150 185	16·96–21·76	138	17·42–20·85 20·85–21·76	126 220	17·69–20·65 20·65–21·76	140 156	133
10·22–24·16	125	10·85–24·16	152	11·03–24·16	152	11·48–24·16	133	11·87–24·16	124	17·24–24·16	118	126
9·68–17·54	90	?	121	10·50–17·54	160	11·01–17·54	128	11·50–17·54	90	11·69–17·54	105	101
17·18–21·09	96	19·61–21·09	133	18·83–21·09	115	19·50–21·09	133	dry	....	dry	....	120
14·08–20·23	90	16·16–20·23	148	15·88–20·23	227	16·57–20·23	135	17·11–20·23	125	17·49–20·23	125	122
7·66– 9·85	96	8·75– 9·85	132	8·81– 9·85	242	9·31– 9·85	200	dry	....	dry	....	123
	....	dry	....	dry	....	dry	....	dry	....	dry	....	96
17·11–34·31	110	18·63–34·31	135	18·05–34·31	140	19·14–34·31	120	19·52–19·78 19·78–34·31	117 120	19·82–19·90	115	110
12·93–23·80	90	15·71–23·80	126	14·90–23·80	131	16·04–23·80	100	16·23–23·80	104	16·50–16·75	100	102
5·53–15·31	82	6·52–15·31	121	6·88–15·31	105	7·36–15·31	118	7·92–15·31	104	8·25–15·31	102	94
4·64–12·48	76	6·07–12·48	121	6·30–12·48	124	6·83–12·48	133	7·43–12·48	104	7·72–12·48	105	95
14·92–36·58	140	16·05–36·58	170	15·34–23·60	168	15·56–36·58	160	15·67–25·00 25·00–29·80	164 190	15·72–18·90 18·90–20·90	160 151	156
....	....	....	....	23·60–30·70 30·70–36·58	215 360	....	....	29·80–36·58	201	20·90–36·58	253	
13·53–41·30	165	14·97–41·30	203	14·24–18·00 28·00–41·30	195 250	14·60–41·30	205	14·82–41·30	155	14·88–41·30	185	169
5·07–31·61	110	6·31–31·61	208	6·17–31·61	260	6·57–31·61	250	6·90–31·61	245	7·02–31·61	230	160
6·65–30·77	60	6·02–30·77	100	5·18–30·77	167	5·56–30·77	208	5·85–30·77	187	6·01–30·77	250	173
13·28–35·65	165	14·94–35·65	220	13·74–35·65	280	14·32–35·65	180	14·10–35·65	245	14·12–17·15 17·15–19·00 19·00–35·65	160 185 170	174
12·82–34·37	82	13·93–34·37	155	13·34–17·00 17·00–34·37	161 210	13·63–34·37	166	13·70–17·50 17·50–34·37	187 200	13·79–34·37	174	152
5·70–44·48	140	5·98–44·48	105	6·98–10·40 10·40–44·48	90 160	6·16–44·48	205	6·83–44·48	170	6·54–44·48	230	123
?	220	5·30–24·19	275	4·87–24·19	270	?	265	?	228	?	234	241

GEOLOGY

The Darling Range forms the western, uplifted rim of the Yilgarn Archaean shield, locally comprising gneissose or granitic rock types intruded by dolerite. These have been deeply weathered and lateritized to provide a mantle over the bed-rock which reaches a thickness of up to 50 m. Bauxite occurs close to the surface in the upper parts of the laterite profile, particularly at high topographic levels. The laterite occurs in massive, gravelly, pisolitic or gibbsitic form and immediately overlies kaolinite which may be subdivisible into a number of zones depending on its physical and mineralogical characteristics. The kaolinite may contain residual quartz from original veining as well as floaters of relatively unweathered rock. These veins, together with old root tubes, may provide favourable infiltration paths through an otherwise poorly permeable sequence.

GROUNDWATER REGIME FOLLOWING MINING

Although relatively few bores have fully penetrated the weathered section, it is evident from the bore records that this section becomes thicker from the north (where it is between 13 and 24 m) to the south (24 and 44 m).

The first set of water-level measurements to be taken at the observation bores after their completion have been reduced to elevation above mean sea level and used to construct a plan of the water table (Fig. 4A). The number of bores is insufficient to accurately place the potentiometric contours on the east side of the mine pit and it has been necessary to assume that they approximate to a mirror image of the pattern on the west. As the measurements were taken on the 19th April 1974 they precede the start of the winter rains and hence represent the lowest position of the water table. It is obvious that the water levels below and downslope of the mine pit are higher than those below the forest to the west.

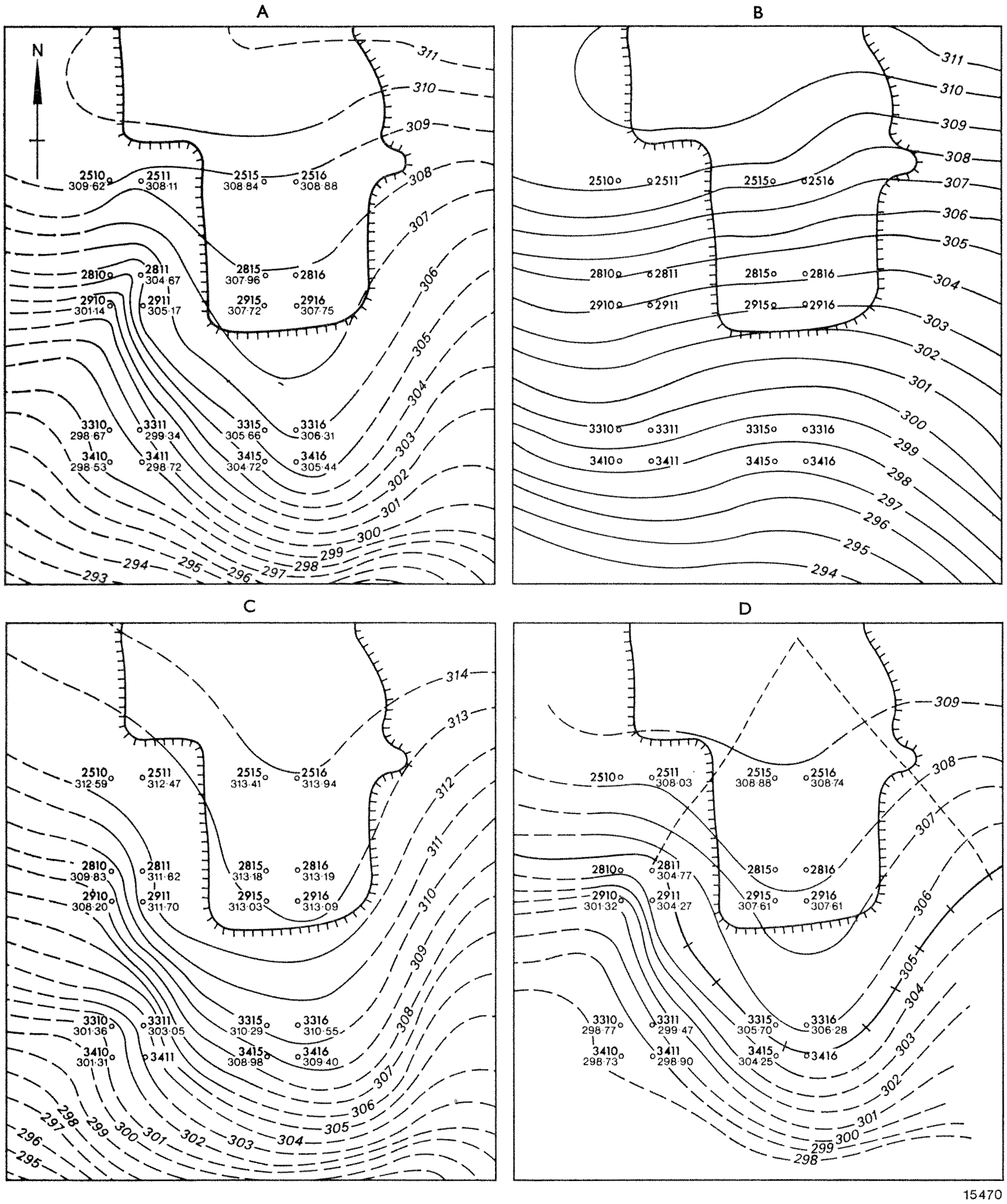


Figure 4. Water-table contours for:—A. April, 1974 ; B. April, pre-clearing ; C. August, 1974 ; D. April, 1975.

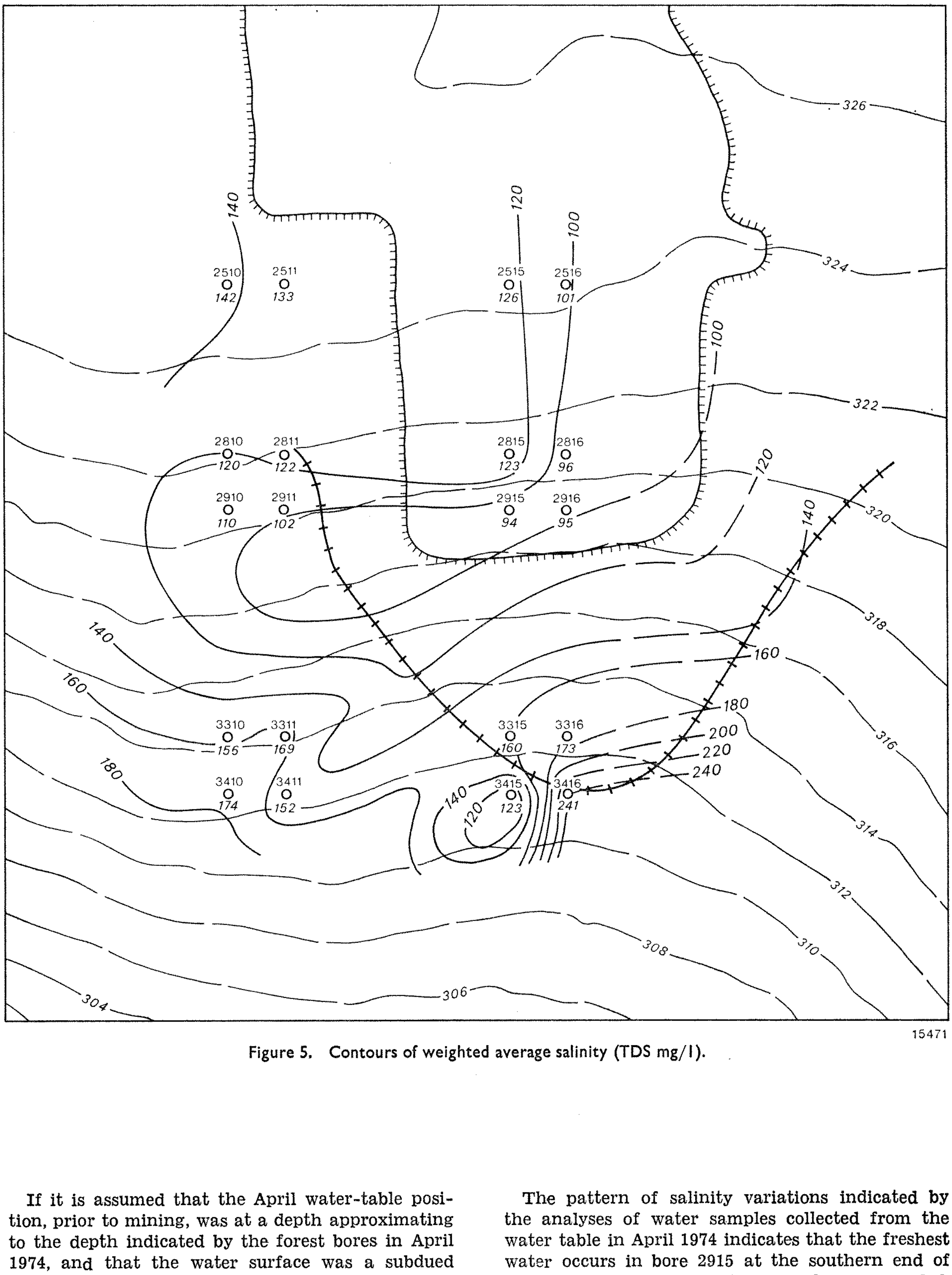


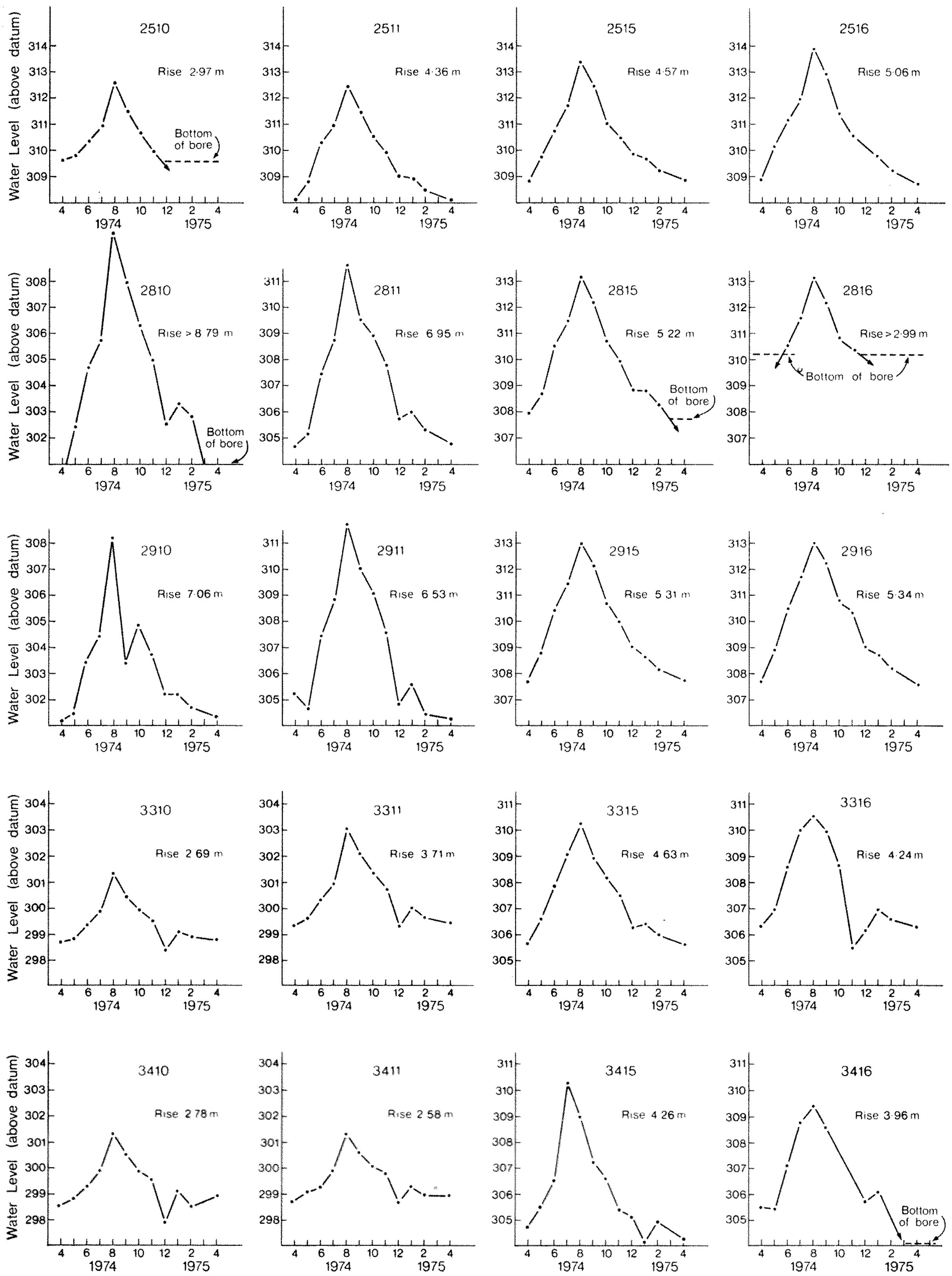
Figure 5. Contours of weighted average salinity (TDS mg/l).

If it is assumed that the April water-table position, prior to mining, was at a depth approximating to the depth indicated by the forest bores in April 1974, and that the water surface was a subdued reflection of the topographic contours, it is possible to very roughly depict the pre-mining water table (Fig. 4B). Comparison between the two plans clearly demonstrates that a groundwater mound has built up below the downslope section of the mine pit and southward below the forest. This has had the effect of steepening the hydraulic gradients to the west and south, possibly also to the east, whereas contours on the east side are subjective.

The pattern of salinity variations indicated by the analyses of water samples collected from the water table in April 1974 indicates that the freshest water occurs in bore 2915 at the southern end of the pit, where a TDS of 115 mg/l was recorded. From this point there is a general increase to the south and west to a maximum of 280 mg/l. There are some variations to this, notably at bore 3415 where relatively low salinities may be due to some annular leakage effects. Perhaps the clearest picture of areal variations in salinity is provided by the contour plan based on the weighted average of 13 monthly analyses between April 1974 and April 1975 (Fig. 5).

SEASONAL CHANGES IN WATER LEVELS

During the months April to August 1974 inclusive, 1 440 mm of rain fell at Del Park. This resulted in a marked rise in the water table in all boreholes. Graphical plots of the reduced level of the water in each bore (Fig. 6) indicate the magnitude and variability of this rise. In the group of bores drilled west and southwest of the pit the average rise was 4.62 m and the range was between 2.58 and 7.06 m. In the mine pit group the variability was less and the range was between 4.57 and 5.34 m with an average of 5.08 m. Similarly, downslope of the pit in the other forest group of bores the rise was between 3.96 and 4.63 m with an average of 4.38 m. The greatest rise amongst all the bores was expressed in bore 2810 in the forest west of the pit. Bore 3411 in this group also exhibited the smallest rise. The maximum levels were experienced in August 1974 with the exception of bore 3415 in which it was July.



15472

Figure 6. Hydrographs at observation bores (April, 1974 to April, 1975).

The August levels have also been used to construct a contour plan of the water table (Fig. 4C). Comparison with the preceding one for April indicates substantially the same pattern of groundwater flow with some differential rises producing minor changes in hydraulic gradient.

Most water levels exhibit a uniform recession from August onward (Fig. 6), whereas some of the hydrographs record an erratic drop in December or January and a subsequent slight recovery to the former line. The drop may be due to some instrumental error but it does coincide with some disturbance of the salinity trends and hence may be due to transpiration. Deep-rooting trees may be expected to increase their water usage with increases in summer temperatures.

The monthly water levels in each of the three bore groups have been averaged to produce mean hydrographs for each area (Fig. 7A). The April 1975 water-level data have been used to draw a further potentiometric contour plan of the water table (Fig. 4D) from which it is evident that the water table has fallen to the same position that it held during the previous April (Fig. 4A).

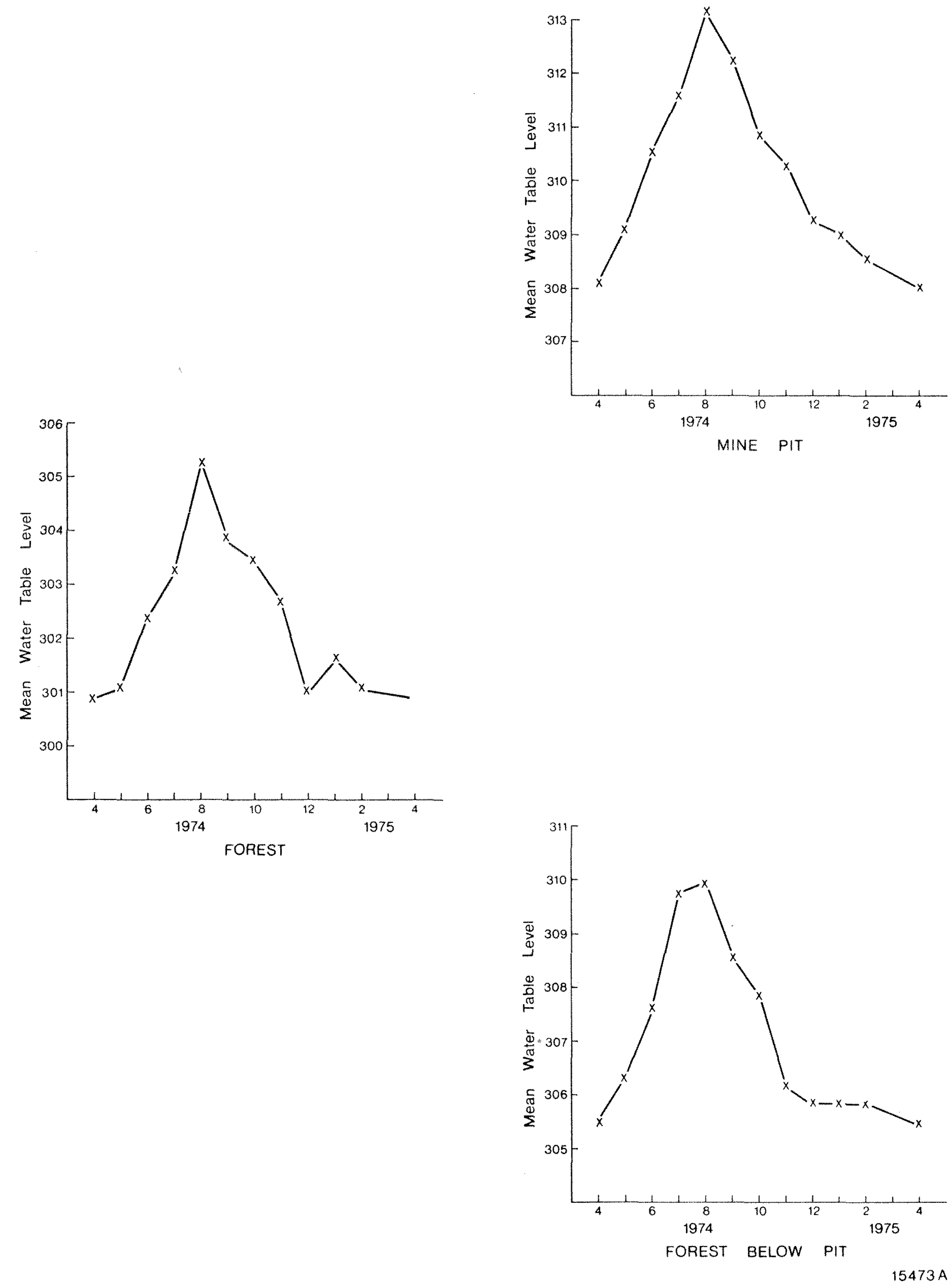
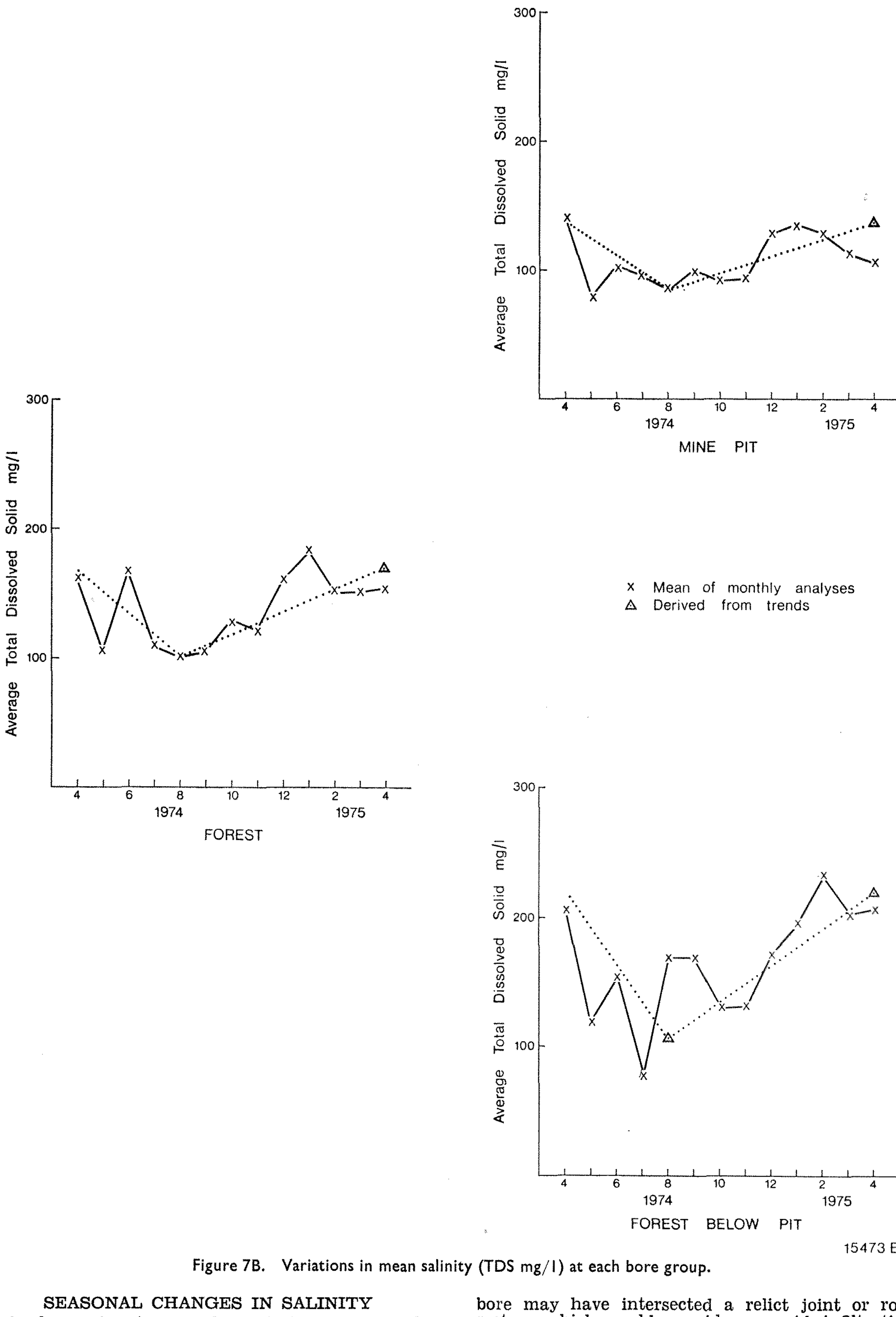


Figure 7A. Hydrographs based on mean water-table levels at each bore group.



15473 B

Figure 7B. Variations in mean salinity (TDS mg/l) at each bore group.

SEASONAL CHANGES IN SALINITY

Analyses of water samples collected each month from the water table (Table 5) have been used to produce graphs of salinity (TDS) against time (Fig. 8). These exhibit a relatively wide range of values for each bore group. The forest bores west and southwest of the mine pit have a range of 60 to 280 mg/l with an average of 140 mg/l. Maximum values tend to occur at any time between January and April and minimum values in July to September. However, there are many somewhat erratic variations that are difficult to account for. They may be due to sampling errors. A sudden drop in salinity during the winter period could be caused by annular leakage in the observation bore or the bore may have intersected a relict joint or root system which could provide a rapid infiltration path for rainwater. Alternatively an excessive disturbance of the natural disposition of water in bores may cause deeper and more saline water to rise and hence provide an indication of salinity above the seasonal trend. Blocking of the upper casing slots may have a similar effect. In order to minimize the effects of these factors, monthly averages of the analyses for bores providing complete records have been used to provide a mean plot of salinity against time for each bore group (Fig. 7B). These clearly indicate the time dependence of salinity, with minima occurring in July-August and maxima in January-April.

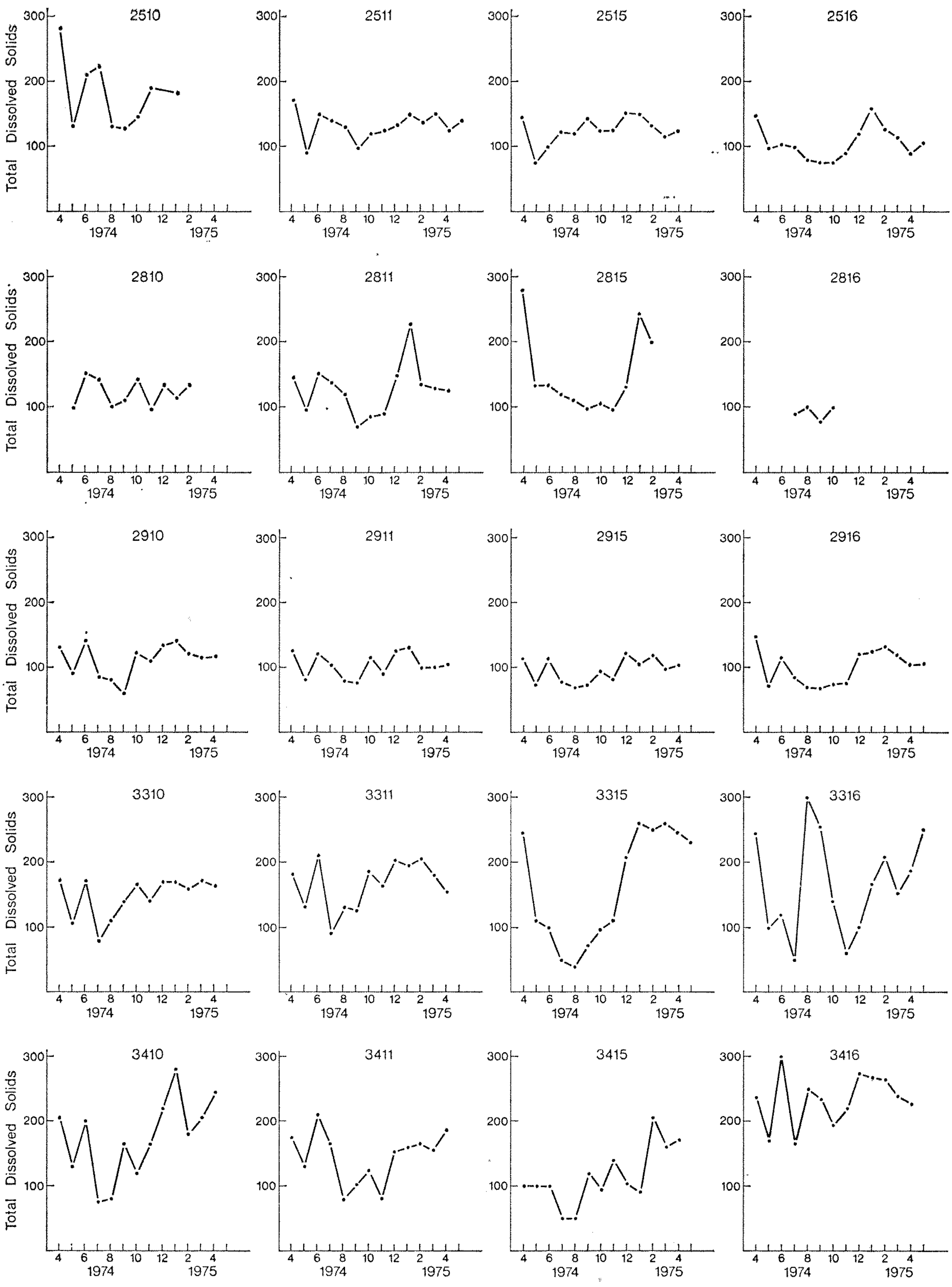


Figure 8. Variations in salinity at observation bores.

The water-table salinities for all bores in the mine pit group range from 70 to 280 mg/l and average 108 mg/l. Monthly averages of analyses of the four bores for which complete records are available (Fig. 7B) show a minimum of 85 in August and a maximum of 139 in April 1974. The graph shows a salinity rise in January to 135 mg/l and a fall to 105 in April 1975.

In the forest bores downslope of the mine pit the salinity range is from 40 to 320 mg/l and averages 168 mg/l. In general the graphs show sharper salinity variations than those for the other two bore groups, and this is reflected in the graph of averages (Fig. 7B). This shows a mean minimum of 77 in July and a maximum of 232 in February.

The forest group west of the mine pit has a minimum average salinity of 101 mg/l in August and a maximum of 181 mg/l in January 1975. The mean is 138 mg/l.

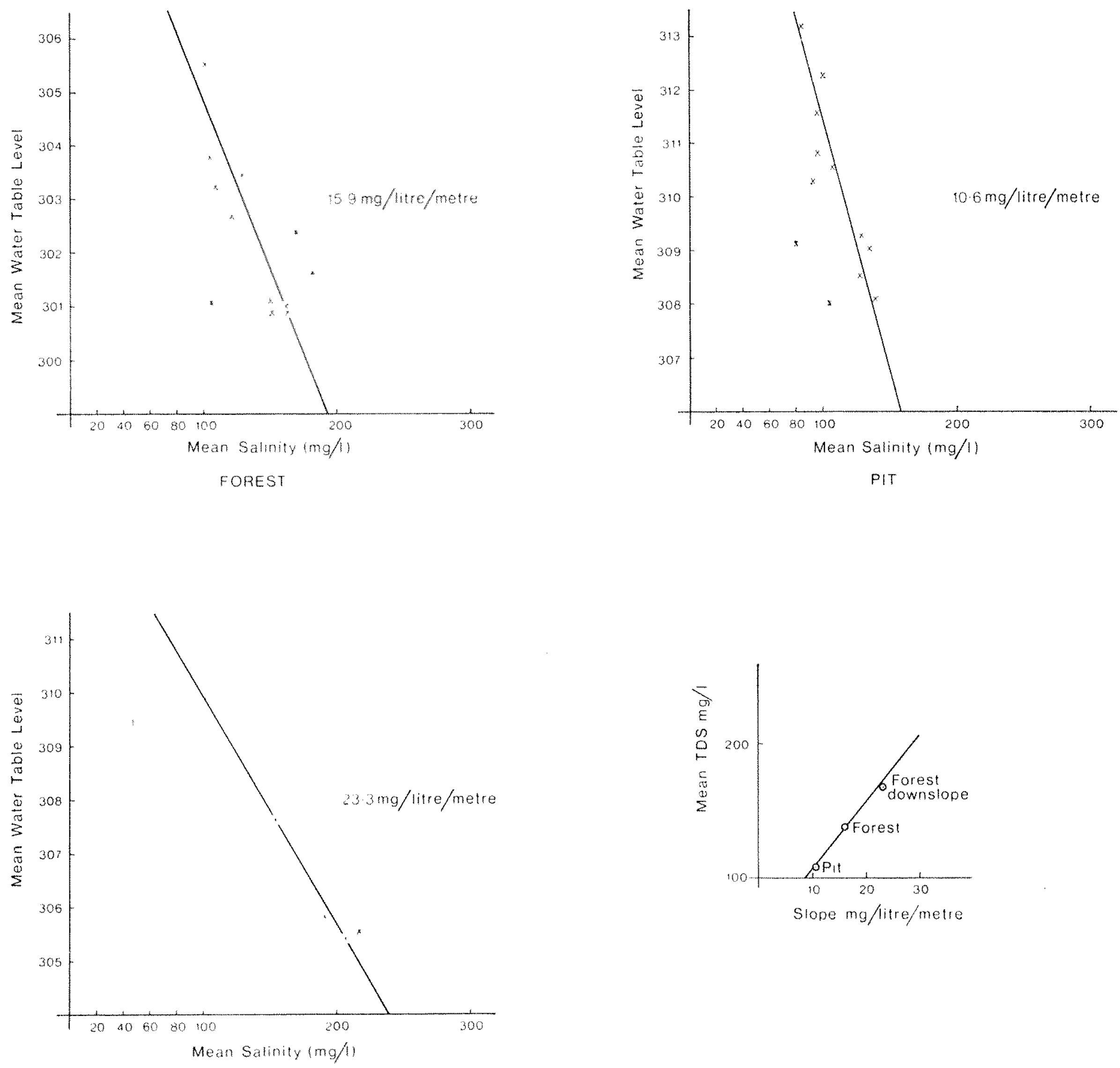


Figure 9. Relationships between mean salinity and mean water-table levels in three bore groups.

When the average salinity for each month in each bore group is plotted against the average water-table level there tends to be a linear correlation (Fig. 9). This is particularly strong in the mine pit group which exhibits an average salinity increase of 10.6 mg/l for every metre fall in water-table level. The increase is at a higher rate in the forest group at 15.9 mg/l/m and higher still in the group downslope of the mine pit. However the scatter of points for this group is wide and it is possible to draw alternative lines of equal validity. If the slope of the drawn line is correct there would appear to be a roughly proportional relationship between the slope and the mean TDS in each area.

RECHARGE TO THE WATER TABLE

The recharge (Q) to a groundwater system that is in balance both with respect to water and salt may be calculated from the relationship:—

$$Q = \frac{Cp}{Cg} \times (P-F) \qquad (1)$$

where Cg is the concentration of chloride in the recharge accession to groundwater (mg/l)

Cp is the concentration of chloride in precipitation (mg/l)

F is the overland flow (mm)

P is the precipitation in a given period (mm)

Q is the amount of recharge reaching the water table.

This presumes that the overland flow has the same chloride content as rainfall.

In order to apply this to the Del Park situation it is necessary to assess both aspects of the hydrologic balance. The hydrographic data reviewed to date have broadly indicated that over a complete climatic cycle the water table returns to the same position and maintains the same form. This was demonstrated by comparison between Figures 4A and 4D which are contoured plans for corresponding months. Detailed comparison between the level in each bore in April 1974 and 1975 indicates that the greatest difference is 470 mm (in one bore) but that the average is about 20 mm. It is therefore possible to say that there has been virtually no change in the saturated groundwater storage and that the output of water from the system is in balance with input.

The present salt balance in the unsaturated zone and at the water table is less easy to assess owing to the variability of the data. However the bores have been placed in three groups for study, each having characteristics which differentiate one from the others. Thus the forest west of the pit may be expected to have a substantial transpirative water loss and be subject to some run-off or overland flow.

Within the mine pit the transpiration loss from the water table would be negligible owing to its limited plant cover, and run-off would be contained within the pit; also a rise has taken place in the water table. The forest downslope of the pit would exhibit a transpiration loss, would have some overland flow and, like the mine pit, has experienced a large rise in the water table. This would partly be due to the influence of the rise below the mine pit immediately up-gradient and partly to extra infiltration allowed by die-back and selective felling. If the rainfall added less salt than was released to saturated groundwater storage from the unsaturated zone, the amount of such salt release would differ from area to area depending on localized conditions.

With the given data such variability may be assessed from the rise in the water table (R) in response to infiltration by assuming that the specific yield at each bore group is approximately the same. The relationship is:—

$$Q = RS \qquad (2)$$

so that combining with (1)

$$RS = \frac{Cp}{Cg} \times (P\text{-}F)$$ where R is the water table rise in mm

or $$\frac{R\ Cg}{P\text{-}F} = \frac{Cp}{S}$$ S is the specific yield

Then for the forest group the value of $\frac{R\ Cg}{P\text{-}F}$ is:—

$$\frac{8\,200^{\dagger} \times (101 \times 0.416)}{1\,440 - 120^{*}} = 261$$

similarly for the mine pit:—

$$\frac{9\,400^{\dagger} \times (85 \times 0.416)}{1\,440} = 231$$

and the forest downslope of the pit:—

$$\frac{7\,200^{\dagger} \times (108 \times 0.416)}{1\,440 - 120^{*}} = 245$$

Values for the two forest areas are fairly close but that for the mine pit differs by being 13 per cent lower which, having regard to the reliability of the salinity data, is a relatively small discrepancy. The results may be interpreted in three ways:

(a) The overland flow estimate is too high;

(b) The response to infiltration in the mine pit is lower than it should be because the specific yield is actually higher than that below the forest;

(c) The salinities in both of the forest bore groups are too high due to the accession of salt from the unsaturated zone.

If overland flow was actually absent in the forest areas the difference between the mine pit and other values would be reduced to about 4 per cent. The last point leads to the conclusion that if infiltration through the unsaturated zone is removing more salt than it adds to that zone, the relatively low salinity below the mine pit would indicate that its effect there must be much lower than below the forest and it could now be negligible. Thus comparison between the effects of bauxite mining and those of Phytopthora cinnamomi and selective felling in the forest areas would indicate that the latter result in higher groundwater salinities.

If it be accepted that the removal of salt from the unsaturated zone below the pit is now negligible, then the amount of the recharge resulting from 1 440 mm of rain in the mine pit may be calculated from equation (1). The chlorinity of the rainfall at Del Park is 9.0 (from Hingston, 1958) and the minimum salinity (TDS) is 85 mg/l. This may be converted to chlorinity by the factor 0.416 which is the ratio of Cl to TDS established from the chemical analysis of 9 samples drawn from various bores in the area (Table 7).

$$\text{Hence the recharge is } \frac{9}{85 \times 0.416} \times 1\,440 = 366 \text{ mm}$$

*Estimated from data from the Little Dandalup River.

†From recessions plotted in Figure 10.

Similar calculations for the forest area west of the pit and downslope to the south indicate infiltration of 283 and 264 mm respectively but these would be higher if the minimum seasonal salinities in these areas were influenced by salt release. Direct comparison of the figures as they stand indicates that the water table below the mine pit receives about 34 per cent more infiltration than the forest areas.

TABLE 7. CHEMICAL ANALYSES OF WATER SAMPLES

Partial analyses of water samples

Borehole	Depth (m)	Date	pH	TDS (mg/l)	NaCl (mg/l)
2511	20	6/3/74	6·3	200	112
2511	21	6/3/74	5·9	200	109
2811	18–19	6/3/74	5·2	140	94
2910	21	17/4/74	5·5	130	101
2910	34	17/4/74	5·1	120	91
3311	19	11/4/74	4·3	320	237
3311	42·12	11/4/74	5·2	170	124
3411	16	11/4/74	4·5	210	152
3411	34	11/4/74	5·5	200	140
	Average	....	....	188	129

Ratio 1 : 0·686 4 NaCl
1 : 0·416 Cl

Standard analysis of water sample from Bore 2910

Bailed sample collected on 17th April, 1974

pH	5·7
TDS by Evaporation	110 mg/l
Conductivity x 0·7	130
NaCl	86
Total hardness	23
Total alkalinity	10
Calcium	3
Magnesium	4
Sodium	30
Potassium	1
Iron (Fe in solution)	<0·05
Boron	0·3
Fluoride	<0·1
Bicarbonate	12
Carbonate	Nil
Sulphate	7
Chloride	52
Nitrate	<1
Silica	7

AQUIFER CHARACTERISTICS

SPECIFIC YIELD

As has already been noted, infiltration reaching the water table causes it to rise by an amount depending on the specific yield. Where both the infiltration and the rise are known, the specific yield can be calculated from equation (2). However, only part of the potential water-table response to infiltration is recorded because recharge takes place over a period during which some losses by groundwater flow and transpiration take place. Account may be taken of this by extrapolating the water-table recessions into the recharge period, and measuring the "instantaneous" rise at a median time (Fig. 10). The indicated rise at the mine pit is 9.400 m, and as this was in response to the infiltration of 366 mm of rain, the specific yield S is

$$\frac{366}{9400} = 0.039\,0.$$

The specific yields for the forest bore groups may be similarly derived using the recharge figures previously quoted, these being 0.034 5 and 0.036 6 for the groups west and south of the pit respectively.

TRANSMISSIVITY

The quantity of water (Q_1) being discharged through a given cross section is given by the Darcy equation:

$$Q_1 = T\ a\ L \qquad (3)$$

where T is the transmissivity
a is the hydraulic gradient
L is the section length.

If the discharge is independently assessed it is then possible to derive the transmissivity at a particular flow section where the hydraulic gradient is known. In Figure 4D the catchment commanded by the section AA is indicated by two converging flow lines which contain an area of 18 590 m^2. The mine pit occupies 8 870 m^2 so that rainfall between April and August, 1974, could be expected to recharge the groundwater by 0.366 x 8 870 = 3 246 m^3 over this area.

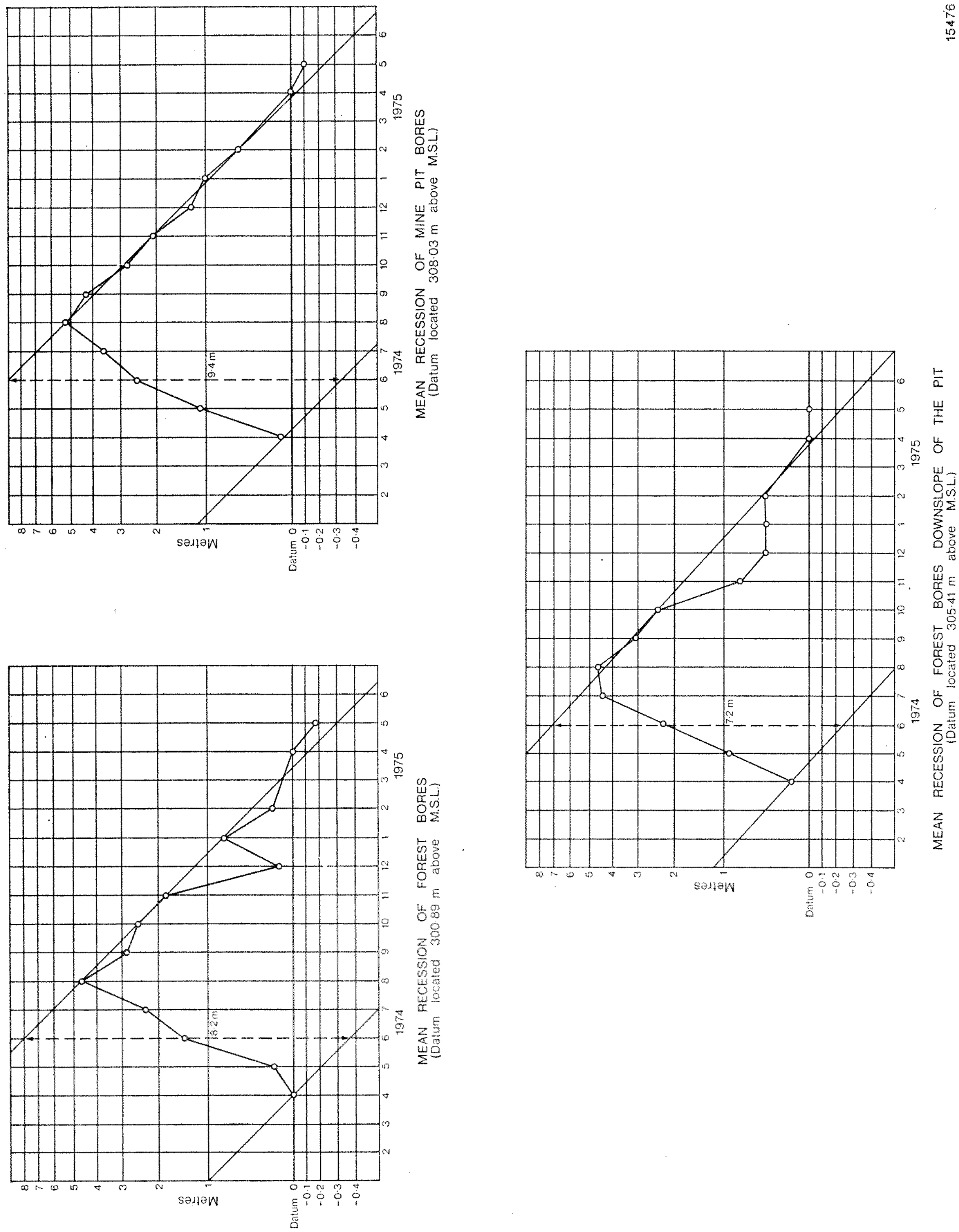


Figure 10. Seasonal rise and water-table recession between April, 1974 and April, 1975.

The recharge figure of 264 mm which has already been quoted for the forest area must be reduced for transpirative losses from the water table. As the water-table salinity in this bore group increases from 108 to roughly 230 mg/l during the recession it could be argued that the losses reduce the discharge to

$$\frac{108}{230} \times 264 = 129 \text{ mm.}$$

However, as will be seen later, some of the increase is due to leaching and indeed 1.22 times more salt is discharged from the area than is received from rainfall. If this factor is applied to the estimate of 129 mm, the estimated discharge becomes 158 mm. The area of the forest between the pit and the discharge section is 9 720 m^2 so that the groundwater discharge from this part of the catchment is 0.158 x 9 720 = 1 536 m^3. The sum of the contributions from each part of the catchment is 4 782 m^3 and the average hydraulic gradient through the section is 1.96 m in 24.38 m (80 feet) or 0.080 39 to 1. The transmissivity (T) through a section 255 m long is

$$T = \frac{Q}{aL} = \frac{4\ 782}{365 \times 255 \times 0.08039} = 0.636 \text{ m}^3/\text{day/m}.$$

HYDRAULIC CONDUCTIVITY

The average hydraulic conductivity may be derived by dividing the transmissivity by the average saturated aquifer thickness. Unfortunately many of the observation bores did not fully penetrate the water-bearing section and so it is only possible to state that the thickness is not less than 16.4 m and to estimate the value may be about 18 m. The hydraulic conductivity would therefore be approximately equal to

$$\frac{0.63}{18} = 0.0354 \text{ m}^3/\text{day}/\text{m}^2$$

or 68×10^{-8} cm/sec

These figures are quite high when account is taken of the lithology of the material through which water is passing, and may be indicative of some discharge taking place through fractures in the bedrock. The figures must in any case be regarded as approximate mean values as large variations are to be expected in relation to depth and possibly area. In the course of drilling several of the observation bores a slurry zone was encountered which defied recovery of samples by augering or coring, and apparently had a lower density than other material.

The hydraulic conductivity (K) may be used in conjunction with porosity and the hydraulic gradient to derive the velocity of water movement (V) from

$$V = \frac{Ka}{\phi} \qquad (4)$$

where ϕ is the porosity

If the porosity is 40 per cent, the velocity becomes

$$\frac{0.035 \times 0.08039}{0.4} = 0.0070 \text{ m/day in the direction of}$$

the hydraulic gradient. However as there is a water-table recession of about 8.2 m in 365 days there is a downward velocity component which averages $\frac{8.2}{365} = 0.022$ m/day. The vectorial addition of the two components yields a velocity of 0.027 m/day in a direction about 22° from vertical. This applies at the water table but deeper in the saturated profile the flow directions progressively veer towards the hydraulic gradient and the velocities approach 0.0070 m/day.

HYDROLOGIC BALANCE

The amount of infiltration which reaches the water table at each of the three groups of bores has been separately estimated. However the subsequent removal of water by transpiration and evaporation in the forested areas may be expected to cause the salinity of water at the water table to increase through the summer; the water loss also contibutes to the rate of recession. Salinities tend to reach a maximum in April, coinciding in time with minimum water-table levels. The relationship between these levels and salinity during the recession appears to be a linear one (Fig. 9) in at least two of the bore groups. However, the absence of deep-rooting trees in the mine pit area would obviously preclude transpirative losses and an alternative mechanism for salinity increase must be sought.

This may be illustrated by a simple model (Fig. 11) in which the water table is represented as moving through a series of 1-m cubes of water-bearing material. As the level falls, water drains successively from one cube to the next in the direction of groundwater movement. Each cube is assumed to have a porosity of 40 per cent of which 36.1 per cent is taken up by moisture of retention and the remaining 3.9 per cent (which is the specific yield) is occupied by water which is essentially mobile and takes part in the dynamic system. The salt stored in each cube is in balance so that when the water of saturation is displaced by an equal volume (Vd) of water having a salt concentration of C_i this is added to the salt stored in the moisture of retention (Vr) which has a concentration C_r. If the two concentrations then come into equilibrium by molecular and dynamic diffusion the water which drains from the first cube to the second will have a concentration C_e. This may be derived from $V_d\ C_i = V_r\ C_r = (Vd + Vr)\ C_e$

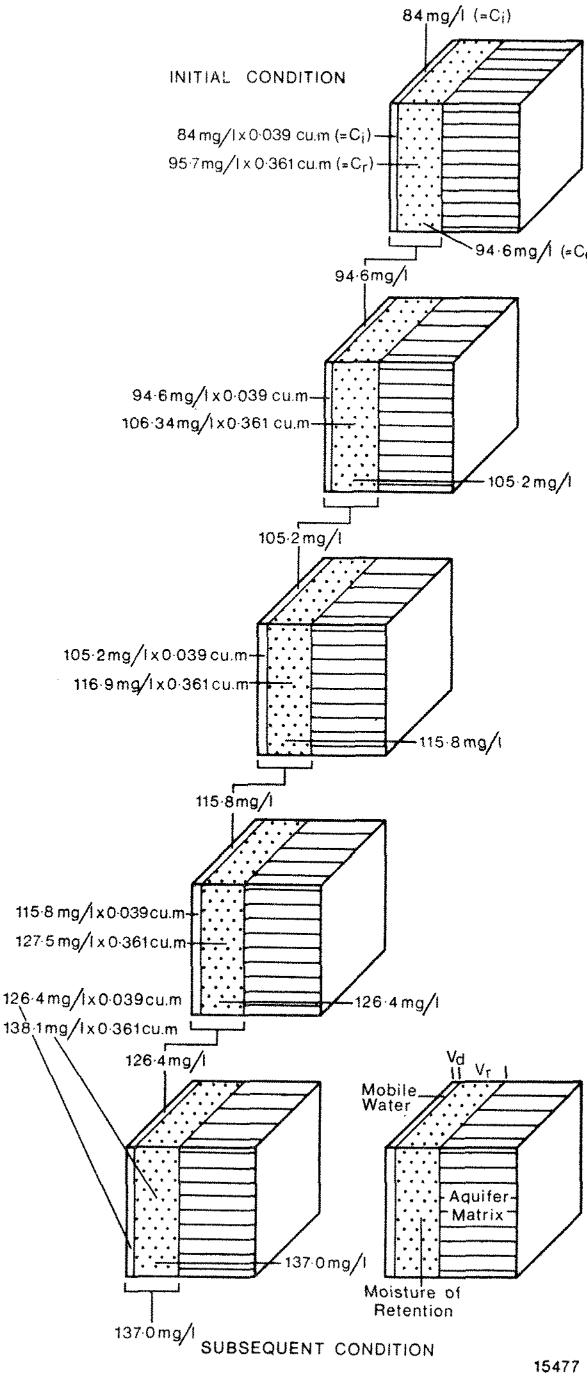


Figure 11. Model illustrating decreasing salinity of moisture of retention during recession in the absence of transpirative loss from water table.

In practice the spaces occupied by mobile water and the moisture of retention are intimately related and distributed throughout the water-bearing volume, so that dispersion over only relatively short distances is necessary to achieve a high degree of mixing. The known salinity increase of 10.6 mg/l/m for the mine group of bores has been applied to each cube successively in Figure 11 not only to demonstrate the mechanism of salinity increase but also to estimate the rate of change in the salt storage within the zone of water-table fluctuation. The model indicates a fall of 1.1 mg/l in the concentration of salt in the moisture of retention during each recession. The model has the disadvantage of taking no account of the passage of more than one volume (0.039 m³) through each cube, in the course of any one recession. However the measured water-table salinities are true ones and, provided the estimates of porosity and specific yield are reasonably correct, it is believed that the model indicates rates of leaching that are of the right order. At 1.1 mg/l per recession it will take

$$\frac{137\text{-}84}{1.1} = 48 \text{ recessions to reduce the salt stored}$$

in the zone of fluctuation to a storage level in balance with the influent water. The wetting or saturating cycle which takes place during the winter would probably have a similar leaching effect on the profile so that about 24 years is the time required for leaching to be completed. It is to be expected that during this period the salinities at all levels in the profile will decline unless water usage by plants increases, in which instance the reverse will occur until balance is again achieved.

In the forest west of the mine pit, the wide variations in the seasonal water-table rise and of the subsequent seasonal increases in salinity during the recession indicate wide variations in infiltration and of transpirative losses from the water table. The average infiltration is about 283 mm but could be a little higher. If the salt stored in water of retention within the zone of water-table fluctuation is in balance, then the average seasonal increase in salinity from 101 to about 170 mg/l would indicate a transpirative loss from the water table of about $283 - \frac{101}{170} \times 283 = 115$ mm. However this may be too high because the leaching of salt from the zone of fluctuation is quite possibly taking place as the forest association has been subject to disturbance due to Phytopthora, selective felling, and the use of forest tracks. The normal salt balance was disturbed before the commencement of mining.

The transpirative loss from the forest area downslope from the mine pit may be similarly calculated. It is not more than 135 mm and could be as low as 106 mm as previously derived.

If the quantity of infiltration reaching the water table is deducted from the incident rainfall (i.e. rainfall less overland flow), then the amount of water either directly evaporated or added to the soil and used by plants can be derived for each bore group. The greatest loss appears to occur in the mine pit where it is 1 074 mm and the smallest, 1 037 mm, in the forest to the west (Table 8). The difference is only about 3.5 per cent which is within the limits of error possible in the measurement of salinity or the estimation of run-off.

TABLE 8. WATER BALANCE (IN MM).

	Forest	Mine pit	Forest below pit
Rainfall (in period April-August)	1 440	1 440	1 440
Run-off	120	0	120
Evaporation and moisture addition to unsaturated zone	1 037	1 074	1 056
Transpirative loss from the water table	115–78	0	135–106
Groundwater discharge	168–205	366	129–158
Infiltration reaching water table from rainfall	283	366	264

As rainfall in the period September to November, 1974, amounting to 225 mm, makes no contribution to the water-table rise, this quantity is almost certainly lost by evaporation and transpiration from the unsaturated zone and may be added to the corresponding figures in the table.

SALT BALANCE

The average annual input of chloride to a particular area may be derived from the rainfall chlorinity and the mean annual rainfall. The latter has been estimated to be 1 500 mm and the chlorinity 9 mg/l.

The input to the area defined by the flow lines and section on Figure 4D is therefore $9 \times 1\,500 \times 18\,590 \times 10^{-3} = 251$ kg. The flow of groundwater through the discharge section has been estimated to be 4 762 m^3/year. The mean salinity (TDS) derived from contours of the weighted means (Fig.5) for each borehole (Table 6) is 149 mg/l which includes a chloride content of $149 \times 0.416 = 62$ mg/l. The chloride discharge by groundwater movement is $62 \times 4\,762 \times 10^{-3} = 295.2$ kg. To this must be added the chloride discharged with the overland flow. This is estimated to be $9 \times 120 \times 9\,720 \times 10^{-3} \times 10^{-3}$ kg $= 10.5$ kg. The ratio of salt output to input is $\frac{295.2 + 10.5}{251} = 1.22{:}1$. An error of even 50 per cent in the estimation of overland flow would result only in a change of the calculated salt ratio of about 2 per cent. A more potent source of error would be any discharge of salt which takes place with flow through fractures in the bed-rock. This is quite possible and would result in the ratio, as calculated, being too low.

Although the preceding discussion of groundwater movement has mainly been in terms of flow through a relatively uniform medium of low hydraulic conductivity, the existence of open old root system tubes and remnant quartz-filled joints could provide a rapid and fairly direct means of recharging any groundwater contained in bed-rock fractures. Indeed such a condition could possibly constitute a distinct flow system which may have been the dominant means of groundwater movement in some forest areas prior to disturbance by felling or Phytopthora. At this time the salt outflow was in balance with inflow and the efficiency of water usage by the forest association was such that it consumed virtually the whole of the rainfall which entered the normal soil profile. The groundwater contribution to stream-flow would then have been almost entirely from the bed-rock joint system.

CONCLUSIONS

1. The infiltration of rainfall to the water table below the mine pit has been estimated by salt balance to average 34 per cent higher than below the forest area. This would be reduced by between 4 and 13 per cent if leaching of salt from the unsaturated zone were still occurring in the forest.

2. Infiltration in the forest area is very variable, and water-table rises are sometimes higher than below the mine pit.

3. Groundwater discharge from below the mine pit is more than twice that of the groundwater discharge from below the forest. This is due to a lack of transpirative loss once water has reached the water table.

4. The development of a large groundwater mound is mainly due to the absence of transpirative loss from the water table and only in minor degree is it due to a greater infiltration.

5. The groundwater mound represents an increase in the groundwater storage. It may be expected to recede when transpirative use both reduces the accession of water to the water table and increases withdrawal of water from it.

6. The average specific yield is approximately 0.039 and the hydraulic conductivity is 0.035 $m^3/day/m^2$.

7. The release of salt from the unsaturated zone in the mine pit is now very small but leaching is taking place in the zone of water-table fluctuation. The same may be occurring below the forest.

8. Although there is salt leaching taking place below the mine pit the lack of transpirative loss from the water table means that the additional salt is discharged in a larger quantity of water and hence is diluted to a salinity that is now lower than that of the main body of groundwater.

The pattern of salinity indicates increasing salinity in the direction of groundwater movement. This is due to the transpirative loss of water from the water table or reduced infiltration for the same reason. If this loss increased because of the water table being shallower, it could nullify the freshening effect of the additional groundwater discharge resulting from clearing upslope.

9. The present salt imbalance is such that approximately 1.2 times as much salt is being discharged as is received in rainfall. It is not possible to separately estimate the contributions of salt made by the disturbed forest and the mine pit.

REFERENCES

Bettenay, E., Blackmore, A. V., and Hingston, F. J., 1964, Aspects of the hydrologic cycle and related salinity in the Belka Valley, W.A.: Aust. Jour. Soil Res., v. 2, p.187-210.

Burvill, G. H., 1947, Soil salinity in the Agricultural area of Western Australia: Aust. Inst. Agr. Science Jour. 13, p.9-19.

Hingston, F. J., 1958, The major ions in Western Australian rainwaters: Australia CSIRO Div. of Soils Rept. 1/58.

Wood, W. E., 1924, Increase of salt in soil and streams following the destruction of native vegetation: Royal Soc. West. Australia Jour. 10(7), p.35-47.

OUTLINE OF THE HYDROGEOLOGY OF THE SUPERFICIAL FORMATIONS OF THE SWAN COASTAL PLAIN

by A. D. Allen

ABSTRACT

The Swan Coastal Plain forms part of the eastern onshore edge of the Perth Basin. In downward order it is underlain by a highly variable sequence of "Superficial Formations" up to 90 m thick of Quaternary age which rest with marked erosional break on about 8 000 m of Phanerozic sedimentary rocks.

Unconfined groundwater occurs in the "Superficial Formations", and is locally in hydraulic continuity with the confined groundwater in the underlying formations. The areas to the north and south of Perth are hydrogeologically distinct. In the northern area the water table forms a pronounced north-south-trending ridge (Gnangara Mound) rising to 70 m above sea level, whereas to the south the groundwater generally slopes downward to the west apart from an area south of the Swan River (Jandakot Mound) where the water table reaches 25 m above sea level.

The Gnangara Mound contains substantially larger resources than those of the area south of the Swan River. The groundwater is replenished annually by rainfall, and north of the river has a salinity generally ranging beween 250 and 500 mg/l TDS. However the presence of iron, turbidity, and colour necessitates treatment before it can be used for public water supply purposes.

INTRODUCTION

LOCATION

The part of the Swan Coastal Plain where groundwater resources are being investigated for the Perth metropolitan region covers the area from Gingin Brook in the north to Peel Inlet in the south, and is shown in Figure 12. It extends for about 70 km north and 65 km south of Perth, and has an area of about 3 600 km^2 of which about 2 200 km^2 are north of the Swan River and 1 400 km^2 are to the south.

The area north of the Swan River has an average elevation of 30 to 60 m above sea level whereas to the south the average elevation is only 15 to 30 m. There is also a marked variation from west to east across the coastal plain. The area adjacent to the coast has an irregular topography typified by linear ridges, while the central part of the coastal plain is relatively flat, gradually increasing in elevation as the Darling Range is approached and increasing very steeply along the foot of the range. Modifying this general pattern are lower areas associated with the major rivers where they cross the plain.

The coastal plain to the north and south of Perth is topographically, hydrodynamically and to a certain extent geologically divisible into two distinct areas. They are described separately and for convenience of description they are hereafter referred to as the northern and southern areas.

PURPOSE AND SCOPE

The increasing demand for water in the Perth region has necessitated the assessment of the groundwater resources in the vicinity of Perth. At present, groundwater provides about 10 per cent of the requirements for Perth's water supply but by the year 2000 may provide 25 per cent.

Beneath the coastal plain there are two major, related groundwater resources: unconfined groundwater in the superficial formations, and confined groundwater (artesian and sub-artesian) in the considerably older, underlying sedimentary rocks.

This account deals with the unconfined groundwater resources. It is not a detailed or complete account because acquisition and assessment of data is still continuing. Nevertheless the broad outline of the hydrogeological regime is now becoming clear, and is described.

DRILLING PROGRAMMES

Exploratory drilling of the unconfined groundwater resources commenced in the northern area in 1962 and in the southern area in 1972. A total of 249 exploratory and production sites have so far been drilled of which 213 have been drilled in the last 3 years. The location of the exploratory and production sites is shown in Figure 13 and the different drilling programmes are summarized in Table 9.

TABLE 9. SUMMARY OF DRILLING PROGRAMMES

Project/ Scheme	Commenced	Completed	No. Sites	Authority
Northern Area				
Gnangara	1962	1969	35*	GSWA & MWB
Mirrabooka	1969	1975	19‡	MWB
Gwelup	1971	1974	15‡	MWB
Whitfords	1972	1972	6†	MWB
Wanneroo	1972	1974	24‡	MWB
Joondalup	1972	1975	23	GSWA
Gingin	1973	1973	11	MWB
Yanchep	1973	1973	10	MWB
Pinjar	1975	1975	30‡	MWB
Southern Area				
Lake Thompson 1	1972	1973	11	MWB
Lake Thompson 2	1974	1975	11	MWB
Lake Thompson 3	1975	1975	54	MWB
Jandakot	1975	Continuing	30	MWB
Total	....	....	279	

* Exploratory and production bores.
† Abandoned production bores.
‡ Production bores.

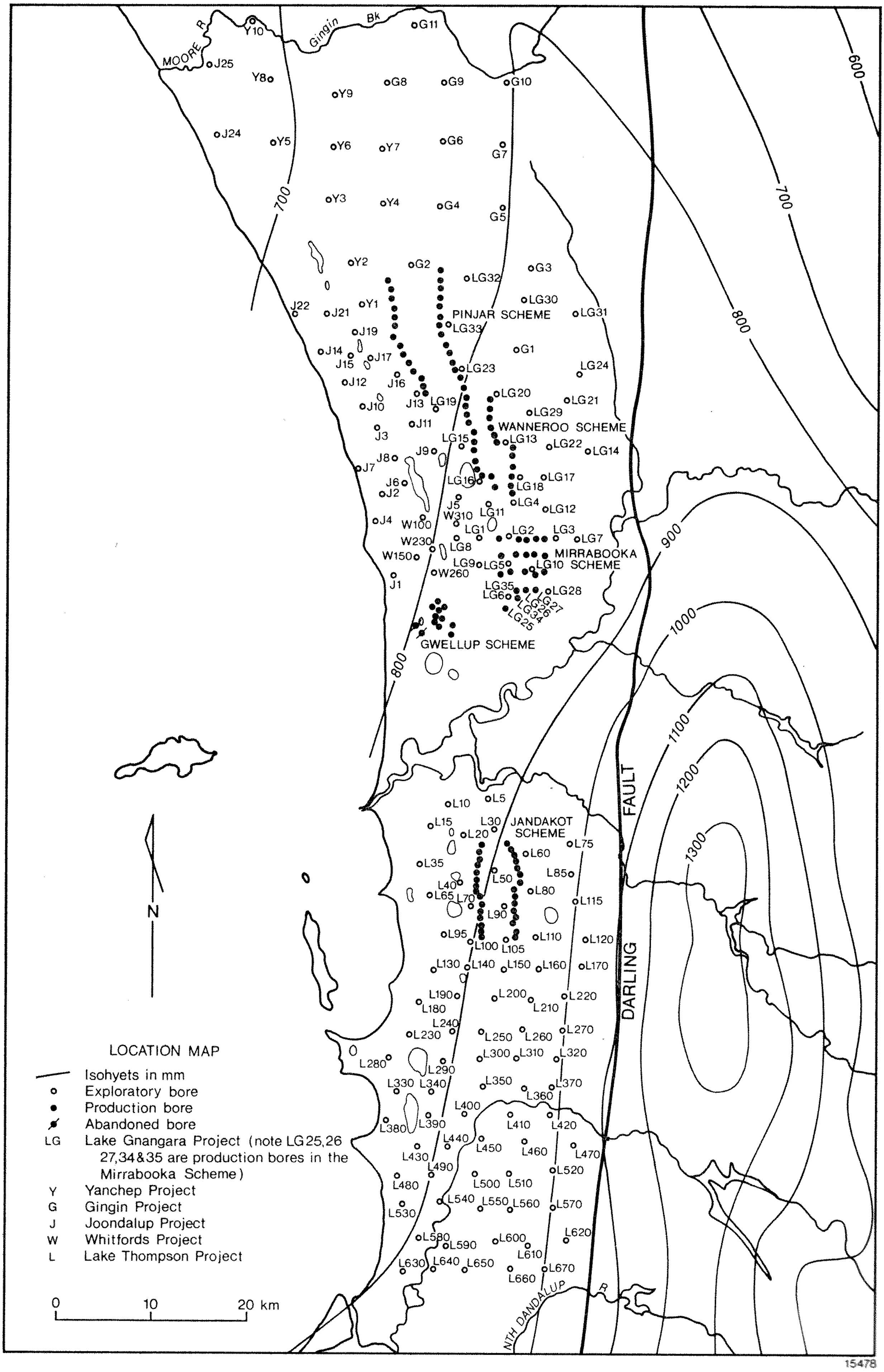


Figure 12. Location Map.

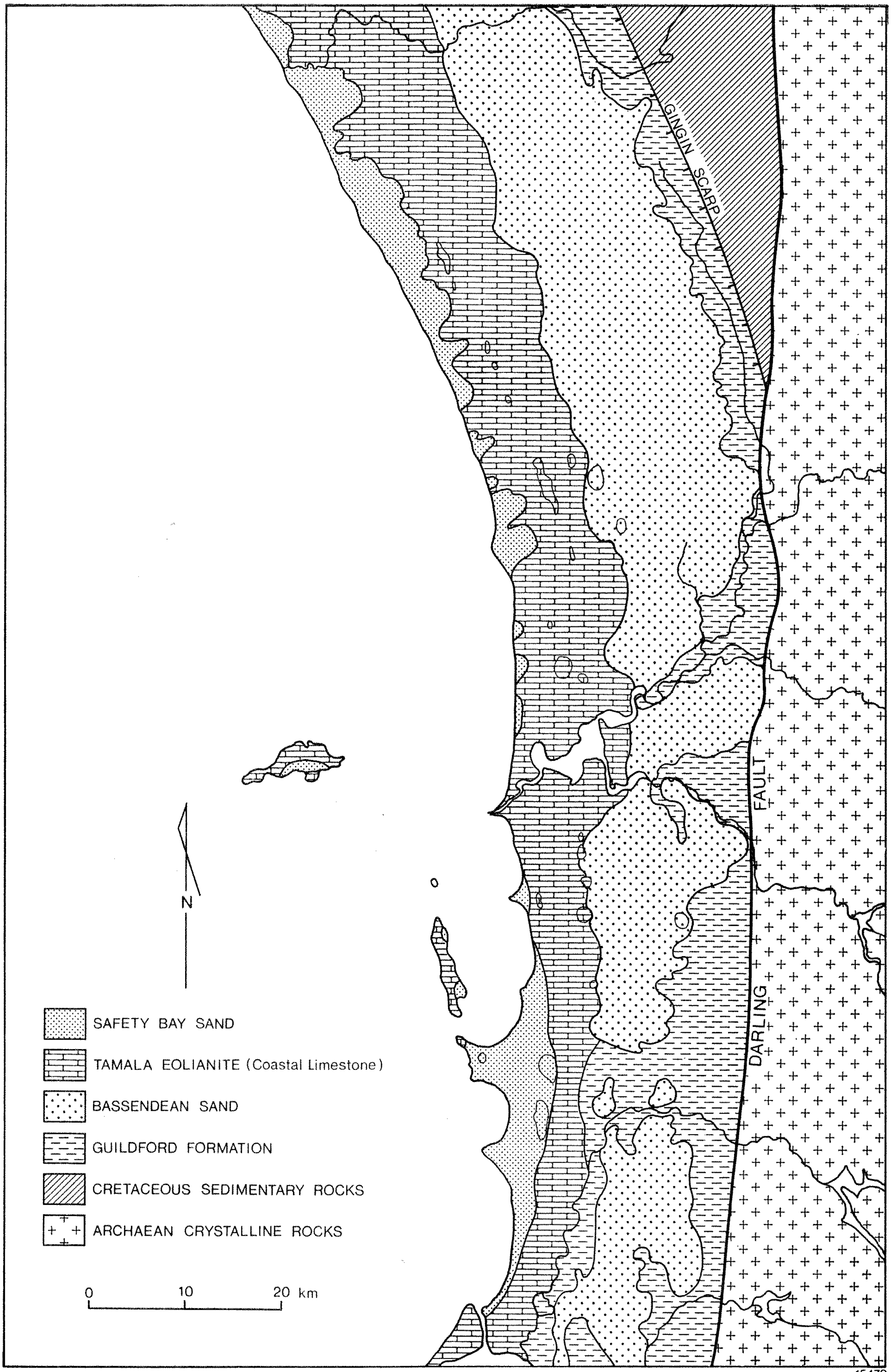


Figure 13. Simplified geology.

54809—(3)

PROCEDURES

Drilling, sampling, construction and testing procedures have varied quite considerably in the different drilling programmes. At exploratory sites a single test-production bore alone, or with one, three or six observation bores was constructed. At production sites an observation bore was first constructed and then later a production bore.

The drilling has mainly been done using cable-tool rigs because of the better samples which can be obtained. However some exploratory bores and many production bores have been drilled using rotary rigs.

Sludge samples were taken at 1.5 m (5 feet) or 3 m (10 feet) intervals, geologically logged and if necessary sieved. The bores were usually sunk a minimum of 3 m into the underlying formations so that fresh samples could be obtained for palynological examination. Gamma-ray logs were run on all bores to assist in defining bed and formation contacts.

Test-production and production bores were usually constructed using 6-inch, 8-inch or 10-inch casing with screens set at the bottom of the bore and extending over about one third of the saturated aquifer thickness.

Observation bores were constructed using 2-inch galvanized iron pipe with short lengths of screen at the base, or more usually with 3-inch P.V.C. tubing slotted over the saturated aquifer thickness and gravel packed to provide stability.

Pumping tests were carried out on exploratory sites which warranted testing to determine the aquifer characteristics, and on all production bores to test their acceptability. Usually the testing was preceded by three to five-stage step up pumping tests, in which the pumping rate was increased in each test and held constant for one hour. The following day a continuous rate test, usually of 24 hours' duration was carried out, while measuring drawdown response in the pumping bore and observation bore(s).

At completion of the pumping test (and during the pumping test in some cases) water samples were taken to determine physical characteristics, principal ions, important trace elements, dissolved gases and bacteriological purity of the water.

When testing was completed the bores were left for observation purposes.

DATA

A very large volume of data has now been obtained. Apart from that given in various reports, detailed information on geology, pumping test results, and water quality are held on file at the Geological Survey and the Metropolitan Water Board.

Strata samples have been stored at the Geological Survey core library.

Monthly water-level measurements from the exploratory bores and pre-existing Metropolitan Water Board monitoring bores, are available from the Water Board computerized groundwater levels storage and retrieval system.

In addition, records of about 2 000 private bores obtained in the bore census work carried out by the Geological Survey are available in the Hydrology Division bore record system.

GEOLOGY

GEOLOGICAL SETTING

The Swan Coastal Plain is situated on the eastern onshore edge of the Perth Basin. It is underlain by about 8 000 m of Phanerozoic sedimentary rocks, separated from Archaean crystalline rocks of the Darling Range by the Darling Fault.

STRATIGRAPHY

The stratigraphic sequence of formations for the Perth Basin has been established from boreholes and regional geological mapping. The Mesozoic and Tertiary formations are reasonably well known, but the lithological complexity resulting from Quaternary formations is less so due to palaeogeographic variations.

The stratigraphic sequence referred to in this account is given in Table 10 (Playford and others, in press).

TABLE 10: STRATIGRAPHIC SEQUENCE

Formal Age		Group	Formation	Maximum Thickness (m)	Summary of Lithology
CAINOZOIC	Quaternary	....	Superficial Formations	90	Sand, limestone, clay
	UNCONFORMITY				
	Late Tertiary	....	Rockingham Sand	100+	Sand, minor siltstone
	UNCONFORMITY				
	Early Tertiary	....	Kings Park Formation	520	Calcareous siltstone, shale, minor sand and limestone
	UNCONFORMITY				
MESOZOIC	Late Cretaceous	Coolyena Group	Gingin Chalk	c. 25	Fossiliferous and glauconitic chalk
		Coolyena Group	Molecap Greensand	c. 15	Glauconitic sand
		Coolyena Group	Osborne Formation	150	Glauconitic shale, siltstone, minor sandstone
	Early Cretaceous	Warnbro Group	Leederville Formation	450	Siltstone, sandstone, shale
	Early Cretaceous	Warnbro Group	South Perth Shale	120	Siltstone, shale, minor sandstone
	UNCONFORMITY				
	Late Jurassic	....	Yarragadee Formation	3 000	Siltstone, shale, sandstone
	Middle Jurassic	....	Cadda Formation	....	Shale, siltstone
	Early Jurassic	....	Cockleshell Gully Formation	2 000	Massive siltstone, sandstone, shale

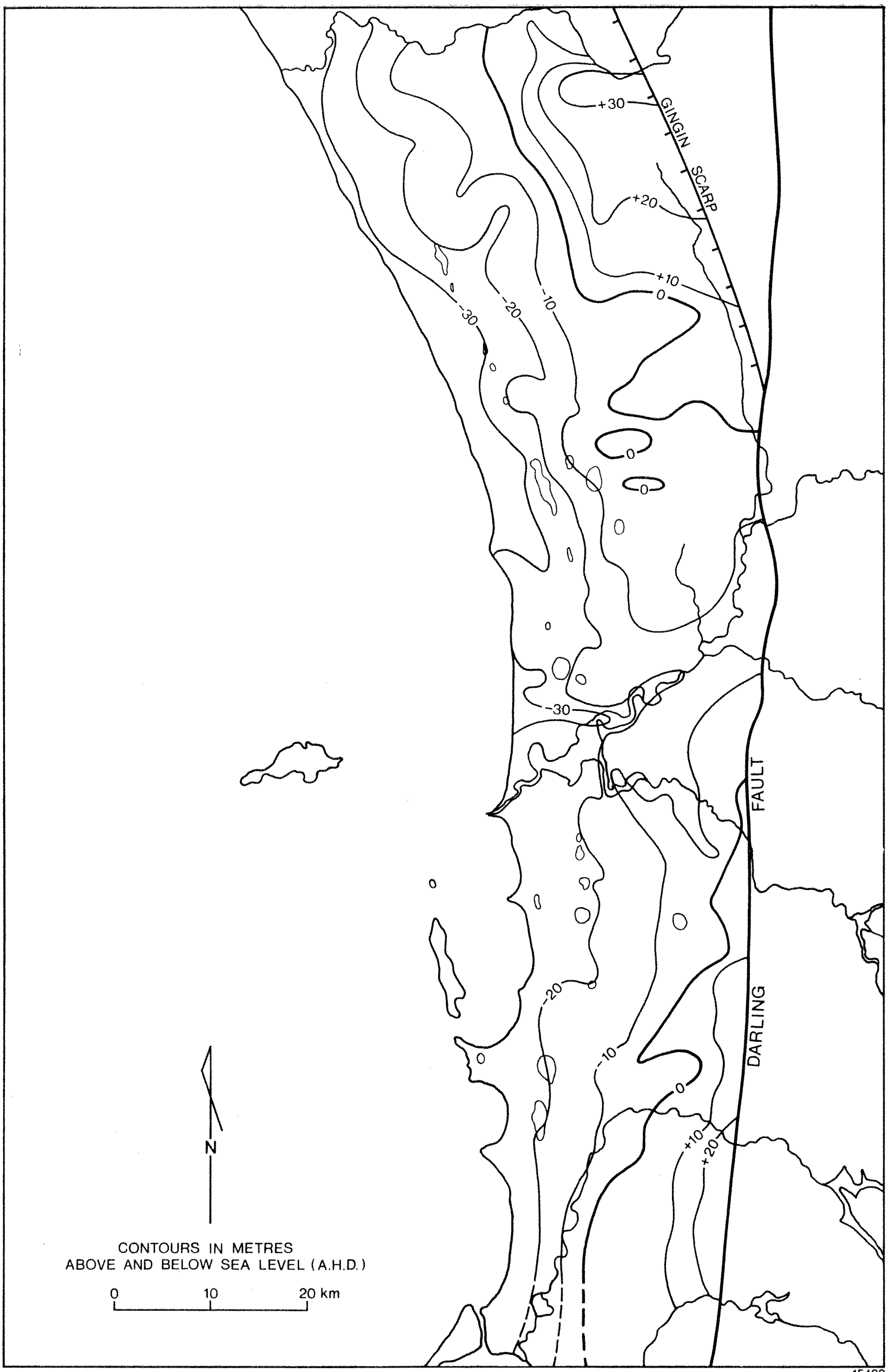


Figure 14. Map of pre-Quarternary erosion surface.

The Quaternary sediments vary in thickness from about 15 to 90 m. They rest with a pronounced unconformity on the much older Mesozoic and Cainozoic formations. The unconformity surface shown contoured in Figure 14 ranges from 35 m below sea level near the coast to about 35 m above sea level near Gingin. The surface is very irregular and is possibly a composite of two periods of erosion. It is below sea level over about three-quarters of the coastal plain, and is traversed by relatively deeper channels apparently associated with former courses of the major rivers.

The Quaternary has been mainly subdivided on the basis of geological mapping of the uppermost units. However, drilling has shown that there are also recognizable subsurface units and that the relationship between units is more complex than suggested by the surface mapping. The complexity results from the palaeogeographic conditions at the time of deposition and the variations in sea level since the Late Pliocene.

The Quaternary formations, despite their variability, form a single aquifer system, and to avoid complications with nomenclature are here referred to collectively as the Superficial Formations.

These formations consist of a laterally and vertically variable sequence of sand, limestone, silt and clay. In broad terms they consist of a sequence of calcareous marine sands and eolianites (Coastal Limestone) near the coast, passing inland to a variable sequence of fine and medium sand with minor silt and limestone (Bassendean Sand), which in turn grade into, and interfinger with, a sequence of clay, clayey sand and minor gravel (Guildford Formation) adjacent to the Darling Range. This general pattern is modified by younger deposits of silt, clay and gravel along the major rivers, and by recent dune sands or marine strand-line deposits along the coast. Remnants of older littoral and eolian deposits are preserved along the foot of the Darling Range. The generalized geology is given in Figure 13.

STRUCTURE

Structurally the Mesozoic formations form a broad, faulted, slightly asymmetric syncline with the steepest limb in the east. The Tertiary formations are preserved in channels, possibly related to the Rottnest Trench, which were eroded into the pre-existing formations. Together, they form a basement to the Superficial Formations which rest on an irregular surface which slopes downward to the west. The Superficial Formations are flat-lying, stratigraphically complex, and are not known to be faulted.

HYDROLOGY

RAINFALL

The average annual rainfall on the coastal plain decreases in a northwesterly direction from about 1 100 mm at Serpentine to less than 700 mm at Guilderton (Fig. 12). About 90 per cent of the average rainfall is received between April and October, but the annual amount may vary quite widely between different years.

DRAINAGE

The coastal plain is traversed by four major drainage systems: the Gingin Brook-Moore River System which forms the northern boundary to the area, the Swan-Canning River System which bisects the coastal plain into the northern and southern areas, the Serpentine River, and the South Dandalup-Murray River System which forms the southern boundary. All are major through-going rivers (some of which are dammed) carrying run-off from the Darling Ranges as well as a proportion of groundwater outflow from aquifers on the plain.

In the northern area the eastern edge of the coastal plain is bounded by Ellen Brook which carries run-off from a number of small tributaries rising in the Darling Range and from a number of small groundwater-fed drainages at the eastern edge of the Gnangara Mound. By contrast, in the southern area, south of Wungong Brook about a dozen small drainages (brooks) flow onto the coastal plain from the Darling Range where they dissipate or are canalized and linked with the Serpentine River.

The minor drainages are usually associated with the more silty or clayey Superficial Formations towards the eastern edge of the coastal plain. On the central and coastal parts of the plain there are no drainages developed because of the permeable nature of the sediments.

LAKES AND SWAMPS

Three main types of lakes can be recognized: circular lakes, linear lakes, and coastal lakes.

The circular lakes, such as Lake Gnangara or Lake Thompson, are usualy located close to the surface boundary between the Coastal Limestone and the Bassendean Sand. A few such as Lake Thompson and Lake Bambun occur toward the eastern edge of the coastal plain. They are not known to exceed about 3 m in depth.

The linear lakes are formed in interdunal areas on the coastal strip, and locally may be quite deep. To some extent their hydrology may be influenced by the presence of limestone caves, as appears to be the case at Lake Joondalup and Loch McNess.

The coastal lakes are restricted to the Rockingham district and appear to result from isolation and partial infilling of part of Cockburn Sound. They range in depth from 3 to 30 m.

All the lakes contain lacustrine sediments up to 10 m in thickness, consisting of clay, peat, diatomite, bog limestone, and peaty sand.

The lakes are outcrops of the water table, and their levels vary seasonally in sympathy with the water-table fluctuations. They are of variable salinity depending on the salt balance of each lake. While the lakes in each group have certain similarities, each is controlled by its own flow system.

Swamps are found mainly in the eastern and central parts of the coastal plain. They are rare on the coastal strip where the elevation of the dune system and depth to water generally precludes their formation. Most of the swamps occur in interdunal depressions but some may be on the sites of former lakes.

The swamps usually contain dense vegetation. They are formed where the water table is at or near the surface and may have areas of open water in the winter months. Peat and peaty sands occur in many swamps and most are underlain by a ferruginous hardpan (coffee rock).

The open water surfaces of the lakes, the dense vegetation which grows around their margins and the vegetation of the swamps directly deplete the groundwater by evaporation and transpiration. Swamps occupy about 9 per cent of the Swan plain and are responsible for very substantial quantities of groundwater being lost. They are also ecologically very important.

GROUNDWATER

GENERAL

The Superficial Formations on the coastal plain are saturated with water to a level controlled by the annual rainfall, the relief, the hydraulic characteristics of the aquifers and by the natural vegetation. The water which the sediments contain is unconfined and the top of the zone of saturation forms a water table which extends beneath all of the coastal plain.

The groundwater originates from rainfall which percolates into, and moves slowly under gravity through, the Superficial Formations, to be discharged at hydraulic boundaries formed by the sea and the major rivers. During movement through the Superficial Formations it is substantially depleted by evapotranspiration from lakes, swamps, and where the roots of vegetation can reach the water table; by infiltration into underlying formations; and by pumping from boreholes. In the vicinity of the coast line and the major estuaries the fresh groundwater is in direct contact with seawater in the Superficial Formations.

The present configuration of the water table is in a general way a reduced facsimile of the major topographic features. It has developed since the stabilization of sea level and under the prevailing climatic conditions. The configuration has been to some extent affected by man's activities, in particular clearing of bushland, drainage, and groundwater use.

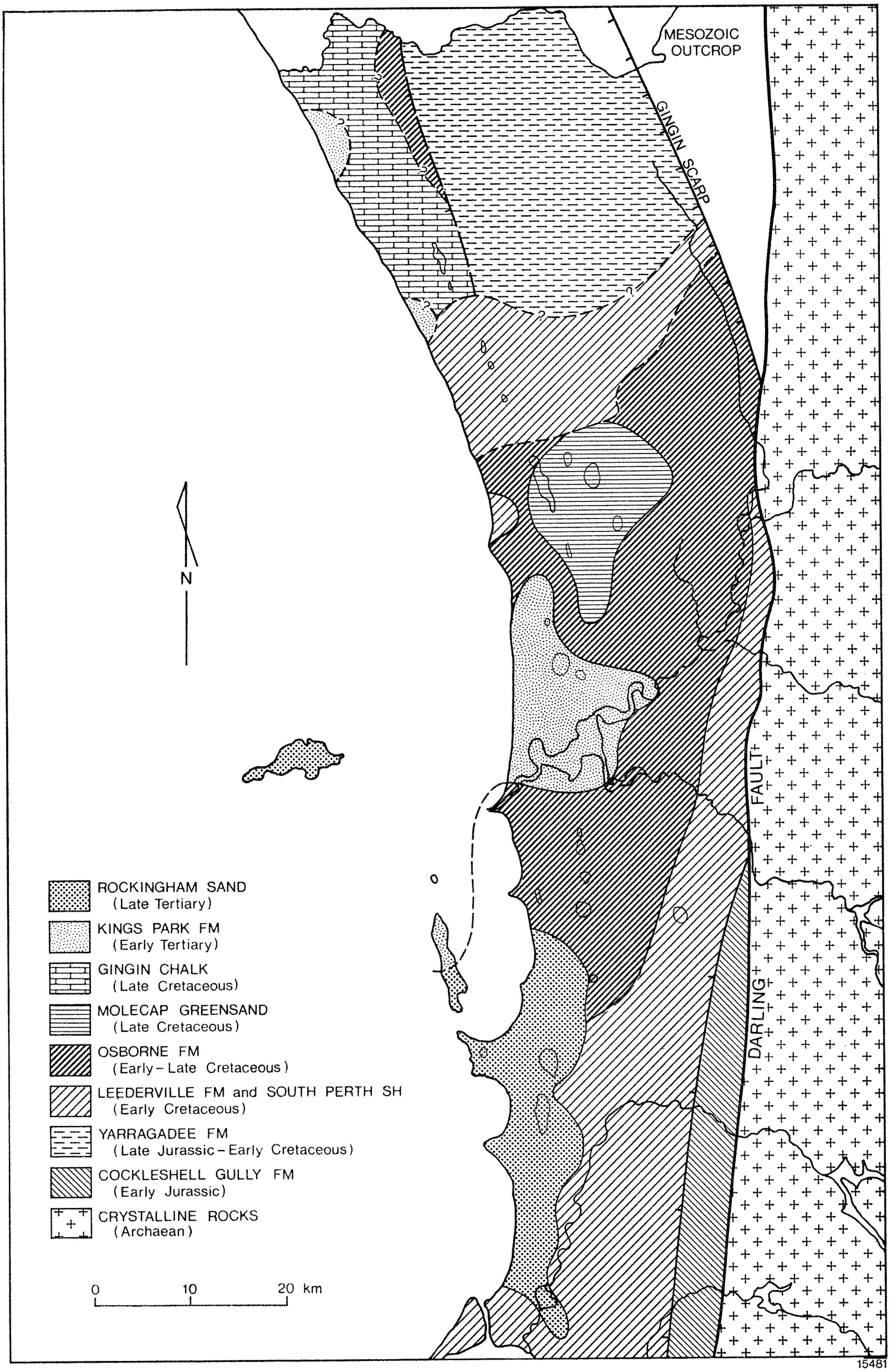


Figure 15. Subcrop map.

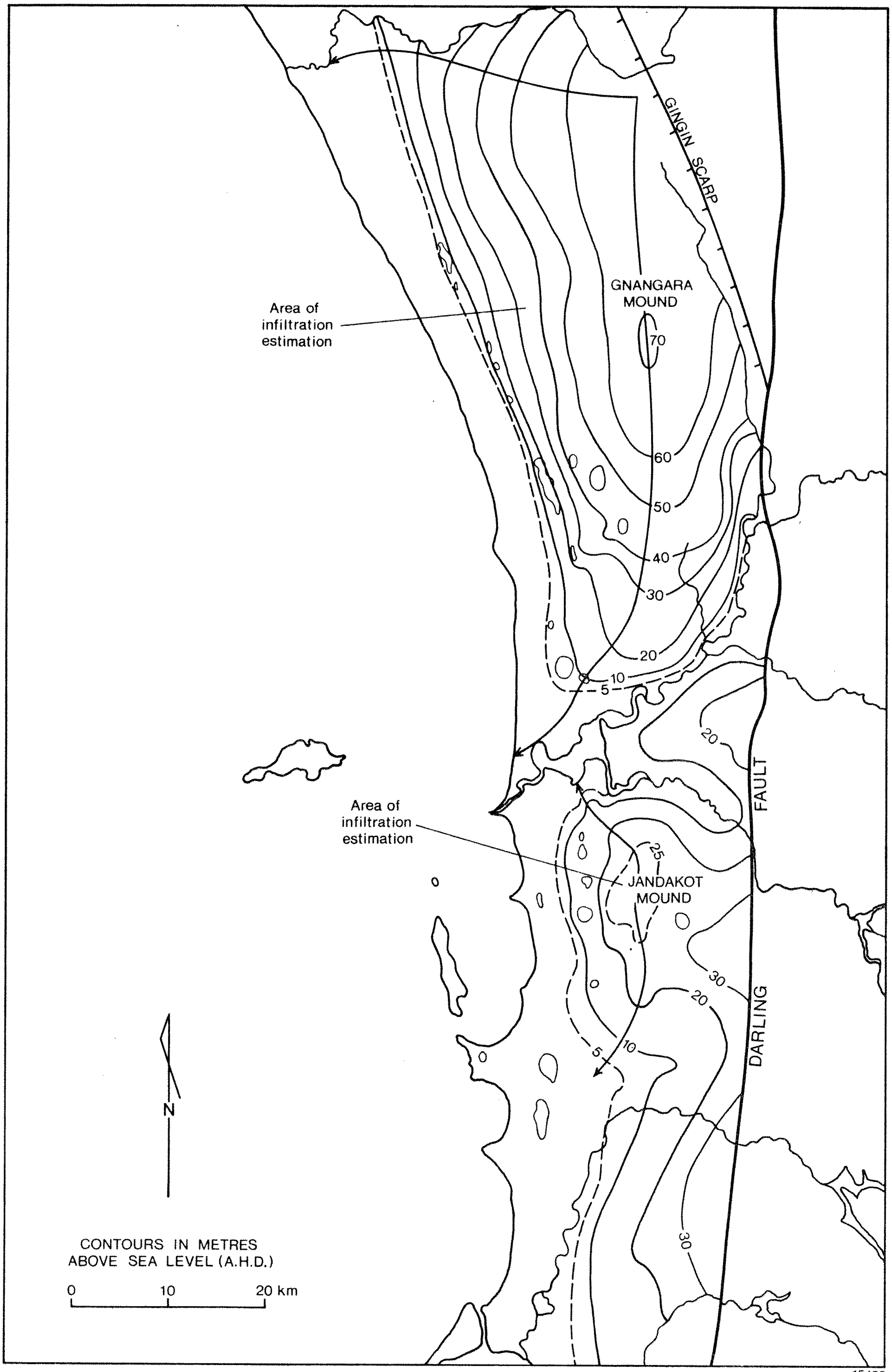


Figure 16. Water-table map.

The water table undergoes seasonal variations in level and configuration. Its general form, based on levels for summer 1974 in the northern area, and summer 1975 in the southern area, is given in Figure 16.

The northern and southern areas are hydrodynamically distinct, and to a certain extent geologically different; they are therefore considered separately.

NORTHERN AREA

Water-table configuration

In the northern area the water table forms a pronounced north-south-trending ridge colloquially referred to as the Gnangara Mound. It has two crests rising to 70 m above sea level coinciding with the areas that are highest.

The water-table contours show that groundwater flow is radial and takes place towards hydraulic boundaries formed by the major rivers and the sea. A steepening of the groundwater gradiant in the vicinity of the linear lakes on the coastal strip possibly results from a reduction in transmissivity caused by the presence of lacustrine sediments or by cementation. The very low gradiants across the coastal strip result from the high transmissivity of the Coastal Limestone whereas the steep gradients around the eastern edge of the mound reflect the lower transmissivity of the Guildford Formation. The uniform low gradient extending south from the mound indicates that the Bassendean Sand, despite wide variation in lithology, has relatively uniform hydraulic characteristics.

Recharge

The water table undergoes seasonal water-level fluctuations. The levels are high in September-October after the winter rainfall, and lowest in March-April at the end of summer. They have a seasonal range between about 0.2 and 1.5 m depending on the location of the bore and depth to water. The smallest water-level variations are observed on the coastal strip and the highest are in the southern crestal area of the Gnangara Mound. Hydrographs show that water levels respond quickly to winter rainfall and that the peaking of water-level maxima and minima between bores may not be in phase because of local effects.

Recharge is not uniform over the coastal plain because of variations in the distribution of rainfall, the depth of the water table, the lithology of the Superficial Formations, and of the cover of vegetation. The frequent presence of a ferruginous hardpan (coffee rock) and limestone capstone may also reduce infiltration over wide areas.

The recharge to the Coastal Limestone along the coastal strip, and the Bassendean Sand forming the central part of the coastal plain are believed to be widely different. Along the coastal strip the water table is relatively deep and most recharge which reaches the water table is unaffected by evapotranspirative losses whereas on the central part of the coastal plain the shallow depth to water and the presence of numerous swamps and lakes allow large evapotranspiration losses.

The areally-averaged recharge to the central coastal plain can be estimated from available data because the throughflow past the 10 m water-table contour can be computed from hydraulic data derived from test pumping, and the area contributing to the throughflow (Fig. 16) can be measured. The recharge can then be estimated from the relationship

$$\frac{\text{Throughflow}}{\text{Contributing area}} = \text{Recharge.}$$

Substituting derived values and solving

$$\frac{71 \times 10^6 \text{ m}^3\text{/year}}{1\,026 \times 10^6 \text{ m}^2} = 0.069 \text{ m/year.}$$

This value is equivalent to 8.5 per cent of the adopted average annual rainfall of 813 mm. It is directly applicable to 47 per cent of the northern area and probably approximates the infiltration to the rest of the area. It represents a more conservative figure than one previously published of 0.085 m/year (Allen, 1975) which was derived by the same means from a 1 183 x 10^6 m² area and a throughflow of 101 x 10^6 m³. This larger area incorporated a sub-area discharging to the Swan River which was estimated to have an exceptionally high groundwater recharge figure of

$$0.191 \text{ m } (= \frac{30 \times 10^6 \text{ m}^3}{157 \times 10^6 \text{ m}^2}).$$

The difference between the two is probably a result of the large evapotranspirative losses from the lakes and swamps which occur in the area discharging to the sea.

Storage

The volume of groundwater in storage can be estimated by superimposing the water-table contour map for 1974 on the map of the pre-Quaternary erosion surface. From this a map of the saturated aquifer thickness can be constructed and the volume of saturated aquifer determined. The saturated aquifer thickness exceeds 40 m over 70 per cent of the northern area and the total volume is estimated to be 65 000 x 10^6 m³. The volume of groundwater in storage based on a specific yield of 0.20 is estimated to be in the order of 13 000 x 10^6 m³.

Outflow

The amount of outflow which takes place from the northern area can not yet be reliably estimated from hydraulic data. This is because of regional variations in transmissivity*, in particular across the coastal strip where estimates of transmissivity based on pumping test data and considerations of continuity of flow from the east differ by a factor of five. Estimates are further complicated by infiltration to and outflow from the underlying formations.

The total outflow can best be approximated by applying the infiltration value of 0.069 m/year to the separate areas contributing to groundwater outflow at the major hydraulic boundaries (Fig. 16). The figures are given in Table 11.

TABLE 11: ESTIMATED OUTFLOW FROM THE NORTHERN AREA

Discharge area	Area km²	Per cent total area	Est. outflow m³/year x 10^6
Sea	1 481	69	102·2
Gingin Brook	155	7	10·7
Ellen Brook	310	14	21·4
Swan River	219	10	15·1
Totals	2 165	100	149·4

The figures for discharge to the sea are probably conservative because no account is taken of the higher recharge which is believed to take place on the coastal strip. The figure for the Swan area is also conservative when compared with the one derived by groundwater hydraulics for flow through the 10-m contour of 30 x 10^6 m³/year. Despite these defects the figures probably indicate the order of magnitude of outflow for the northern area. In other terms the outflow is equal to about 1 per cent of the groundwater in storage.

Infiltration to underlying formations

Mesozoic and Tertiary formations subcrop beneath the Superficial Formations and their upturned edges are in direct hydraulic continuity with groundwater in the Superficial Formations. The erosion surface which truncates the Yarragadee and Leederville Formations (Fig. 15) and forms the floor on which the Superficial Formations rest, has an elevation of 0 to 35 m above sea level over about one third of the area (Fig. 14) and over the same area the water table is 50 to 70 m above sea level (Fig. 16).

A large head difference has been observed between the water table and the potentiometric surface of the underlying Leederville Formation. In Wanneroo 305 for example, the water table has a head 17 m higher than the potentiometric surface. This shows that there is a large potential difference to facilitate downward infiltration. It is not yet possible to accurately define the actual area of recharge or the amount of infiltration but as the indicated area is large it must be very substantial.

*Hydraulic conductivity of the "Bassendean Sand" 15 m³/day/m² and "Coastal Limestone" estimated to be 100 m³/day/m².

Quality

In the northern area the groundwater salinity is 250 milligrams per litre, or less, of total dissolved solids over 50 per cent of its area, 250 to 500 mg/l TDS over 40 per cent of the area; and the remaining 10 per cent around the periphery contains water of variable but higher salinity. The salinity pattern is shown in Figure 17.

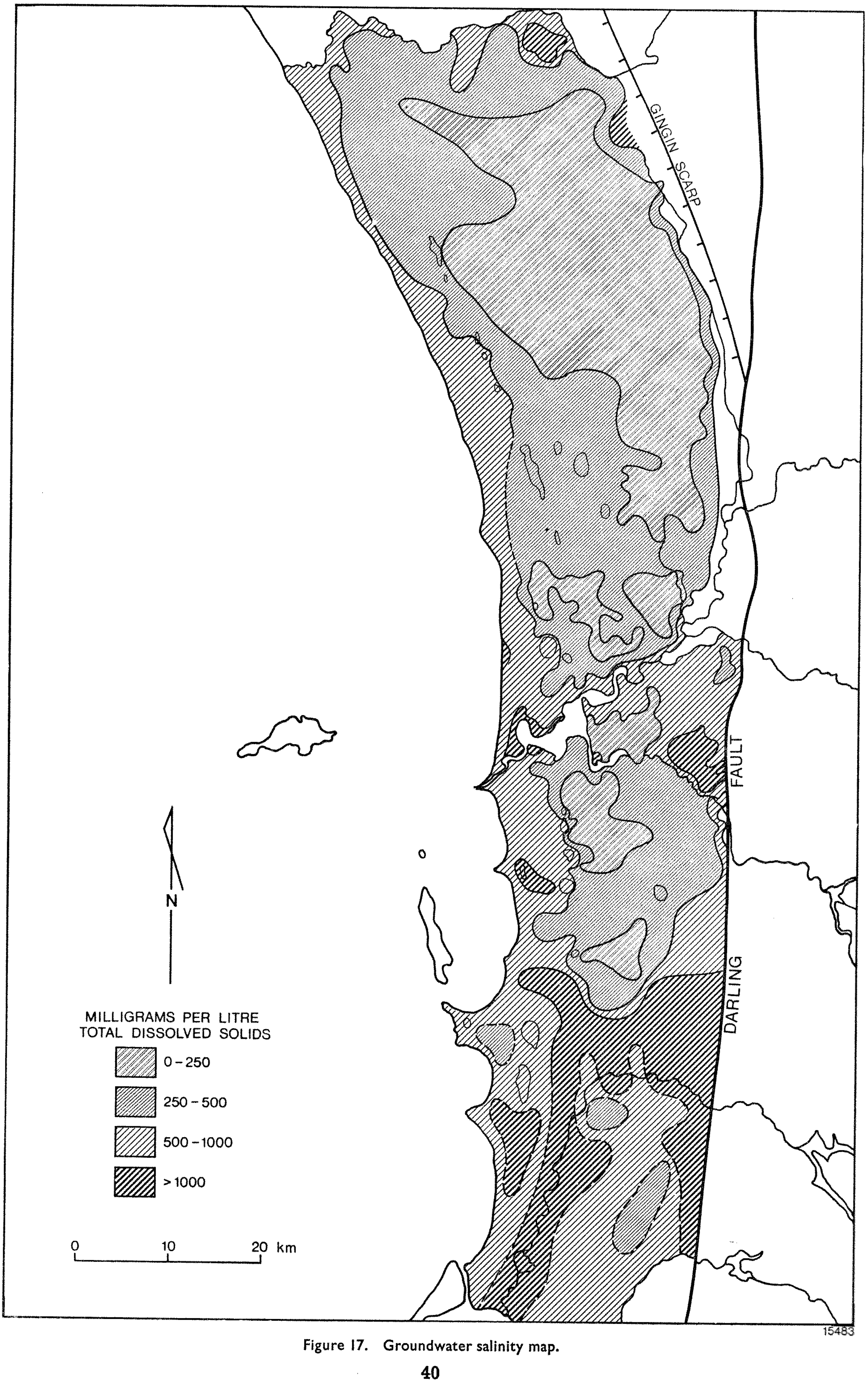


Figure 17. Groundwater salinity map.

The general increase in salinity towards the discharge boundaries results mainly from concentration of the rainfall recharge by evapotranspiration. There is evidence (not shown) to indicate that plumes of more saline water extend downstream from Lakes Pinjar and Joondalup and possibly other lakes. The decrease of cyclic salt inland from the coast may also affect the salinity pattern.

The relatively rapid increase in groundwater salinity along the eastern side of the mound reflects the effect of increased evapotranspiration from numerous springs and soaks.

Near the crest of the mound most bores encounter groundwater with a light brown colouration resulting from organic acids produced in the many swampy depressions. Colouration tends to decrease with depth and is not a problem in the calcareous sediments along the coastal strip.

Turbidity is also high in many bores, but not on the coastal strip. It results from the presence of suspended kaolin clay derived from kaolinized feldspar grains which occur in large quantities in some beds.

Ferrous iron occurs in most bore waters in various concentrations but usually at levels necessitating treatment for public water supply use.

Water with low pH and dissolved carbon dioxide and hydrogen sulphide occurs frequently on the central part of the mound but only rarely on the coastal strip.

Hardness ranges from moderately soft to slightly hard for groundwater near the crest of the Gnangara Mound and moderately hard to very hard for water obtained from the calcareous sediments of the coastal strip.

Wide differences in physical and chemical properties may commonly be found in nearby bores.

SOUTHERN AREA

Water-table configuration

Immediately to the south of the Swan River and covering about half the southern area, the water table forms a groundwater prominence referred to as the Jandakot Mound. Over the rest of the area the water table slopes gently downward to the west from the foot of the Darling Range.

The water table has an elevation of about 25 m on the Jandakot Mound and 30 m adjacent to the Darling Range in the Serpentine-Keysbrook area. The high parts of the water table coincide with areas that are topographically high and reach an elevation of only half that of the Gnangara Mound.

Groundwater flow is mainly westward to the sea with some flow taking place northward and north-eastward into the Swan and Canning Rivers. Notable features of the water-table map are the presence of a water-table divide which extends along the length of the Jandakot Mound; a water-table col in the vicinity of Lake Forrestdale indicating an area of large groundwater loss, and a large re-entrant in the water-table contours indicating significant groundwater outflow contributing to base flow of the Serpentine River. As in the northern area, there is a very low hydraulic gradient across the coastal strip.

Recharge

The water table undergoes seasonal fluctuations in level which are of essentially similar timing and amplitude as those of the northern area. During the winter large areas near the top of the Jandakot Mound and in the vicinity of the Serpentine River are flooded despite the sandy nature of the sediments. This suggests that although a large proportion of rainfall is available for infiltration, the hydraulic conditions or the widespread occurrence of a ferruginous hardpan (coffee rock) inhibit recharge.

An estimate of recharge to the Jandakot Mound can be made in a similar way as for the northern area. The area taken for the calculation is shown in Figure 16 and the throughflow calculation is based on an hydraulic conductivity of 10 $m^3/day/m^2$ (15 $m^3/day/m^2$ Gnangara Mound). The recharge is computed from the relationship

$$\frac{\text{Throughflow}}{\text{Contributing area}} = \text{Recharge}$$

Substituting

$$\frac{7.8 \times 10^6 \text{ m}^3/\text{year}}{166 \times 10^6 \text{ m}^2} = 0.047 \text{ m/year.}$$

The average recharge of 0.047 m/year is only about 70 per cent of that for a comparable area on the Gnangara Mound. Presumably the lower transmissivity of the sediments and their more uniform relief are the main reasons for the lower recharge.

The recharge to the coastal strip is presumably considerably higher and in the same order as for the northern area. Elsewhere in the southern area, considering the geology and topography, it is expected that infiltration is probably of the same order for the sandy sediments but possibly somewhat less in the clayey sediments along the eastern edge of the coastal plain and associated with the Serpentine River.

Storage

The volume of saturated aquifer (including some interbedded clay) has been estimated from cross-sectional areas, using Simpson's prismoidal rule, as 25 000 x 10^6 m^3. The volume of groundwater in storage, applying a specific yield of 0.20 is estimated to be 5 000 x 10^6 m^3. Hence the figures for saturated aquifer volume and the volume of groundwater in storage are considerably smaller in the southern area than in the northern area.

Outflow

The groundwater outflow from the southern area cannot yet be reliably estimated because of the wide variability of the hydraulic properties of the Superficial Formations, the effect of surface drainages, and the role played by surface water imported from the Darling Range.

The order of magnitude of the outflow based on the groundwater recharge rate of 0.047 m/year and the area of 1 400 km^2 is very approximately 65 x 10^6 m^3/year.

Infiltration to underlying formations

Areas where the water table has a higher head than the underlying Leederville Formation appear to exist all across the coastal plain, but the generally silty or shaley nature of the Mesozoic formations subcropping in this area probably considerably reduces the amount of infiltration which would otherwise take place. Some direct infiltration to the Rockingham Sand, possibly around its eastern subcrop also takes place.

Quality

The variation in groundwater salinity in the southern area is shown in Figure 17. The map is based on data of variable reliability and only shows the salinity pattern in a very general way. The variation in salinity is known in reasonable detail only on the Jandakot Mound, elsewhere considerable variation results from local effects of geology and sampling.

As in the case of the Gnangara Mound, colour, turbidity, iron, and hydrogen sulphide are present and the water requires treatment before it can be used for public water supply purposes.

CONCLUSIONS

Perth is extremely fortunate in having large supplies of low salinity water adjacent to developing urban areas, both to the north and south. The northern area is considerably better known than the southern area, and is hydrogeologically distinct. In terms of estimated recharge and groundwater in storage it is far more prosepective for large-scale groundwater abstraction.

The presence of iron, turbidity, and organic colouration will necessitate treatment before most of the unconfined groundwater can be used for public water supply purposes.

A constraint on the use of the unconfined groundwater will be the effect caused by pumping on wetlands. However, these effects will be offset to some extent by increased recharge due to clearing and lowering of the water table. In addition the network of monitoring bores around the borefields and the supplemental use of confined water should allow management of the resource so that deleterious effects on the wetlands are minimal.

REFERENCES

Allen, A. D., 1975, Interim report on the progress of investigation and present understanding of the groundwater resources in the Perth area: West. Australia Geol. Survey Hydro. Rept. No. 1303 (unpublished).

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

GEOTECHNICAL PROPERTIES OF THE COASTAL LIMESTONE IN THE PERTH METROPOLITAN AREA

by G. Klenowski

ABSTRACT

The Coastal Limestone is variable in composition and includes cemented rocks (calcareous quartz sandstone, limestone), calcretized rocks (caprock, pinnacles, solution pipes), rocks crystallized in cavities (dripstones), sand, and thin lenses of calcareous silt, clay, and marl. Geological structures that affect rock conditions include bedding, disconformities, slump planes, and solution structures.

Ranges in mechanical properties were determined using the uniaxial compressive strength test, Los Angeles test, Schmidt Hammer test and Brazilian test. A relationship has been established between the degree of rock cementation identified in the field and the range of uniaxial compressive strength.

Rock strength varies with the degree of cementation and type of carbonate cement. Tests show that rocks of uniform grain size are stronger than rocks with variable grain sizes. All rocks show a considerable increase in strength on drying, thought to be caused mainly by increasing molecular cohesive strength, but also by the evaporation of pore water containing $Ca(HCO_3)_2$ in solution and $CaCO_3$ in suspension, to form a carbonate cement.

The results of field investigation and mechanical testing have been applied to tunnelling and open-excavation problems, and the selection of suitable material for road bases and breakwaters. Mixed-face tunnelling in the Coastal Limestone requires special techniques such as shield protection and hydraulic spilers to prevent sand runs. Jacks would need to thrust against the tunnel lining or some other preconstructed support. Solution cavities can be detected by probe drilling. Drilling and blasting rather than ripping is generally necessary for massive zones of caprock or well-cemented rock.

Limestone base-course material for roads becomes recemented in time by the precipitation of dissolved carbonate to form a firmer layer. Calcretized and well-cemented rocks are undesirable materials. Careful selection of quarries will facilitate quality control.

In breakwater construction, caprock limestone may be used for armour blocks when dense material is required. Evaporation of pore water from limestone blocks prior to transport will increase rock strength and help prevent breakage during handling. Once placed the rock gradually undergoes case hardening if exposed to alternate wetting and drying.

INTRODUCTION

According to Fairbridge (1953) the term "Coastal Limestone Series" was first used in 1872 by the Government Geologist, H.Y.L. Brown, in a report to Parliament (Brown, 1872). Since then the term Coastal Limestone has been used in a general way to refer to a Quaternary deposit of mainly eolian origin, formed in a narrow belt along the west coast of Western Australia. In this paper, discussion is restricted to rocks from the Perth metropolitan area.

Investigation has been primarily oriented towards evaluating the geological problems expected in civil engineering works. Studies were made in the Shire of Wanneroo, where base-course material for roads is excavated. Correlations were also made with rock from the W.A. Limestone Co. quarry, Wattleup. Material from this quarry was used as breakwater aggregate for the Garden Island Causeway. Fletcher (1933) has discussed the use of Coastal Limestone as a building stone.

LITHOLOGY

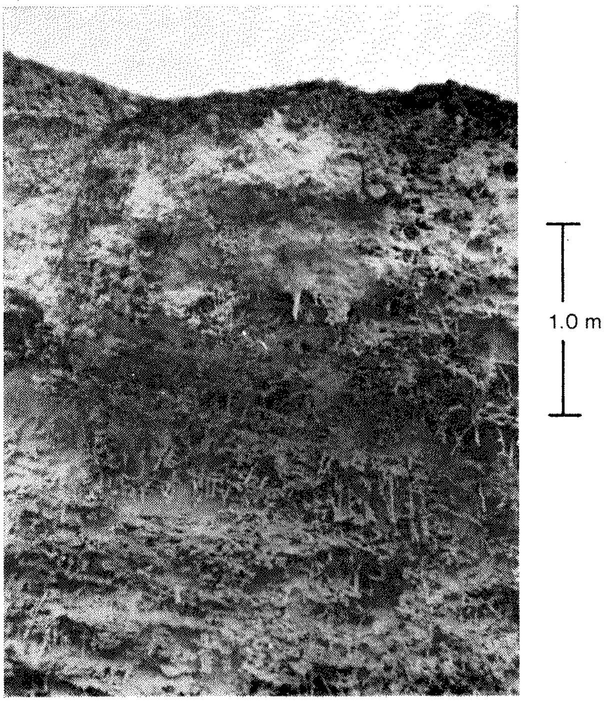
For the special purpose of this paper the Coastal Limestone has been divided into five types of material:—

(1) cemented rocks,
(2) calcretized rocks,
(3) rocks crystallized in cavities,
(4) sand,
(5) thin lenses of calcareous silt, clay, and marl.

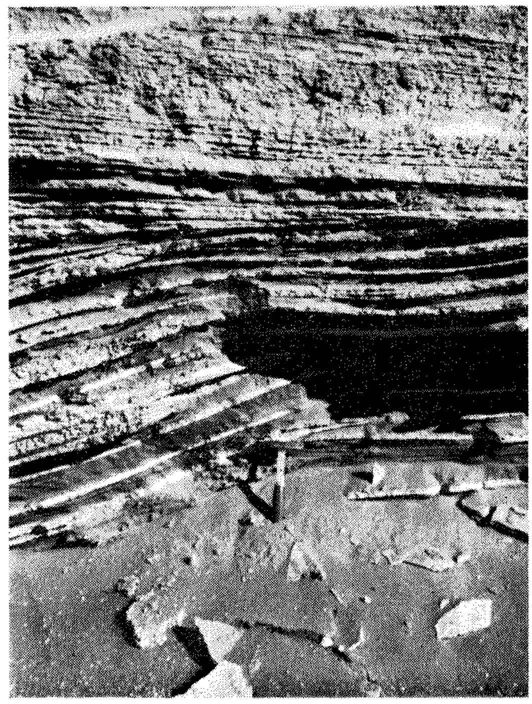
Cemented rocks are grainstones and are mainly of eolian origin, but shallow-marine types, probably beach deposits, do occur, characterized by coarse-grained quartz (some of grit size), abundant shell fragments, and graded bedding. The degree and type of carbonate cementation is variable, the cement being either micrite or sparite. At depth sparite is more common. These rocks have also been variably leached by downward percolating water. Two distinct rock types occur. Calcareous quartz sandstone (quartzose arenite) contains greater than 50 per cent quartz grains. Limestone (calcarenite) is subdivided into eolian and shallow-marine (shelly) rocks.

Calcretized rocks described here are formed by secondary carbonate enrichment at or near the surface, the precipitated mineral being cryptocrystalline or microcrystalline calcite. The term calcrete is used similarly to Goudie (1971 and 1972) and Read (1974). Three structurally different rock types occur in the Perth metropolitan area. Caprock forms a thin duricrust which shows a marked increase in friability with depth. It appears to result from capillary action and the evaporation of vadose water containing dissolved carbonate, and may be as much as several metres thick. Distribution does not conform with any stratification in the sediments, but rather follows the general surface of the ground. There are differences from the idealized calcrete profile described by Read (1974) for the Shark Bay area. Around Perth laminar calcrete either crops out or is overlain by thin topsoil or eolian sand. At Shark Bay pisolitic soil forms the uppermost layer in the profile. Below the laminar calcrete zone, which is generally a few centimetres thick, lies the massive calcrete zone. This is structureless and quite dense, but becomes friable and powdery with depth. A transitional zone from calcrete to unaltered parent rock occurs in the lower part of the profile. The lower massive calcrete and transitional zones sometimes form a network zone (see figure 18 opposite).

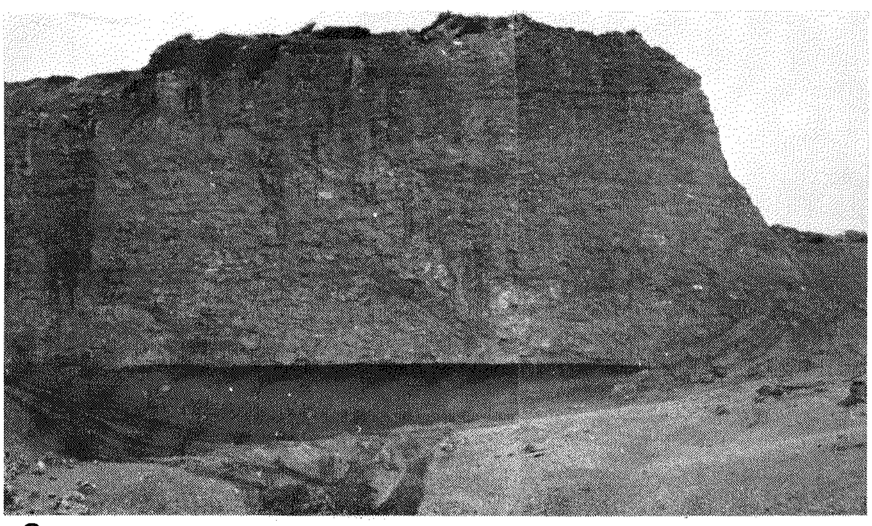
Figure 18. (opposite). Geological structures in the Coastal Limestone.
A. Massive caprock overlying network zone containing abundant solution pipes and relict cross-bedding ; quarry north of Mullaloo.
B. Bedding with alternating poorly cemented limestone and yellow quartz sand layers ; Wanneroo Shire Council quarry.
C. Cross-bedded limestone disconformably overlying yellow quartz sand; Wanneroo Shire Council quarry.
D. Whitish calcareous shallow marine sediments with cross-bedding and graded bedding, disconformably overlying yellowish, slightly cemented quartz sand. Trench excavated 4·4 m deep, 2 km north of Mullaloo.
E. Typical profile of material north of Mullaloo, next to waters edge.


1.0 m

A

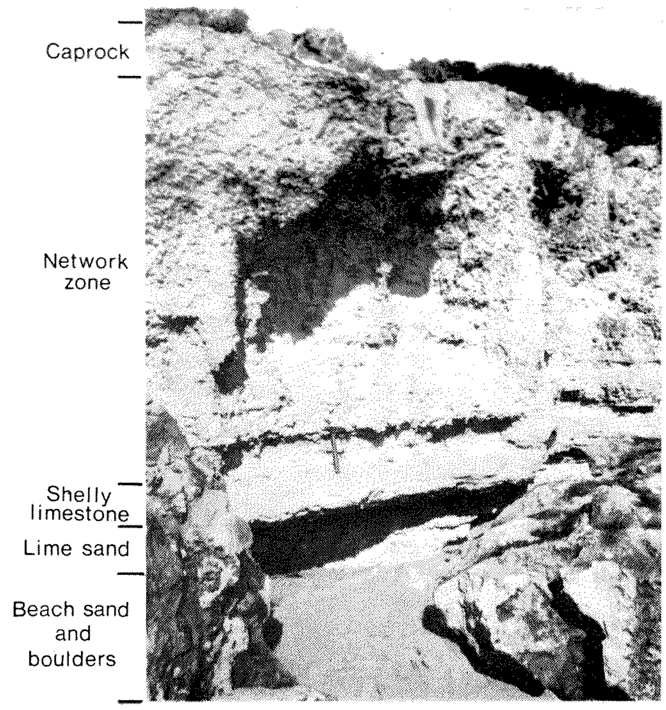


B



C

D


Caprock
Network zone
Shelly limestone
Lime sand
Beach sand and boulders

E

Pinnacles are either massive or concretionary and range in diameter from 0.2 m to 1.0 m. They may result from the break-up of caprock by penetrating plant roots, or alternatively they may form directly in carbonate-rich sediments where solution and precipitation occur in localized zones, such as adjacent to tap roots. Pinnacles formed in this way can be eventually infilled with carbonate.

The lower part of the caprock sometimes forms a network zone containing root matter (Figs. 18, A and E). Generally the organic matter has been partially or completely replaced by concretionary calcite to form solution pipes. These are usually 1 to 5 cm in diameter, and are separated by lime sand and voids.

Rocks crystallized in cavities in the zone below the surface and above the water table are known as dripstones. They generally consist of well-crystallized calcite and occur as stalactites, stalagmites, encrustations, and druses.

Yellow sand consists mainly of quartz and is sometimes bedded. It usually occurs where former dunes have been stabilized by vegetation, and forms thicker sequences in depressions. Yellow sand may also disconformably underlie rock strata. The colour is mainly due to iron oxides.

Calcareous silt, clay, and marl form thin lenses within the Coastal Limestone. These fossil horizons are either lacustrine deposits or subaerial humic deposits.

GEOLOGICAL STRUCTURES

Although the Coastal Limestone is essentially unjointed, structures that affect rock condition include slump planes, bedding, disconformities, and solution structures.

Bedding structures are gradually obliterated with depth. They include cross-bedding, bedding formed by the eolian deposition of thin, alternating carbonate-rich and quartz-rich layers (Fig. 18B), and graded bedding.

Three distinct types of disconformities have been observed. These are cross-bedded, cemented limestone disconformably overlying loose, yellow quartz sand with pinnacles (Fig. 18C); whitish, calcareous, shallow marine sediments disconformably overlying yellowish, slightly cemented quartz sand (Fig. 18D); and poorly to moderately cemented, bedded, shelly limestone disconformably overlying fine-grained lime sand (Fig. 18E).

Solution structures are divided into two types. Cavities formed by the solution of carbonate are generally irregular in shape, may be partially filled with sand, are variable in size (1 or 2 cm to several metres across), and may be iron stained or encrusted with calcite. Structures resulting from precipitation of dissolved carbonate include structures formed by near-surface zone calcretization and dripstone structures formed in cavities.

MECHANICAL TESTING

Fletcher (1933) utilized the results of uniaxial compressive strength testing for assessing Coastal Limestone as a building stone. Various tests were done by Brooksbank (1967) to determine the suitability and parameters of limestone as a road base-course material.

The tests described in this paper were primarily done to determine the ranges in strengths of rock types that could be encountered during mechanical excavation of tunnels. Although the penetration rate of tunnelling machines is often considered to be related to the compressive strength of the rock, this can be misleading. At present there is no single index or empirical test which can reliably forecast the advance rate of a machine for a given rock type. According to Bawa and Bumanis (1972), investigations indicate that a value based on abrasion and rebound is likely to best reflect the machine tunnelling advance rates. Physical properties were determined by means of the uniaxial compressive strength test, Los Angeles test, Schmidt Hammer test and Brazilian test.

In mechanical tunnelling and trenching, it is important to know the proportion of mechanically rippable rock, to rock requiring blasting. These properties were analysed using the methods of Duncan (1969).

Brooksbank (1967) in his study of the Coastal Limestone as a base-course material concentrated on the lower limit of suitable strength range. Because of compaction problems with some of the stronger rock, an upper strength limit is considered here from Los Angeles test results.

Rock properties that could be utilized in breakwater construction include increase in strength caused by the evaporation of pore water, case hardening due to alternate wetting and drying, and utilization of dense caprock for armour. Testing was done on rock from the W.A. Limestone Company quarry, Wattleup.

All rock testing was done in the Civil Engineering Department of the University of Western Australia by J. M. Campbell (in prep.) who is currently working on the application of rock mechanics techniques in the determination of mechanical properties of certain Western Australian rocks.

UNIAXIAL COMPRESSIVE STRENGTH TEST

Uniaxial compressive strength was determined with loading rates of 2.03 t/min for moist samples (containing pore water), 2.64 t/min for air-dried samples and 2.10 t/min for 7-day oven-dried samples (see Tables 12, 13, and 14). Although not all of the requirements of the standards adopted by the International Society of Rock Mechanics (Bieniawski and Franklin, 1972) could be met, the results should give a good indication of rock strengths. Rock tested included diamond drill cores and quarry caprock, and pinnacle samples. All hand specimens were cored in the laboratory. The drillholes have six digit numbers, with the first two referring to the year of drilling (75) and the next four indicating the distance(in metres) along the line from the start point. An upper case letter is used if more than one hole was drilled at a particular locality.

TABLE 12. UNIAXIAL COMPRESSIVE STRENGTHS OF MOIST SAMPLES

Sample location		Description	Uniaxial compressive strength	
Drill-hole no.	Depth (m)		MPa	psi
750100A	12·94–13·10	Well-cemented calcareous quartz sandstone	34	4 930
750100A	13·33–13·45	Moderately cemented calcareous quartz sandstone	13	1 890
750100A	15·13–15·27	Well-cemented limestone	47	6 820
750100B	10·10–10·41	Well-cemented limestone	41 58	5 950 8 400
750400	14·98–15·11	Poorly to moderately cemented calcareous quartz sandstone	5	730
750400	18·77–18·93	Well-cemented calcareous quartz sandstone	39	5 600
750400	19·57–19·70	Moderately to well-cemented calcareous quartz sandstone	25	3 630
750400	23·21–23·35	Moderately to well-cemented calcareous quartz sandstone	16 (failure along cavity)	2 320
750400	23·93–24·13	Moderately to well-cemented calcareous quartz sandstone	24 28	3 480 4 060
750400	25·65–25·78	Well-cemented limestone	38	5 510

TABLE 13. UNIAXIAL COMPRESSIVE STRENGTHS OF AIR-DRIED SAMPLES

Sample location: Drill-hole no.	Sample location: Depth (m)	Description	Uniaxial compressive strength: MPa	Uniaxial compressive strength: psi
750100B	10·51–10·63	Well-cemented limestone	50	7 250
750400	18·40–19·28	Well-cemented calcareous quartz sandstone	23 47	3 340 6 820
750400	24·42–25·65	Well-cemented limestone	35 35 58 31	5 080 5 080 8 410 4 500
750700	25·86–26·07	Well-cemented limestone	86 58	12 470 8 410
751000	22·28–22·52	Well-cemented calcareous quartz sandstone	47 50	6 820 7 250
751900	37·83–38·31	Poorly to moderately cemented calcareous quartz sandstone	4 6 6	580 870 870
752200	18·14–18·28	Moderately cemented limestone	24	3 480
752200	32·24–32·37	Moderately cemented calcareous quartz sandstone	9	1 310
752500	27·65–27·82	Moderately cemented shelly limestone	5	730
Caprock from north of Mullaloo		Calcretized rock	37 10	5 370 1 450
Caprock from near drill-hole no. 753100		Calcretized rock	21 30	3 050 4 350
Pinnacle from north of Mullaloo		a. Calcretized rock with core axis parallel to rock lamination	27 80	3 900 11 600
		b. Calcretized rock with core axis normal to rock lamination	16	2 320

TABLE 14. UNIAXIAL COMPRESSIVE STRENGTHS OF MOIST AND 7-DAY OVEN-DRIED SAMPLES

Sample location	Description	Uniaxial compressive strength: Moist MPa	Moist psi	Oven-dried MPa	Oven-dried psi
W.A. Limestone Co. quarry, Wattleup	Poorly to moderately cemented limestone	4 6	580 870	9 11	1 350 1 595
Caprock from near drillhole no. 753100	Calcretized rock	12 20	1 740 2 900	24 36 62	3 480 5 220 8 990

Discussion

The fracture appearance of the uniaxially failed rock is generally a straight split or conical splits. Rock laminated parallel to the core axis fails as a series of splits parallel to the laminations. Poorly to moderately cemented rock often has a barrel-shaped type of failure.

Table 15 represents the relationship between the degree of rock cementation identified in the field and the range of strength determinted in the laboratory.

TABLE 15.

	Poorly cemented rock	Moderately cemented rock	Well-cemented rock
Uniaxial compressive strength range	<3·5 MPa (<500 psi)	3·5–24·0 MPa (500–3 500 psi)	>24·0 Mpa (> 3 500 psi)
Field identification	Rock is friable in the hand	Pieces of rock can be broken by hand	Hammer required to break rock

Although the main factor in the strength of the Coastal Limestone is the degree of cementation which is inversely related to rock porosity, there are rocks of equivalent porosities with differences in strength. This is due to the type of cement. Sparite cement forms a stronger bond than micrite cement, which generally contains impurities. On the other hand, caprock and pinnacles (which consist mainly of micrite), have similar strengths to well-cemented rocks with sparite cement. This is related to grain size. Tests show that rocks of uniform grain size are stronger than rocks with variable grain sizes.

All the rocks tested show a considerable increase in uniaxial compressive strength on drying. This is thought to be caused mainly by increasing molecular cohesive strength, but also by the evaporation of pore water containing $Ca(HCO_3)_2$ in solution and $CaCO_3$ in suspension, to form a carbonate cement.

LOS ANGELES TEST

Testing was done using 5 000 g of test sample (2 500 g passing the ¾ in. sieve size and retained on the ½ in. size, and 2 500 g passing the ½ in. size and retained on the ⅜ in. size), 11 spheres, and 500 revolutions. After the completion of the test the material was sieved on a B.S.I. No. 10 sieve. The percentage of wear calculated is given in Table 16.

TABLE 16.

Rock type	Percentage of wear
Well-cemented limestone	32
Well-cemented calcareous quartz sandstone	45
Caprock	35

Discussion

Testing was restricted by the amount of core available, but the results do indicate the lower limits of wear of the Coastal Limestone.

The comparison of test results for rocks of different grain sizes can be somewhat misleading. For example, a poorly cemented rock with a grain size greater than a B.S.I. No. 10 sieve will give a lower wear percentage than a similarly cemented rock with grains smaller than the sieve size. In Los Angeles testing, if the bond strength between individual grains or between grains and cement within a rock fragment is sufficient to allow rounding rather than disaggregation of the fragment on impact, then meaningful interpretations of abrasion values can be made.

SCHMIDT HAMMER TEST

A standard type N Schmidt Hammer was used to determine rebound hardness. This test requires pressure against the head of an impact plunger to disengage the plunger. When the plunger is pressed against a rock face, the mass of the hammer is released. After the impact the mass rebounds to a height indicated by a pointer against a scale. The rebound height as a percentage of the forward travel of the mass can be read off the scale, and is called the rebound number (see Table 17).

Although essentially a field test to assess *in situ* rock strength, it was necessary to do some laboratory testing on core because of the lack of suitable outcrops of certain rock types. The laboratory results are expected to be more variable than the field results because of the difficulty of stabilising the core during testing.

TABLE 17

Sample location (m)	Description	Range of rebound numbers	Average rebound number
Drillhole no. 750400: 18·40–18·78	Well-cemented calcareous quartz sandstone	21–24	32
Drillhole no. 750400: 19·12–19·28	Well-cemented calcareous quartz sandstone	28–42	34
Drillhole no. 750400: 19·28–19·37	Well-cemented calcareous quartz sandstone	38–46	42
Drillhole no. 750400: 25·56–25·65	Well-cemented limestone	32–43 33–42 30–36	36 39 33
Caprock from north of Mullaloo	Calcretized rock....	36–58 15–50 11–40	51 30 24
Pinnacle from north of Mullaloo	Calcretized rock....	28–50 20–64	41 37

Discussion

The wide range in rebound numbers of individual samples is attributed partly to variation in degree of cementation and recrystallisation over short distances of rock, and partly to experimental error.

BRAZILIAN TEST

Indirect tensile strength was determined using a loading rate of 1.19 t/min. The results are given below in Table 18.

TABLE 18.

Sample location		Description	Indirect tensile strength	
Drill-hole no.	Depth (m)		MPa	psi
750100A	12·94–13·10	Well-cemented calcareous quartz sandstone	3	435
750100A	15·53–15·64	Moderately cemented calcareous quartz sandstone	1	145
750100B	10·10–10·41	Well-cemented limestone	3, 5	435, 725
750100B	13·06–13·14	Moderately cemented calcareous quartz sandstone	2	29

ENGINEERING SIGNIFICANCE

TUNNELLING AND OPEN EXCAVATION PROBLEMS

There are various problems in mixed-face tunnelling into material ranging from sand to well-cemented rock. The presence of loose sand and weak rock within more competent rock necessitates shield protection during tunnel excavation. Excessive sand-runs into a tunnel can be prevented by mounting hydraulic spilers. The thrust jacks for the shield and its excavating mechanism probably cannot use the tunnel walls as a footing, and may need a specially constructed support to bear against. The application of pressure to tunnel walls is precluded by the highly variable rock strength and the presence of cavities.

Solution cavities up to at least several metres across occur within the Coastal Limestone. These are hazardous if they exist just below tunnel invert level, but can be detected by probe drilling. Sand or sand/cement grouting would then be necessary. Rippability characteristics were determined for well-cemented rock and caprock (Fig. 19). The samples lie in the upper part of the rip field rather than the blast field. Although the Coastal Limestone is variable both vertically and horizontally, it often lacks structural discontinuities such as joints, which also assist in ripping. Therefore if more massive zones of caprock or well-cemented rock are intersected, conventional drilling and blasting, or percussion methods may be necessary, but should be used with caution.

Open excavations in sand will fret and need to be battered back or supported in some way.

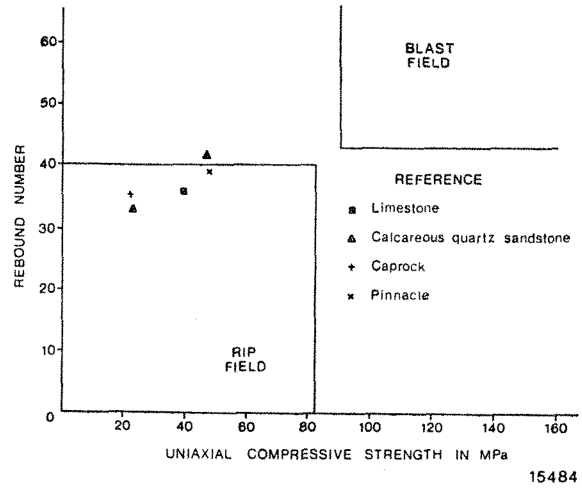


Figure 19. Relationship between rebound number and uniaxial compressive strength (after Duncan, 1969).

ROAD BASE-COURSE MATERIAL

The life-expectancy and maintenance of limestone-based roads compare very favourably with gravel-based roads. Limestone has the advantage of recementing in time to form a harder, firmer layer than when first laid. This is caused by the solution of finely divided carbonate by circulating groundwater, and precipitation to form a cement. When compared to gravel base course, the prime disadvantage is lack of cohesion, and therefore a thin sheeting of gravel or a greater thickness of bituminous surfacing is required. A bitumen seal will also not adhere directly to a limestone base course due to the fine, loose material which collects on top of the limestone.

Brooksbank (1967) has stated that the best material appears to have a carbonate content of between 60 and 85 per cent and a Los Angeles abrasion value of less than 60 per cent. The large spalls must also be broken down to less than 8 cm diameter, otherwise they will move under traffic and cause potholes. If caprock, pinnacles, solution tubes or well-cemented rock are used, breakdown will be hindered and differential compaction will occur. These rocks generally have a Los Angeles abrasion value of between 30 and 40 per cent.

Careful selection of quarries will facilitate quality control and minimise compaction problems. Site excavation where caprock is thin or discontinuous will minimise quarry development costs. When the lower caprock profile contains a network zone, greater excavation is required to reach suitable material. If quartz sand layers (Fig. 18B) occur within the limestone, or there are disconformities with quartz sand below the limestone (Fig. 18C), quality will be adversely affected by quartz contamination. These problems can be overcome by adequate investigation prior to excavation.

BREAKWATER MATERIAL

The economic attractiveness of using Coastal Limestone as breakwater rock is its proximity to construction areas. Prior geological investigation of proposed quarry sites will provide information about the quality and quantity of material available.

Design considerations for different wave sizes on the Garden Island Causeway were determined by Hicks, Foster, and Wilkinson (1973). Quarry run limestone was used for the core. Limestone armour was used for 2 m waves and granite armour for 4 m waves. A granite blanket was placed on the sea bed along each side of the core, to prevent erosion. Limestone was also used as a base-course material for the access road.

If extensive zones of massive caprock occur close to site areas, these could be used as armour for greater than 2 m waves. Caprock is one of the denser types of limestone and its resistance to wear is high.

The excavation of limestone for breakwaters requires controlled blasting to obtain a sufficient amount of large rock sizes. Excavation methods for the Garden Island Causeway have been described by Hicks, Buchanan, Fernie, and Tabert (1973). A small charge of ammonium nitrate fuel oil (ANFO) sufficient only to loosen the rock into required sizes, was introduced into the limestone through horizontal toe holes. Occasionally vertical drilling was necessary.

Large limestone blocks are susceptible to breakdown during handling. If the rock is stockpiled prior to transport the pore water will evaporate and the strength is increased. Once placed on the breakwater, the limestone gradually undergoes case hardening. A skin of hard, dense calcite, as much as several centimetres thick, is gradually formed by alternate wetting and drying of the rock.

REFERENCES

Bawa, K. S., and Bumanis, A., 1972, Design considerations for underground structures in rock: 1st North American Rapid Excavation and Tunnelling Conference Proc., p. 399.

Bieniawski, Z. T., and Franklin, J. A., 1972, Suggested methods for determining the uniaxial compressive strength of rock materials: Int. Soc. Rock Mechanics, Committee on Laboratory Tests, Document No. 1.

Brooksbank, B., 1967, W.A. Coastal Limestone as a road sub-base material: Univ. West. Australia Engineering Hons. thesis (unpublished).

Brown, H. Y. L., 1872, Report on the geology of the country examined in the neighbourhood of the Swan, Sclaters, and Yarrogin, Bindoon, Gingin, Moore River, Yatheroo, Dandaragan, Hill River and Jurien Bay: West. Australia Parl. Pap. No. 6, p. 7-8.

Campbell, J. M., in prep., Univ. West. Australia Engineering Masters thesis (unpublished).

Duncan, N., 1969, Engineering geology and rock mechanics: London, Leonard Hill, v. 1, p. 173.

Fairbridge, R. W., 1953 Australian stratigraphy: Univ. West. Australia Press, CH. XII, p. 23-27.

Fletcher, R. W., 1933, The limestone of the Swan Coastal Plain: its use as a building stone: Royal Soc. West. Australia Jour., v. 20, p. 17-46.

Goudie, A. S., 1971, A regional bibliography of calcrete, *in* W. J. McGinnies, B. J. Goldman, and P. Paylore (eds.), Food, fiber and arid lands: Tucson, Univ. Arizona Press, p. 421-437.

———1972, The chemistry of world calcrete deposits: Jour. Geology, v. 80, p. 449-463.

Hicks, A. B., Buchanan, F. J., Fernie, G. N., and Tabert, P. W. J., 1973, Design and construction of the Garden Island Causeway, Cockburn Sound: Inst. Engineers, Australia, Annual Engineering Conference, Perth, 1973, p. 25-36.

Hicks, A. B., Foster, D. N., and Wilkinson, F. L., 1973, Coastal engineering aspects of the Garden Island Causeway, Western Australia: Engineering Dynamics of the Coastal Zone, 1st Australian Conference on Coastal Engineering, p. 108-117.

Read, J. F., 1974, Calcrete deposits and Quaternary sediments, Edel Province, Shark Bay, Western Australia: Am. Assoc. Petroleum Geologists, Mem. 22, p. 250-282.

PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1975

by K. A. Crank

ABSTRACT

The tempo of oil exploration in Western Australia, which has declined steadily since 1972, showed an even more rapid decline in 1975. The number of test wells completed decreased by 70 per cent compared to 1974 and seismic activity was reduced by 75 per cent.

Drilling activity was restricted to the Perth and Carnarvon Basins, mainly offshore. The only onshore drilling was on Barrow Island where West Australian Petroleum Pty. Ltd's Biggada No. 1, a deeper pool test within the Barrow Field, revealed gas-bearing sands at a similar depth to those found at Barrow Deep No. 1 in 1973.

BOCAL Pty. Ltd. discovered significant gas-bearing sands at Tidepole No. 1 in a previously untested structure close to the Goodwyn Field. An oil-bearing section was also found in this well.

Only six wells were completed during 1975, and one was drilling ahead at the end of the year, for a total of 17 115 m. Geophysical activity was restricted to land and marine seismic surveys in the Perth, Carnarvon and Canning Basins.

During the year many onshore and offshore tenements were surrendered, relinquished or cancelled in almost all basins.

INTRODUCTION

Exploration drilling for petroleum in Western Australia showed a marked decline in 1975 compared to 1974 as is seen in the following table:

	Wells completed		Wells drilling on 31 December	
	1974	1975	1974	1975
New field wildcats	15	5	0	1
Extension wells	1	0	0	0
Deeper pool tests	0	1	0	0
Development wells	1	0	0	0
Stratigraphic tests	4	0	0	0
	21	6	0	1

Total effective drilling : 1974—46 626 m
1975—17 115 m*

* The aborted South Turtle Dove Nos. 1 and 1A, and Lewis No. 1, which drilled to 350, 330 and 265 m respectively, are not included in these tabulations.

Two successful wells were drilled in 1975: Biggada No. 1 is classified as a deeper pool test suspended gas discovery, and Tidepole No. 1 as a suspended gas/condensate/oil discovery.

Geophysical survey activity also declined compared to 1974. The totals for 1975 are shown below (with the 1974 figures in brackets). Geological survey totals are also listed:

Type of survey	Line km	Party months or geologist months
Land seismic	484 (559)	....
Marine seismic	2 737 (11 815)	....
Aeromagnetic	Nil (6 373)	....
Gravity land	....	Nil (1·0)
Gravity marine	....	....
Magnetic	....	....
Geological	....	5·0 (3·0)

PETROLEUM TENEMENTS

During 1975 large areas were relinquished, cancelled and surrendered in all major sedimentary basins. Large areas are currently available for application in all basins.

Twelve offshore and 20 onshore permits were surrendered or cancelled, 12 offshore and 10 onshore permits were partially relinquished, surrender was pending on one onshore permit, applications for renewal were under consideration on four onshore permits, and applications for one new offshore and one onshore exploration permit were being considered. Permits surrendered or cancelled are as follows:

Offshore: WA-2-P, WA-7-P, WA-15-P, WA-17-P, WA-21-P, WA-26-P, WA-27-P, WA-30-P, WA-39-P, WA-40-P, WA-50-P, WA-51-P.

Onshore: EP4, EP5, EP6, EP8, EP9, EP14, EP15, EP17, EP18, EP20, EP26, EP27, EP28, EP29, EP31, EP37, EP38, EP43, EP44, EP69.

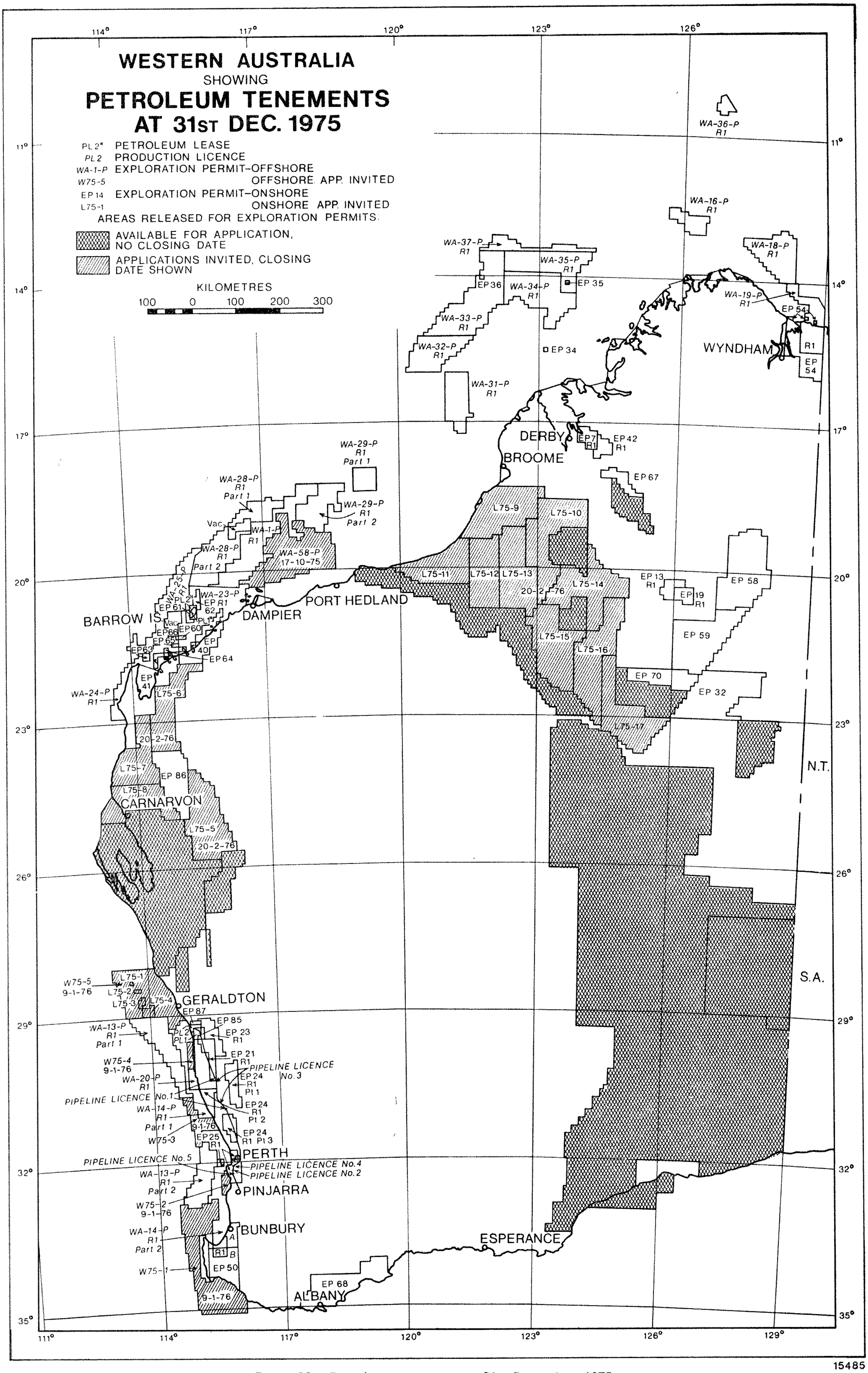


Figure 20. Petroleum tenements at 31st December, 1975.

Petroleum tenements current on December 31st, 1975 are shown in Figure 20, and the following tabulation lists details of the various holdings:

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

Exploration Permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
WA-1-P R1	178	14/11/79	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd.
WA-13-P R1 Part 1 / R1 Part 2	110 / 84 } 194	29/8/79	West Australian Petroleum Pty. Ltd. (WA-13-P, WA-14-P)
WA-14-P R1 Part 1 / R1 Part 2	77 / 121 } 198	29/8/79	
WA-16-P R1	40	16/4/80	Arco Aust. Ltd., Australian Aquitaine Petroleum Pty. Ltd., Esso Exploration & Production Aust. Inc. (WA-16-P, WA-18-P)
WA-18-P R1	105	16/4/80	
WA-19-P R1	49	20/3/80	Alliance Oil Development Aust. N.L.
WA-20-P R1	15	10/10/79	West Australian Petroleum Pty. Ltd. (WA-20-P to WA-25-P)
WA-23-P R1	199	30/10/79	
WA-24-P R1	104	17/10/79	
WA-25-P R1	128	16/10/79	
WA-28-P R1 Part 1 / R1 Part 2	52 / 126 } 178	24/3/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd.
WA-29-P R1 Part 1 / R1 Part 2	36 / 84 } 120	18/5/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd.
WA-31-P R1	80	18/5/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd.
WA-32-P R1	100	2/7/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd. (WA-32-P to WA-35-P)
WA-33-P R1	194	18/5/80	
WA-34-P R1	149	2/7/80	
WA-35-P R1	123	2/7/80	
WA-36-P R1	18	18/5/80	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd. (WA-36-P, WA-37-P)
WA-37-P R1	59	2/6/80	
WA-58-P	222	Appn.	Western Energy Pty. Ltd.

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT, 1936

Petroleum Leases

Number	Area (square miles)	Expiry date of current term	Holders
1H	100	9/2/88	West Australian Petroleum Pty. Ltd. (1H, 2H)
2H	100	9/2/88	

PETROLEUM TENEMENTS UNDER THE PETROLEUM ACT, 1967

Exploration Permits

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 7 R1	24	27/8/80	West Australian Petroleum Pty. Ltd. (EP 7, EP 13, EP 19)
EP 13 R1	23	27/8/80	
EP 19 R1	18	27/8/80	
EP 21 R1	32	26/7/80	West Australian Petroleum Pty. Ltd.

Exploration Permits—continued.

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 23 R1	33	6/8/80	West Australian Petroleum Pty. Ltd.
EP 24 R1 Part 1 / R1 Part 2 / R1 Part 3	39 / 24 / 22 } 85	6/8/80	West Australian Petroleum Pty. Ltd. (EP 24, EP 25)
EP 25 R1	36	6/8/80	
*EP 32	200	15/4/76	Beach-General Exploration Pty. Ltd., Australian Aquitaine Petroleum Pty. Ltd.
EP 34	1	15/4/76	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., BOCAL Pty. Ltd. (EP 34 to EP 36)
EP 35	1	15/4/76	
EP 36	1	15/4/76	
EP 40	67	26/7/76	West Australian Petroleum Pty. Ltd.
EP 41	180	18/7/76	West Australian Petroleum Pty. Ltd. (EP 41, EP 42)
EP 42 R1	19	1/9/80	
EP 50	110	1/9/75	West Australian Petroleum Pty. Ltd.
R1	18	Appn.	
EP 54	123	22/9/75	Alliance Oil Development Aust. N.L.
R1	47	Appn.	
EP 58	200	20/7/76	Associated Australian Resources N.L., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil N.L., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L., West Australian Petroleum Pty. Ltd. (EP 58 to EP 67)
EP 59	186	18/7/76	
EP 60	2	Appn.	
EP 61	4	19/9/76	
EP 62	8	19/9/76	
EP 63	4	19/9/76	
EP 64	1	Appn.	
EP 65	2	19/9/76	
EP 66	1	19/9/76	
EP 67	29	25/10/76	
EP 68	175	27/7/77	W. I. Robinson
EP 70	71	25/9/77	Associated Australian Resources N.L., Australian Aquitaine Petroleum Pty. Ltd., Abrolhos Oil N.L., Ashburton Oil N.L., Flinders Petroleum N.L., Longreach Oil Ltd., Pursuit Oil N.L.
EP 85	4	19/7/80	Endeavour Oil Co. N.L., Target Minerals N.L., IOL Petroleum Ltd., Associated Australian Resources N.L., Alliance Minerals (Aust.) N.L.
EP 86	118	9/1/80	XLX N.L.
EP 87	3	Appn.	Elvert Exploration Pty. Ltd.

* Surrender Pending.

Production Licences

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

PETROLEUM TENEMENTS UNDER THE PETROLEUM PIPELINES ACT, 1969

Pipeline Licences

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

DRILLING

The positions of wells drilled for petroleum exploration in Western Australia during 1975 are shown in Figures 21 and 22. Details relating to wells drilled during the year are given in Table 19. All the petroleum exploration wells drilled in Western Australia up to the end of 1975 are listed in the Geological Survey Record 1976/1 (Crank, in prep.). A summary of the principal results of the drilling in each basin during the year is as follows:

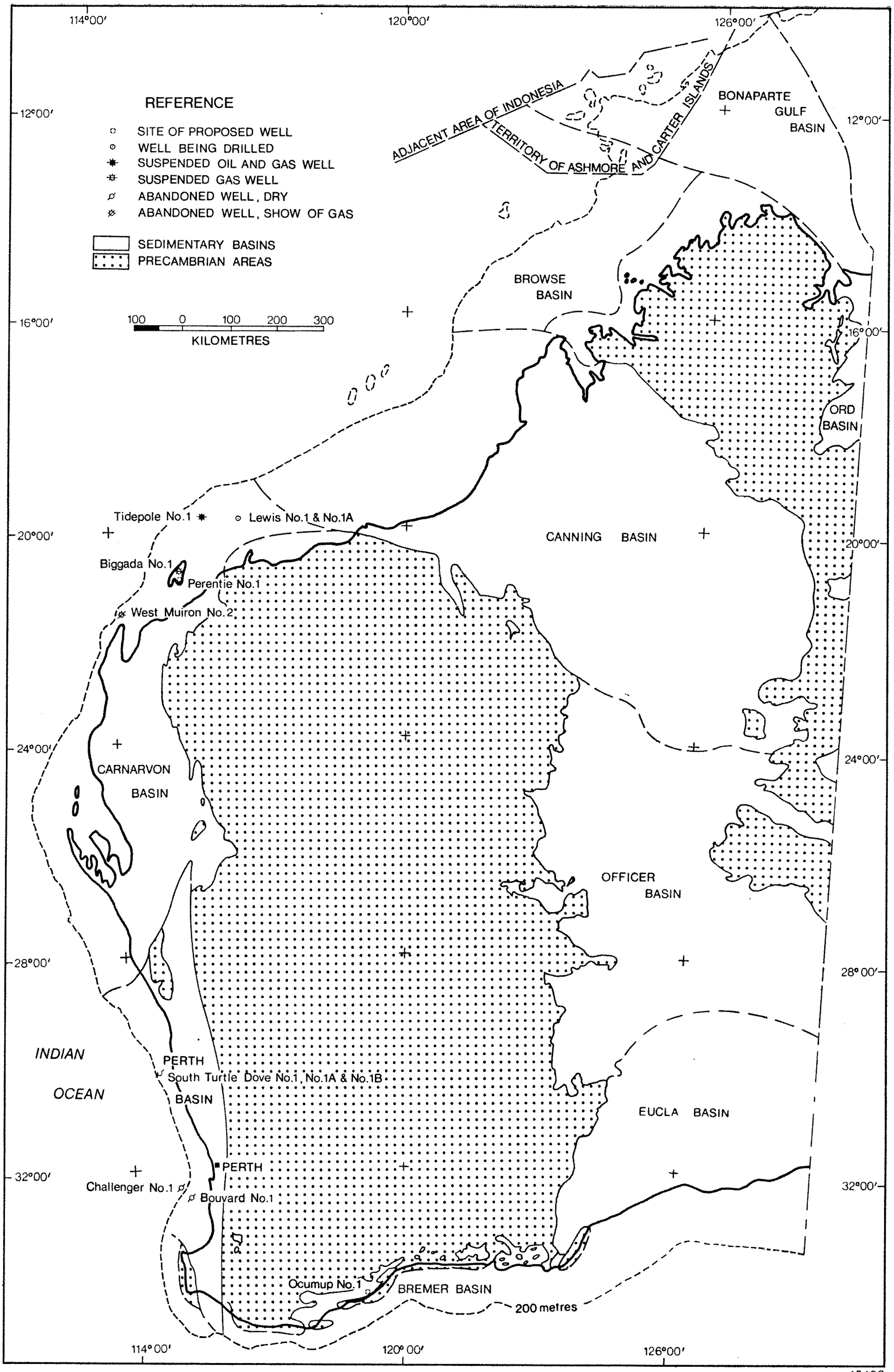


Figure 21. Wells drilled for petroleum exploration in W.A. during 1975.

PLATE 4

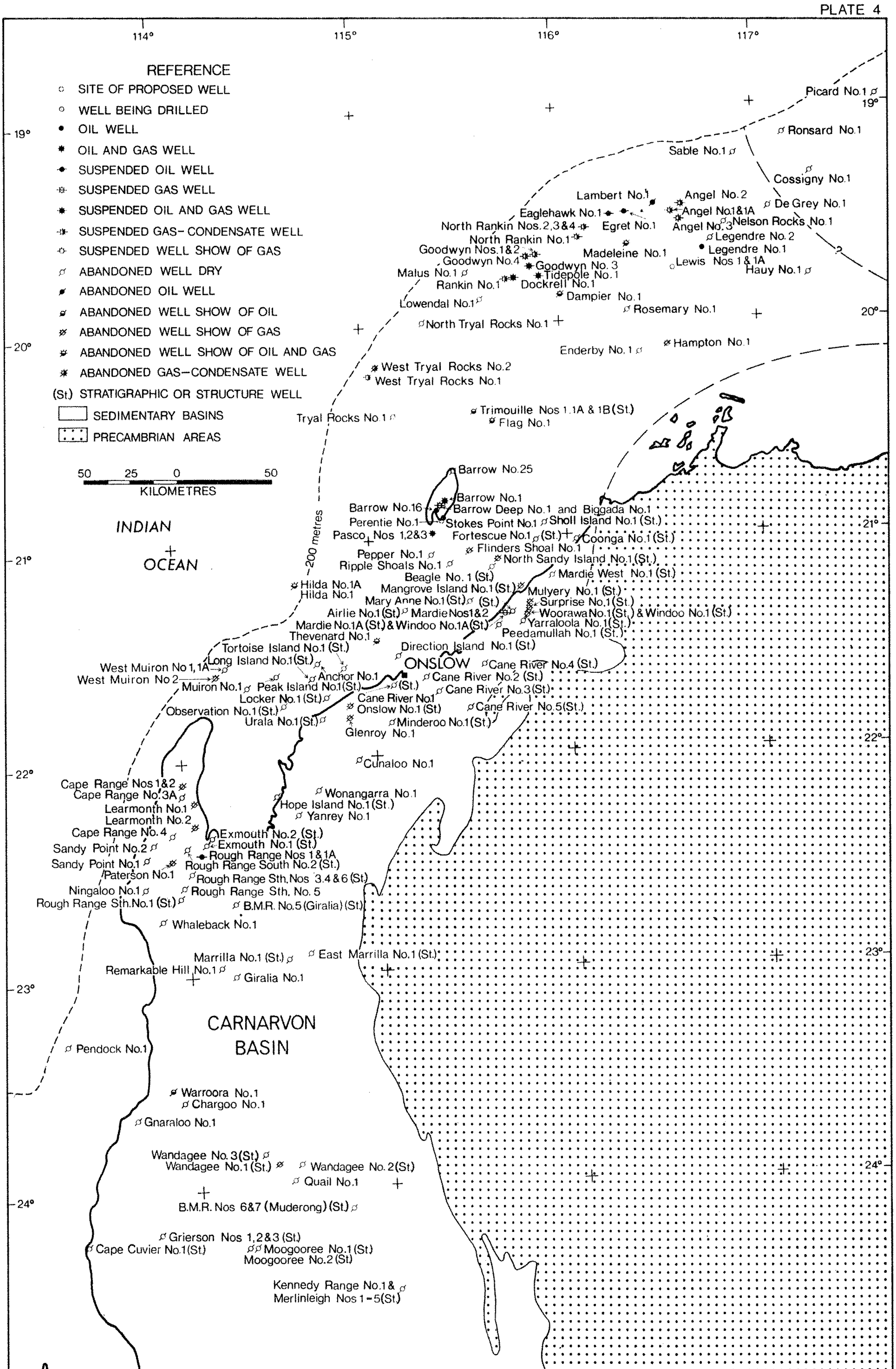


Figure 22. Northern Carnarvon and southwestern Canning Basin showing wells drilled for petroleum to 31st December, 1975.

TABLE 19. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1975

Basin	Well	Concession	Operating Company	Type	Position: Latitude South ° ′ ″	Position: Longitude East ° ′ ″	Elevation and water depth (metres): G.L.	R.T.	W.D.	Dates: Commenced	Reached T.D.	Rig released	Total depth (or depth reached) m	Bottomed in	Status on 31/12/75
PERTH	Bouvard No. 1	WA–14–P	WAPET	NFW	32 31 26	115 15 11	....	12	51	3/1/75	28/1/75	3/2/75	1 980	L. Cretaceous	Dry, P & A
	Challenger No. 1	WA–13–P	WAPET	NFW	32 25 21	115 00 46	....	12	212	14/2/75	20/3/75	3/4/75	2 250	U. Jurassic	Dry, P & A
	S. Turtle Dove No. 1	WA–13–P	WAPET	NFW	30 07 46	114 38 12	....	30	63	16/4/75	23/4/75	....	350	....	Dry, P & A
	No. 1A	WA–13–P	WAPET	NFW	30 07 46	114 38 11	....	30	63	25/4/75	29/4/75	....	330	....	Dry, P & A
	No. 1B	WA–13–P	WAPET	NFW	30 07 46	114 38 11	....	30	63	4/5/75	15/6/75	6/7/75	1 830	L. Permian	Dry, P & A
CARNARVON	Biggada No. 1	PL–1H	WAPET	DPT	20 48 36	115 23 10	55	63	....	20/6/75	13/10/75	27/12/75	3 624	M. Jurassic	Suspended gas well
	W. Muiron No. 2	WA–24–P	WAPET	NFW	21 35 39	114 13 31	....	30	62	10/8/75	10/10/75	15/10/75	3 320	U. Triassic	Gas shows, P & A
	Tidepole No. 1	WA–28–P	BOCAL	NFW	19 46 07	115 53 06	....	30	110	18/10/75	26/11/75	17/12/75	3 491	Triassic	Suspended gas/cond./ oil well
	Lewis No. 1	WA–1–P	BOCAL	NFW	19 47 36	116 36 04	....	30	60	20/12/75	23/12/75	23/12/75	265	....	Dry, P & A
	No. 1A	WA–1–P	BOCAL	NFW	19 47 36	116 36 04	....	30	60	24/12/75	....	....	620	....	Drilling

BOCAL = BOCAL Pty. Ltd.
WAPET = West Australian Petroleum Pty. Ltd.
DPT = Deeper pool test well
NFW = New-field wildcat well
P & A = Plugged and abandoned

PERTH BASIN

Three wells were drilled by West Australian Petroleum Pty. Ltd. (WAPET) in the Perth Basin during 1975, all offshore. Bouvard No. 1 and Challenger No. 1 were both new-field wildcats in the southern part of the Vlaming sub-basin, designed to test culminations on anticlinal axes flanking the deepest part of the basin. No shows were encountered in either well and both were plugged and abandoned in the Yarragadee Formation, Bouvard No. 1 at 1 980 m and Challenger No. 1 at 2 250 m total depth.

South Turtle Dove No. 1B was located in the southwestern part of the Abrolhos sub-basin. The South Turtle Dove feature is a structural culmination on the Turtle Dove Ridge, a shallow basement high with an overall northwesterly plunge. The No. 1B well was plugged and abandoned at a total depth of 1 830 m in the Upper Permian after no shows were reported and the predicted Upper Permian and Lower Triassic sands were found to be absent. The South Turtle Dove No. 1 well was abandoned at 350 m and the No. 1A well, 15 m west of No. 1, was abandoned at 330 m, both due to mechanical problems.

CARNARVON BASIN

The only onshore well in Western Australia was Biggada No. 1 drilled by WAPET on Barrow Island. This was a deeper pool test, a follow-up to Barrow Deep No. 1 drilled in 1973, which was a Middle Jurassic gas discovery. After considerable problems with supernormal formation pressure, the well was eventually suspended as a gas well in the Middle Jurassic. Potential production is from several sands at a depth similar to those discovered in Barrow Deep No. 1. Production testing had not been completed at the year's end.

WAPET drilled one well offshore in the Carnarvon Basin, West Muiron No. 2, which was plugged and abandoned at 3 320 m in Late Triassic siltstone after encountering gas shows and abnormal pressures near the total depth. Mechanical problems contributed to the abandonment at this depth, but no potential pay zones were encountered.

BOCAL drilled one offshore well, Tidepole No. 1, which was located to evaluate Upper Triassic sands on a horst block adjacent to the oil-productive Goodwyn No. 3 block. The well was classed as a gas/condensate/oil discovery in the Triassic with a total net pay of 102 m including 17 m of oil. The oil zone tested 36° API gravity oil which flowed at the rate of 3 317 barrels per day. The average porosity of the sands was 23 per cent, calculated from wireline logs. BOCAL was drilling one well, Lewis No. 1, at the end of the year.

There was no drilling in any of the other basins during 1975.

GEOPHYSICAL SURVEYS

SEISMIC

During 1975 seismic surveys were conducted in the Perth, Carnarvon and Canning Basins. Details are as follows:

SEISMIC SURVEYS

Basin	Tenement	Company	Line kilometres	
			Marine	Land
Perth	EP 21	West Australian Petroleum Pty. Ltd.	....	4
,,	EP 23	,, ,, ,,	....	108
,,	EP 24	,, ,, ,,	....	80
,,	EP 25	,, ,, ,,	....	40
,,	PL–1	,, ,, ,,	....	94
,,	PL–2	,, ,, ,,	....	16
,,	WA–13–P	,, ,, ,,	85	....
,,	WA–14–P	,, ,, ,,	498	....
Carnarvon	EP 41	,, ,, ,,	....	88
,,	WA–1–P	BOCAL Pty. Ltd.	369	....
,,	WA–23–P	West Australian Petroleum Pty. Ltd.	347	....
,,	WA–24–P	,, ,, ,,	223	....
,,	WA–25–P	,, ,, ,,	150	....
,,	WA–28–P	BOCAL Pty. Ltd.	710	....
Canning	EP 7	West Australian Petroleum Pty. Ltd.	....	12
,,	EP 42	,, ,, ,,	....	42
,,	WA–29–P	BOCAL Pty. Ltd.	357	....

There were no gravity or magnetometer surveys during 1975.

GEOLOGICAL SURVEYS

XLX N.L. carried out 4 party months of surface geological surveys in the Carnarvon Basin (EP 86), while WAPET spent 1 party month, half in the Canning Basin (EP 42) and half in the Carnarvon Basin (EP 41).

REFERENCES

Crank, K.A., in prep., Wells drilled for petroleum exploration in W.A. to the end of 1975: West. Australia Geol. Survey Rec. 1976/1 (unpublished).

REVISED STRATIGRAPHIC AND FACIES NOMENCLATURE IN DEVONIAN REEF COMPLEXES OF THE CANNING BASIN

by P. E. Playford and A. E. Cockbain

ABSTRACT

Three basic facies are now distinguished in Devonian reef complexes of the Canning Basin: the platform, marginal-slope, and basin facies. The platform facies is subdivided into reef-margin, reef-flat, patch-reef, back-reef, and bank sub-facies, while the marginal-slope facies is subdivided into reefal-slope, fore-reef, fore-bank, and stromatolite sub-facies.

A new formation, the Nullara Limestone, is defined; it embraces the Famennian back-reef and bank deposits and was formerly included in the upper part of the Pillara Limestone. The Windjana Limestone is redefined so as to exclude the Frasnian reef deposits, which are now placed in the Pillara Limestone.

INTRODUCTION

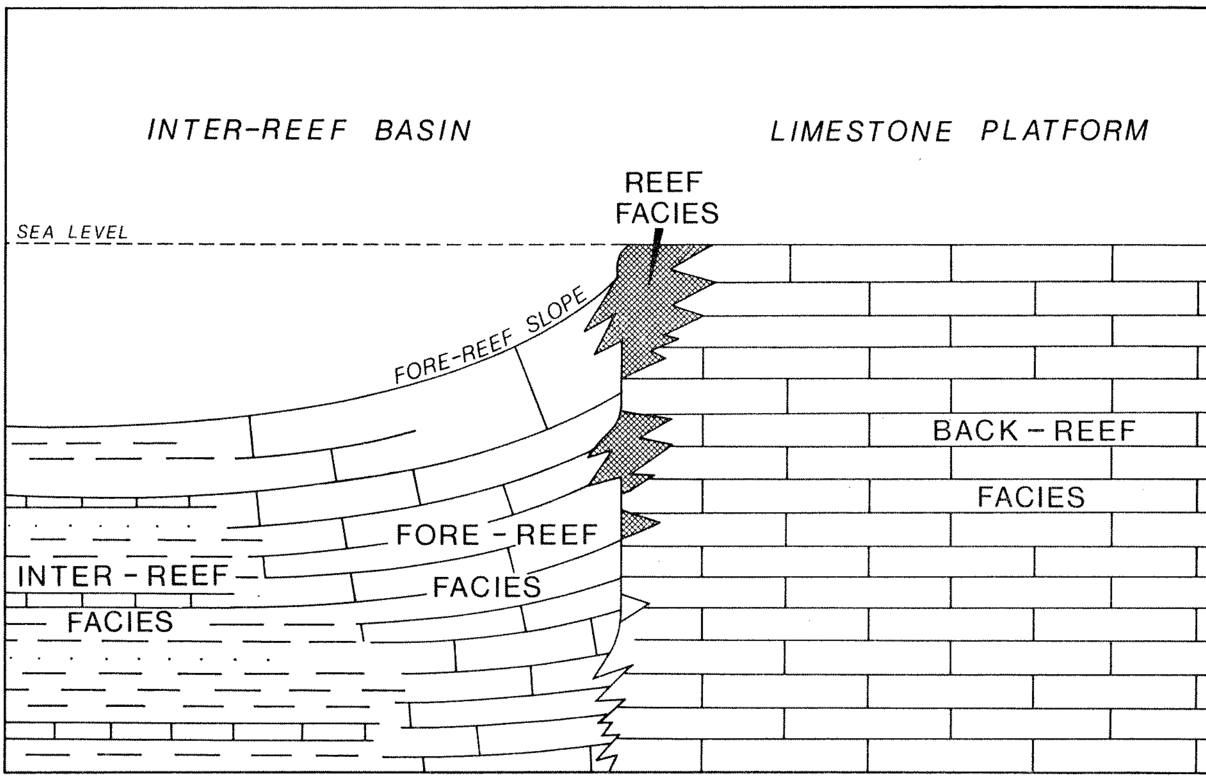
Since the Devonian reef complexes of the Canning Basin were described in Bulletin 118 of the Geological Survey (Playford and Lowry, 1966) more detailed studies have been carried out at Bugle Gap, Windjana Gorge, and other areas by the Geological Survey in association with the Bureau of Mineral Resources. As a result of this work it is desirable that the facies nomenclature adopted by Playford and Lowry be amended to facilitate more detailed description of the reef complexes. Some changes in the formal stratigraphic nomenclature are also now required.

The purpose of this paper is to formally introduce the new terminology so that it can be used in forthcoming publications.

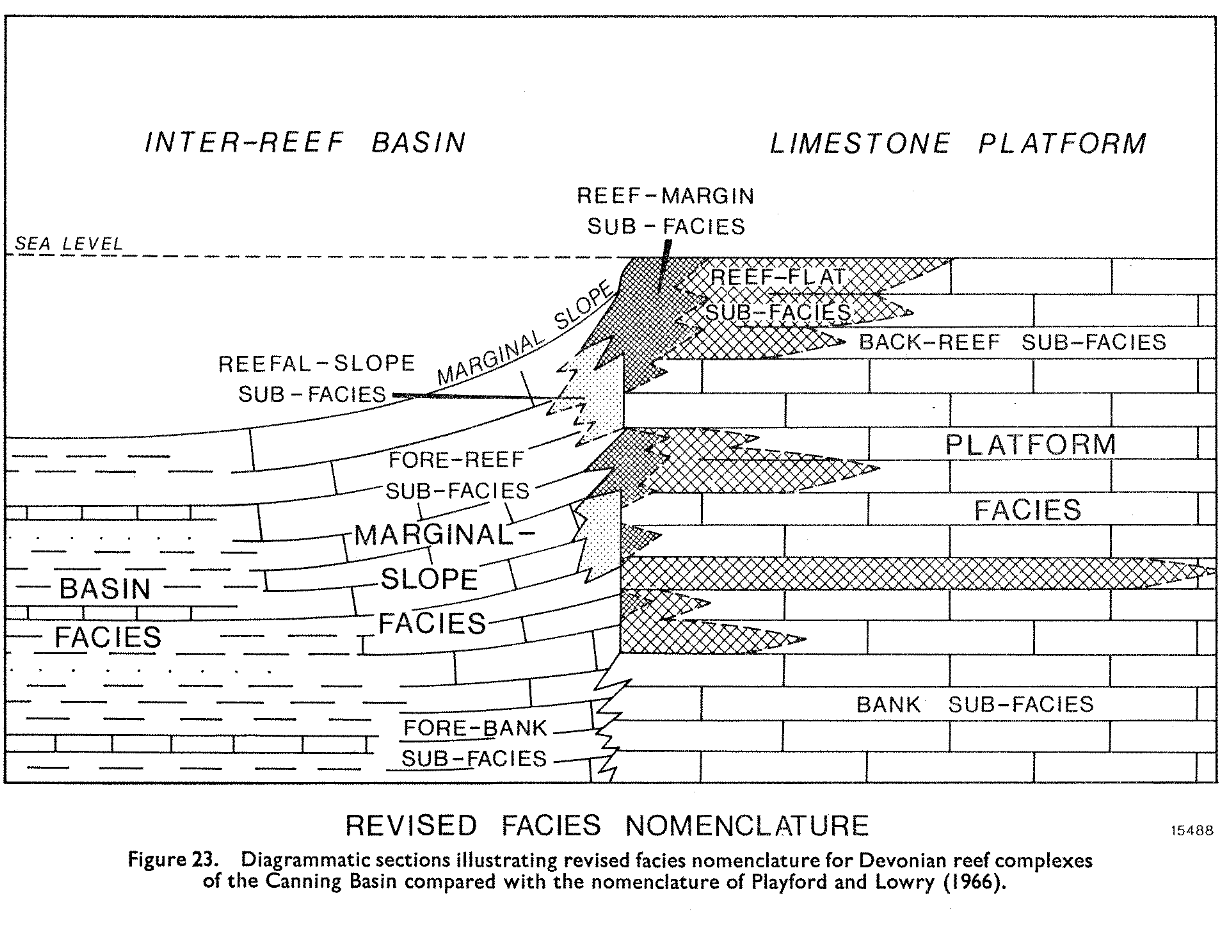
We wish to express our thanks to E. C. Druce and R. S. Nicoll of the Bureau of Mineral Resources and to M. H. Johnstone, D. N. Smith, W. J. Witt, and D. A. Lyons of West Australian Petroleum Pty. Ltd. (Wapet) for their co-operation and assistance in our work on the Devonian of the Canning Basin.

FACIES NOMENCLATURE

Playford and Lowry (1966) recognised four facies in the reef complexes, naming them the reef, back-reef, fore-reef, and inter-reef facies. This nomenclature proved to be adequate at the time for regional studies of the reef complexes. However, as pointed out by Playford (1969), it differs from the nomenclature applied to similar Devonian carbonate complexes in Canada. Moreover, it was realised that the terms fore-reef and back-reef facies were not appropriate in all cases, as these facies are not always separated by reef.



FACIES NOMENCLATURE OF PLAYFORD AND LOWRY (1966)



REVISED FACIES NOMENCLATURE

15488

Figure 23. Diagrammatic sections illustrating revised facies nomenclature for Devonian reef complexes of the Canning Basin compared with the nomenclature of Playford and Lowry (1966).

The recent work has now shown that a more detailed facies terminology is desirable. The proposed new nomenclature is illustrated on Figure 23, where it is also compared with the older usage.

Three basic facies are now recognised in the complexes, and are named the platform, marginal-slope, and basin facies. Reef-margin, reef-flat, patch-reef, back-reef, and bank sub-facies are distinguished in the platform facies, and fore-reef, fore-bank, reefal-slope, and stromatolite sub-facies in the marginal-slope facies.

PLATFORM FACIES

The platform facies was constructed mainly by colonial organisms, but oolite and terrigenous sediments contributed substantially to the section in some places. Stromatoporoid and coral limestones are dominant in the Givetian-Frasnian platforms, while cryptalgal limestone and oolite characterize the Famennian platforms.

The *reef-margin sub-facies* consists of massive to crudely thick-bedded limestone, dolomitized in places, which forms a narrow rim around most limestone platforms. It was constructed largely by algae (skeletal and non-skeletal) and stromatoporoids and is believed to have been lithified penecontemporaneously.

The *reef-flat sub-facies* is commonly developed between the reef-margin and back-reef deposits. The reef-flat deposits are better bedded than those of the reef margin, but are otherwise similar, having been constructed largely by algae and stromatoporoids.

The *patch-reef sub-facies* consists of massive or crudely bedded stromatoporoid or algal limestone, forming masses that are generally less than 300 m across. It is also very similar to the reef-margin sub-facies, but it lacks associated reef-flat and back-reef deposits.

The *back-reef sub-facies* consists of well-bedded limestones with or without interbedded terrigenous deposits, which were laid down in widespread shelf lagoons behind reef margins and flats. Five main lithotopes (referred to by Playford and Lowry, 1966, as "sub-facies") are recognized in the back-reef deposits, and are termed the stromatoporoid, fenestral, coral, oolite, and oncolite lithotopes.

The *bank sub-facies* has lithological characteristics closely resembling those of the back-reef sub-facies. It was also laid down in widespread shelf lagoons, but the platforms lacked significant reef developments around their margins. The same lithotopes as those present in the back-reef sub-facies also occur in the bank sub-facies, but because of the lack of a reef rim they generally show evidence of more open circulation conditions (such as the presence of brachiopods and crinoid ossicles).

MARGINAL-SLOPE FACIES

The marginal-slope facies was laid down on slopes ranging from a few degrees to nearly vertical, flanking reefal limestone platforms or overlying drowned platforms. The facies was formed partly of material derived from the platforms, and partly of indigenous biogenic material and terrigenous sediments.

The *reefal-slope sub-facies* consists of poorly bedded to massive reef-like deposits which formed on the upper part of the marginal slope. It was built partly by organisms (mainly algae) and partly by sediment, derived from the platforms, which was trapped and bound by those organisms. The sub-facies is characterized by steep depositional dips, which range up to nearly vertical.

The *fore-reef sub-facies* makes up the major part of the marginal-slope facies. It consists of calcarenite, calcirudite, and megabreccia, with variable amounts of terrigenous material. Much of the clastic carbonate material is talus, derived from the platforms. Depositional dips in the fore-reef deposits are commonly up to 35°.

The *fore-bank sub-facies* consists of well-bedded calcarenite and calcilutite, made up of bank-derived sediment supplemented by indigenous biogenic material together with interbedded terrigenous sediment in some areas. They were laid down with only low depositional dips (commonly less than 10°).

The *stromatolite sub-facies* forms stromatolite bioherms and beds flanking and capping drowned reef pinnacles and ridges. It interfingers with other marginal-slope deposits and with basin deposits.

BASIN FACIES

The sediments of the basin facies were laid down in inter-reef basins between the reefal limestone platforms, in water depths ranging from perhaps 10 m to 200 to 300 m. The deposits consist mainly of terrigenous material (shale, siltstone, sandstone, and conglomerate) with some interbedded limestone, and were deposited nearly horizontally, or with very low initial dips.

STRATIGRAPHIC NOMENCLATURE

The revised rock-unit nomenclature for the reef complexes compared with that of Playford and Lowry (1966), is shown on Figure 24. The changes involve the introduction of a new name, Nullara Limestone, and redefinition of the limits of two formations, the Pillara and Windjana Limestones.

NULLARA LIMESTONE

Definition

The name Nullara Limestone is proposed for the unit of limestone with subordinate sandstone and siltstone, which overlies the Pillara Limestone (as redefined), overlies and interfingers with parts of the Windjana Limestone, interfingers with the Piker Hills Formation and the upper part of the Virgin Hills Formation, and is conformably overlain by the Fairfield Formation.

The name of the formation is taken from Nullara Spring near the northeastern end of the Oscar Range, and the type section is located nearby, extending from 17° 39′ 15″ S, 124° 56′12″ E to 17° 38′45″ S, 124° 54′ 20″ E.

The name "Nullara Oolite" was first used by Smith and others (1957) in an unpublished Wapet report. They nominated the type section near Nullara Spring, and believed that the formation was a fore-reef deposit equivalent to part of the "Oscar Calcarenite" and overlain by the upper part of that unit. Playford and Lowry (1966) included the "Nullara Oolite" and the overlying "Oscar Calcarenite" in the upper Pillara Limestone, recognising that these rocks formed part of the platform facies. They included the rest of Smith and others' "Oscar Calcarenite" in the Napier Formation.

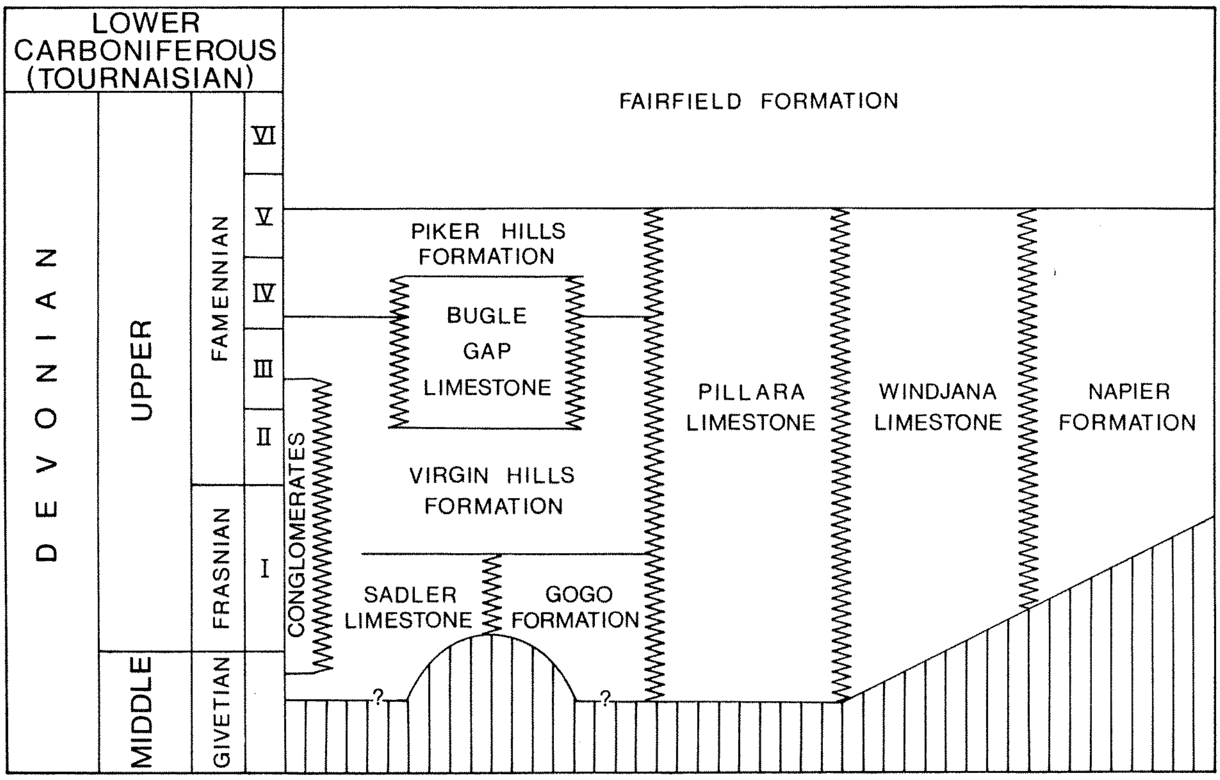
Recent studies have shown that the upper part of Playford and Lowry's Pillara Limestone can in fact be distinguished as a separate unit in both the surface and subsurface of the Lennard Shelf. Following discussions between ourselves and Wapet geologists (especially M. H. Johnstone, W. J. Witt, and D. A. Lyons) it was decided that it would be appropriate to apply the name Nullara Limestone to this unit, and it has since been used in a number of unpublished Wapet reports. The name "Nullara Formation" was also shown on a stratigraphic chart published by Read (1973) which was said to have been modified from an unpublished Wapet chart.

Lithology

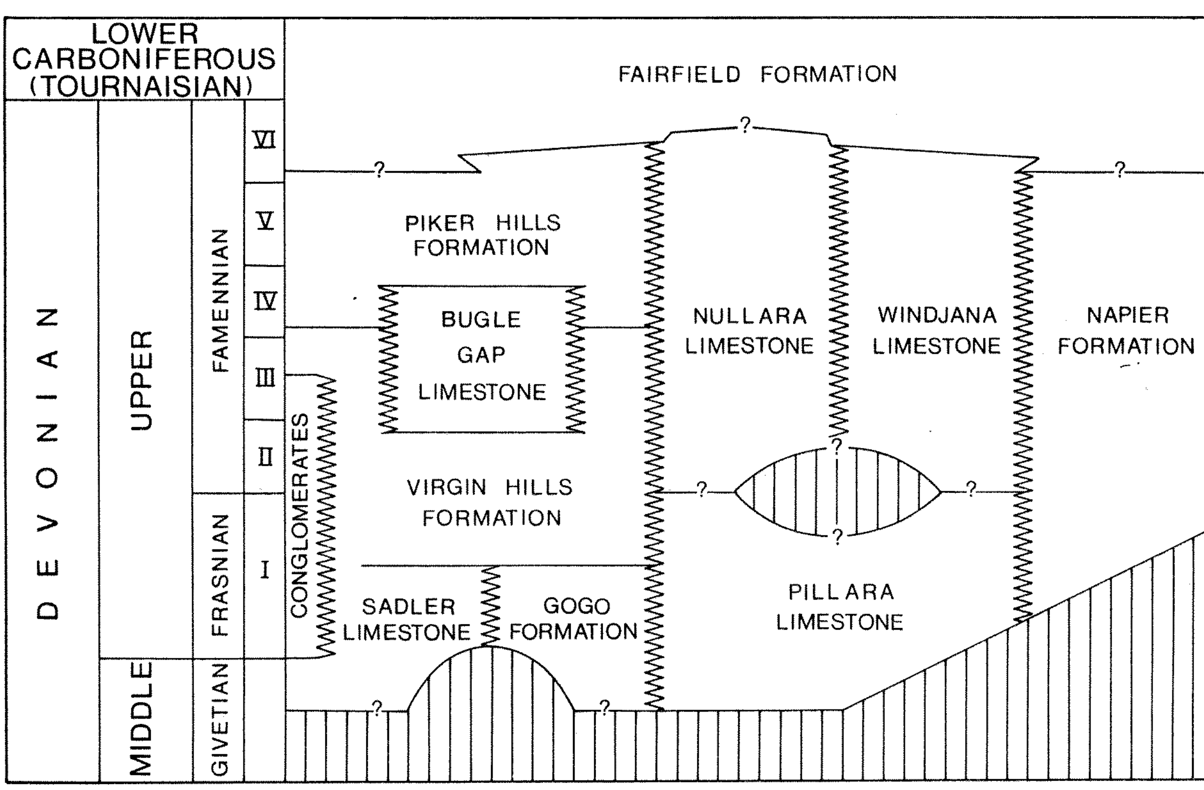
The Nullara Limestone is dominantly a unit of well-bedded fenestral (cryptalgal) calcarenite and oolite, with some interbeds of sandstone and siltstone. Oncolite-rich beds occur, and columnar stromatolitic structures are common in some areas.

Stratigraphic relationships

The Nullara Limestone is a back-reef and bank deposit, which, together with the Windjana Limestone, formed the Famennian limestone platforms. The formation overlies the Windjana Limestone in some areas (such as at the base of the type section in the Oscar Range), where the platform has expanded laterally at a low angle. Elsewhere it interfingers with the Windjana Limestone (in the Oscar and Napier Ranges) and interfingers with or is abutted by the Piker Hills and Virgin Hills Formations (in the Horseshoe Range area).



STRATIGRAPHIC NOMENCLATURE OF PLAYFORD AND LOWRY (1966)



REVISED STRATIGRAPHIC NOMENCLATURE

15489

Figure 24. Correlation charts illustrating revised stratigraphic nomenclature for Devonian reef complexes of the Canning Basin compared with the nomenclature of Playford and Lowry (1966).

The Nullara Limestone overlies the Pillara Limestone in Hawkstone Peak No. 1 well, but the two formations have not been seen in juxtaposition at the surface, and it is not known whether they are conformable. It is clear that rapid subsidence occurred in certain areas at about the Frasnian-Famennian boundary, drowning some of the Pillara Limestone platforms. However, it is possible that uplift and erosion of the platforms may have occurred in different areas, while other platforms may have continued growth without significant interruption.

The Nullara Limestone is overlain with apparent conformity by the Fairfield Formation in the Horseshoe Range and Red Bluffs areas and in a number of subsurface well sections.

Distribution and thickness

The Nullara Limestone is about 400 m thick in the type section at the northwestern end of the Oscar Range. The formation is also exposed in various parts of the Napier Range, and in the Horseshoe Range and Red Bluffs areas. It has been encountered in several wells drilled on the Lennard Shelf, where it is up to 320 m thick (in the Meda wells).

Fossils and age

The Nullara Limestone contains few fossils of value for precise dating. Most of the unit consists of cryptalgal limestone and oolite with few skeletal fossils other than thick-shelled gastropods and bivalves. Icriodid conodonts occur rarely, and there are also some stromatoporoids and brachiopods. These fossils indicate that the formation is of Famennian age, and E. C. Druce (written comm., 1973) suggests that it probably extends as high as *do* VI. As pointed out by Roberts and others (1971) there is no evidence of any early Famennian section in the Nullara Limestone (then regarded as the Famennian part of the Pillara Limestone). However, as mentioned previously, the older part of the Nullara Limestone is not exposed, and no definitive fossils have been found in it in the subsurface. We believe that there is no reason why the formation should not extend in age through most of the Famennian.

PILLARA LIMESTONE

The Pillara Limestone is revised so as to exclude the Famennian platform deposits now placed in the Nullara Limestone and to include reef deposits of Frasnian age that had previously formed part of the Windjana Limestone. As redefined, the Pillara Limestone embraces the whole of the Frasnian platform facies.

WINDJANA LIMESTONE

The Windjana Limestone is to be restricted to the massive limestone which underlies and interfingers with the Nullara Limestone. The formation embraces the reef-margin deposits of the Famennian platforms. It no longer includes Frasnian reef, which is now placed in the Pillara Limestone.

REFERENCES

Playford, P. E., 1969, Devonian carbonate complexes of Alberta and Western Australia: a comparative study (in collaboration with Marathon Oil Company): West. Australia Geol. Survey Rept. 1.

Playford, P. E., and Lowry, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: West. Australia Geol. Survey Bull. 118.

Read, J. F., 1973, Carbonate cycles, Pillara Formation (Devonian), Canning Basin, Western Australia: Canadian Petroleum Geology Bull., v. 21, p. 38-51.

Roberts, J., Jones, P. J., Jell, J. S., Jenkins, T. B. H., Marsden, M. A. H., McKellar, R. G., McKelvey, B. C., and Seddon, G., 1972, Correlation of the Upper Devonian rocks of Australia: Geol. Soc. Australia Jour., v. 18, p. 467-490.

Smith, D. N., Playford, P. E., and Williams, F. B., 1957, Oscar Range reef complex, Fitzroy Basin, Western Australia: West Australian Petroleum Pty. Ltd., unpublished rept.

PERMIAN STRATIGRAPHIC NOMENCLATURE, NOONKANBAH 1:250 000 SHEET

by R. W. A. Crowe[1] and R. R. Towner[2]

ABSTRACT

Mapping during 1974 on the Noonkanbah Sheet area has resulted in recognition of new mappable units in the Early Permian Grant Formation and Poole Sandstone. The topmost unit of the Grant Formation, consisting mainly of sandstone, is named the Millajiddee Member and the underlying siltstone unit containing tillite, the Wye Worry Member.

Within the upper part of the Poole Sandstone a coarse-grained sandstone and conglomerate sequence is named the Christmas Creek Member. Previously this member had been included in the overlying Noonkanbah Formation.

INTRODUCTION

In 1974, a joint party from the Geological Survey of Western Australia and the Bureau of Mineral Resources remapped the Phanerozoic Canning Basin part of the Noonkanbah 1:250 000 Sheet area. New stratigraphic units mapped in the Early Permian sequence in that area are defined below.

[1] Geological Survey of Western Australia.
[2] Bureau of Mineral Resources.

Published with the permission of the Director, B.M.R.

SUBDIVISIONS OF THE GRANT FORMATION

The Grant Formation was originally defined by Guppy and others (1952), and Playford and others (1975) state that the Grant Range (lat. 18° 00′ S, long. 124° 10′ E), from which the formation is named, is also the type locality. In the Fitzroy Trough (see Fig. 25) three subsurface divisions of the Grant Formation can be identified in well logs (e.g. Saint George Range No. 1, Mount Hardman No. 1). These subdivisions consist of a "lower sandstone unit", a "middle shale unit" and an "upper sandstone unit" (Shannon and Henderson, 1966, Young and O'Shaughnessy, 1973). To the south of the Fitzroy Trough, in the southern part of the Canning Basin, the "upper sandstone unit" is missing and a "basal tillite unit" is present underlying the "lower sandstone unit" of the Fitzroy Trough (see Koop, 1966). These subdivisions of the Grant Formation have been tentatively correlated with named surface units in company reports but, as Playford and others (1975) point out, there is doubt about the validity of these correlations, and for this reason it is impossible to formally define the units at this stage.

Recent mapping on the Noonkanbah Sheet area has allowed subdivision of the exposed part of the Grant Formation in that area, and these surface subdivisions are herein defined as members of the Grant Formation. They are the uppermost Millajiddee Member and the underlying Wye Worry Member. Rocks below the Wye Worry Member were mapped as undivided Grant Formation.

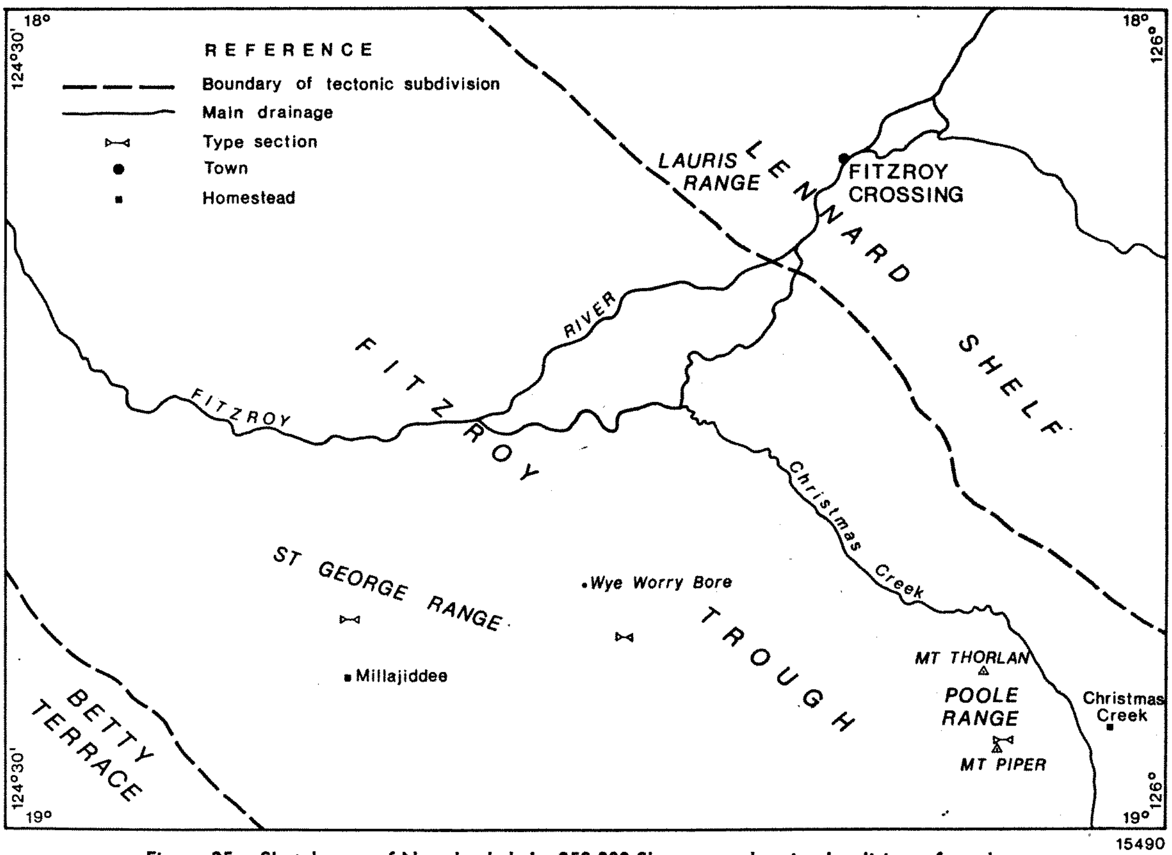


Figure 25. Sketch map of Noonkanbah 1 : 250 000 Sheet area showing localities referred to.

Saint George Range No. 1 well (Shannon and Henderson, 1966) spudded just below the base of the Wye Worry Member and shows that both of the newly defined members belong to the "upper sandstone unit" discussed above. When the correlatives of the units identified in subsurface are better known it may be possible to name them as formations and to upgrade the Grant Formation to group status.

PROPOSED NEW MEMBERS OF THE GRANT FORMATION

(1) *WYE WORRY MEMBER*

Derivation of name: Wye Worry Bore, lat. 18" 42' 25° S, long. 125° 15' 20" E, on Cherrabun Station in the Saint George Range.

Distribution: The member crops out in the Saint George Range and the Poole Range. It is also present in the Lauris Range and in isolated hills around Fitzroy Crossing, and it extends into the Mount Ramsay Sheet area to the east. It probably also crops out in the Mount Anderson Sheet area to the west, but has not yet been mapped in that area.

Lithology: At its type section the member consists mainly of sandy siltstone and shale with calcareous concretions and striated and faceted glacial dropstones. Near the base it contains varves of graded silt and clay, though in the middle and upper parts of the sequence silt and clay are not separated. The member contains lenses of tillitic conglomerate and it is sandy towards the top. In the western Saint George Range the member contains more sand than at its type section. In the Poole Range the member is slumped and deformed, so that it is mixed with parts of the overlying Millajiddee Member.

Type section locality: Lat. 18° 46' 45" S, long. 125° 18' 50" E in the eastern Saint George Range.

Thickness: The base of the member is not exposed at the type section, though at least 95 m is estimated to be present in this area. In the central Saint George Range the member is 25 m thick and in the western Saint George Range it is 65 m thick. In the Poole Range it is at least 45 m thick.

Fossils and age: Apart from trace fossils and indeterminate plant fragments, marine fossils were found in the middle part of the member. The fossils found have been identified by J. M. Dickins and are as follows:

Bivalves
- *Eurydesma*? sp. ind.
- *Deltopecten lyonsensis* Dickins 1957
- *Etheripecten* cf. *tenuicollis* (Dana) 1847
- *Streblopteria* sp.

Gastropods
- *Keeneia*? sp. ind.

Brachiopods
- Unidentifiable dielasmatids and spiriferids

Bryozoans
- *Fenestella* sp.

Crinoids
- *Calceolispongidae* sp. nov.

The fauna has much in common with the fauna of the upper part of the Lyons Group of the Carnarvon Basin, Western Australia, and similarly it is a cold water fauna and is of Sakmarian *sensu lato* (Early Permian) age (J.M. Dickins, written comm.).

Relationships: No clear exposure of the lower boundary was seen, but the member everywhere overlies undivided Grant Formation sandstone, probably disconformably. The Wye Worry Member is conformably overlain by the Millajiddee Member in most of the Saint George Range and probably in the Poole Range; however, in the southwestern Saint George Range and at Mount Thorlan, the Nura Nura Member of the Poole Sandstone rests unconformably on the Wye Worry Member. In the Lauris Range and in the southwestern Mount Ramsay Sheet area the Millajiddee Member rests disconformably on the Wye Worry Member.

(2) *MILLAJIDDEE MEMBER*

Derivation of name: Millajiddee homestead (lat. 18° 49' 00" S, long. 124° 55' 25" E) at the southwestern edge of the Saint George Range.

Distribution: Crops out in the Saint George Range and the Poole Range, although in the latter it is mixed with the underlying Wye Worry Member due to slumping. At Mount Thorlan and in the southwestern Saint George Range the Millajiddee Member is cut out by the unconformity at the base of the Poole Sandstone. The member is well exposed in the Lauris Range, and other more isolated exposures in the Noonkanbah Sheet area have been assigned to it. The member also occurs in the southwestern Mount Ramsay Sheet area and probably extends westwards into the Mount Anderson Sheet area.

Lithology: Consists mainly of sandstone and minor siltstone and conglomerate. The grain size is mainly fine though a medium and coarse-grained middle part is present. The bedding is commonly poorly defined so that the member characteristically forms cliffs on weathering. Both large and small-scale cross-bedding are common and the upper part of the unit is slumped in many areas.

Type section locality: Lat. 18° 45′ 00″ S, long. 124° 55′ 25″ E in the western Saint George Range.

Thickness: In the western Saint George Range, at the type section, the member is 70 m thick. It is 65 m thick in the centre and 75 m thick in the eastern part of the range although in the southeastern part it is estimated to be over 100 m thick. No other complete sections were measured, but it is at least 30 m thick in the Lauris Range.

Fossils and age: The lower part of the member locally contains abundant trace fossils. Indeterminate wood fragments are also present.

The age of the member can be taken as Sakmarian *sensu lato*. The underlying Wye Worry Member is dated as Sakmarian by the fossils it contains and the overlying Nura Nura Member of the Poole Sandstone contains marine fossils whose limits appear to be between late Sakmarian and early Artinskian (Thomas and Dickins, 1954; Glenister and Furnish, 1961). The Millajiddee Member does not appear to be younger than Sakmarian (J. M. Dickins, written comm.).

Relationships: The boundary with the underlying Wye Worry Member is gradational in the Saint George Range and probably in the Poole Range. In the Lauris Range and in the southwestern Mount Ramsay Sheet area the boundary is a disconformity. In the Noonkanbah Sheet area the Millajiddee Member is overlain by the Nura Nura Member of the Poole Sandstone. The contact is an unconformity and in places the Millajiddee Member is cut out by it.

SUBDIVISIONS OF THE POOLE SANDSTONE

Guppy and others (1952) defined the Poole Sandstone and designated the Poole Range (lat. 18° 50′ S, long. 125° 45′ E) as the type area. They also defined the basal Nura Nura Member, although the name had been used in previous unpublished company reports.

During the recent mapping a further member was recognised at the top of the Poole Sandstone in the eastern part of the area. This upper member, herein defined as the Christmas Creek Member, consists of coarse-grained sandstone and conglomerate. It was previously considered to be part of the overlying Noonkanbah Formation (Guppy and others, 1958). They described the contact between the Poole Sandstone and the Noonkanbah Formation thus: "the contact may be seen at Mount Synnot" (now called Mount Thorlan) "where a sandstone and conglomerate sequence capping Mount Synnot represents the base of the Noonkanbah. The persistent conglomerate bed at the junction of the two formations in the area between the Poole Range and the Saint George Range suggests that a disconformity separates the Poole Sandstone and the Noonkanbah Formation".

The contact between the fine-grained part of the Poole Sandstone and the Christmas Creek Member was clearly seen to be interfingering in the Poole Range, whereas the boundary between the Christmas Creek Member and the Noonkanbah Formation, although poorly exposed, appears planar and probably represents a disconformity. For this reason the Christmas Creek Member is identified by us as the topmost member of the Poole Sandstone.

PROPOSED NEW MEMBER OF THE POOLE SANDSTONE

CHRISTMAS CREEK MEMBER

Derivation of name: Christmas Creek, a tributary of the Fitzroy River which crosses the eastern part of the Noonkanbah Sheet area.

Distribution: The member crops out in the highest parts of the Poole Range and at Mount Thorlan. It is exposed discontinuously on the plains between the Pool Range and the Saint George Range and it occurs along the northern flank of the Saint George Range. The member is not present along the southern and western flanks of the Saint George Range, and was not identified elsewhere in the sheet area.

Lithology: The Christmas Creek Member consists of large-scale cross-bedded poorly sorted granule conglomerate and fine to coarse-grained sandstone. The beds are medium to thin and are graded in places. Asymmetrical ripple marks occur on many bedding planes.

Type section locality: Mount Piper in the Poole Range, lat. 18° 54′ 00″ S, long. 125° 47′ 30″ E.

Thickness: The thickest measured section was only 15 m thick, but the top is eroded. The maximum thickness is variable but is thought to be less than 25 m.

Age: Artinskian, based on the ages of the overlying and underlying units.

Fossils: No fossils were found in the member.

Relationships: The Christmas Creek Member overlies and laterally interfingers with undivided Poole Sandstone, although it is locally unconformable. The member is everywhere overlain by the Noonkanbah Formation, and the contact, although poorly exposed, appears planar. The unit wedges out to the south and west in the Saint George Range.

REFERENCES

Glenister, B. F., and Furnish, R. T., 1961, The Permian ammonoids of Australia: Jour. Paleontology, v. 35, p. 673-736.

Guppy, D. J., Lindner, A. W., Rattigan, J. H., and Casey, J. N., 1952, the stratigraphy of the Mesozoic and Permian sediments of the Desert Basin, Western Australia: Int. Geol. Congress XIX, Gondwana Symposium, Alger., 1952.

——— 1958, The geology of the Fitzroy Basin, Western Australia: Australia Bur. Mineral Resources Bull. 36.

Koop, W. J., 1966, Sahara No. 1 well, stratigraphic nomenclature. Appendix I *in* West Australian Petroleum Pty. Ltd., 1966, Sahara No. 1 Well: Australia Bur. Mineral Resources Petroleum Search Subsidy Act Pub. 89.

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

Shannon, P. H., and Henderson, S. W., 1966, St. Georges Range No. 1 Well completion report: Unpublished rept. for Continental Oil Co.

Thomas, G. A., and Dickens, J. M., 1954, Correlation and age of the marine Permian formations of Western Australia: Australian Jour. Sci., v. 16(6), p. 219-223.

Young, R. J. B., and O'Shaughnessy, P. R., 1973, Mt. Hardman No. 1 Well completion report: Unpublished rept. for West Australian Petroleum Pty. Ltd.

ENVIRONMENTAL INTERPRETATION OF THE PERMIAN NURA NURA MEMBER OF THE POOLE SANDSTONE, NOONKANBAH SHEET AREA, CANNING BASIN: A GRADATION BETWEEN FLUVIATILE AND SHALLOW-WATER MARINE FACIES

by R. W. A. Crowe[1] and R. R. Towner[2]

ABSTRACT

During mapping in 1974, the late Sakmarian Nura Nura Member of the Poole Sandstone was mapped in the Noonkanbah Sheet area. In the western Saint George Range the member was laid down in shallow-water marine conditions, and in the eastern part of the range the deposits are interpreted as deltaic in origin. Further east, at Mount Hutton, a meandering-river environment of deposition is inferred and still further east, in the Poole Range, the evidence indicates higher energy deposits of the braided-river type. It is concluded that the late Sakmarian land surface probably sloped towards the west.

INTRODUCTION

In 1974 a joint party from the Geological Survey of Western Australia and the Bureau of Mineral Resources re-mapped the Noonkanbah 1:250 000 Sheet area. The area was originally mapped at a scale of 4 miles to 1 inch by Guppy and others (1958). This paper records the data collected from the Nura Nura Member of the Poole Sandstone (see Table 20), and presents an interpretation of the environment of deposition of this unit.

TABLE 20. PERMIAN STRATIGRAPHY: NOONKANBAH SHEET AREA

LIVERINGA GROUP—	
Hardman Formation	Cherrabun Member Hicks Range Sandstone Member Kirkby Range Member
Condren Sandstone	
Lightjack Formation	
Noonkanbah Formation	
Poole Sandstone	Christmas Creek Member middle Poole Sandstone Nura Nura Member
Grant Formation	Millajiddee Member Wye Worry Member Undivided

The name Nura Nura was first used by Wade (1937, and unpublished company reports) and the Nura Nura Member was later defined by Guppy and others (1952) as "calcareous sandstone, sandy limestone, and limestone, with bands of unsorted, coarser sediments". The middle part of the Poole Sandstone above the Nura Nura Member (herein referred to as the middle Poole Sandstone) has not been formally named (see Crowe and Towner, 1976, and Table 20).

In the Noonkanbah Sheet area, Guppy and others (1958) recorded "a marine, fossiliferous, lensing bed" in the southern and north-central portions of the Saint George Range (see Fig. 26) and they correlated this unit with the Nura Nura Member in the adjoining Mount Anderson Sheet area to the west. Further fossil collections made in 1974 have confirmed this correlation (J. M. Dickins, pers. comm.) and it is on this basis that the Nura Nura Member is identified in the Noonkanbah Sheet area. The fossils indicate an age of latest Sakmarian for the unit (Glenister and Furnish, 1961; J. M. Dickins, pers. comm.).

[1] Geological Survey of Western Australia.

[2] Bureau of Mineral Resources.

Published with the permission of the Director, B.M.R.

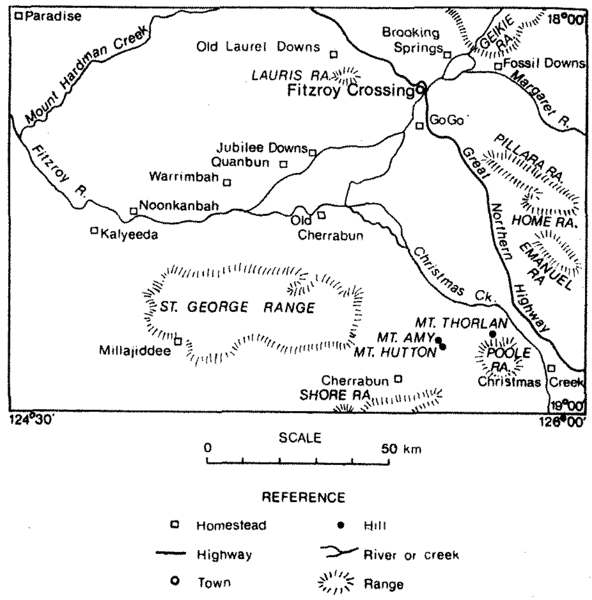


Figure 26. Sketch map of Noonkanbah 1 : 250 000 Sheet area showing localities referred to.

In the exposures described by Guppy and others (1952 and 1958) the Nura Nura Member lies with slight angular unconformity on the Grant Formation and is conformably overlain by fine-grained, ripple-marked, quartz wacke of the middle Poole Sandstone. The boundaries are relatively distinctive features and have been traced throughout the rest of the Saint George Range and into the Poole Range, enabling the Nura Nura Member to be mapped throughout these areas. Previously the member was not known to extend into the eastern Saint George Range and Poole Range. This paper deals mainly with the lateral variations within this member and the lithology and depositional environments are discussed for four different localities (shown in Fig. 26).

WESTERN SAINT GEORGE RANGE AREA

In the western Saint George Range area the Nura Nura Member unconformably overlies the Wye Worry Member (of Crowe and Towner, 1976) of the Grant Formation. The Millajiddee Member (of Crowe and Towner, 1976), which is the uppermost member of the Grant Formation (see Table 20), is cut out by the unconformity.

The base of the Nura Nura Member is marked by discontinuous conglomerate containing poorly sorted pebbles and boulders. The clasts are subangular and are mainly composed of quartzite and granite, and some of the boulders are faceted. These faceted boulders are believed to be derived from tillite in the underlying Wye Worry Member. Embedded in the sandstone matrix of the basal conglomerate are fossil shells, many of which are unbroken. The unbroken shells suggest a low-energy environment, so the larger clasts cannot have been transported far. This would explain the preservation of facets on the boulders.

Above the basal conglomerate in the western Saint George Range there are approximately 12 m of interbedded sandstone, siltstone and granule conglomerate. Fining-up cycles of 20 to 60 cm thickness are common. These contain ripple-marked tops and basal fossiliferous lag conglomerates, with vertical burrows and bioturbated zones. Scour-and-fill structures are present and the scour troughs are filled with fossiliferous intraformational conglomerate suggesting that these deposits were laid down by currents in channels. Marine channel deposits are commonly formed as a result of tidal action (Reineck and Singh, 1973, among others) and although additional data, particularly current readings, are needed, it is suggested that this part of the sequence was deposited in a tidal environment.

Above these deposits, the sequence grades into 5 m of wavy and lenticular, thin-bedded, medium to fine-grained lithic wacke and mudstone with minor flaser bedding (terms of Reineck and Wunderlich, 1968). This type of bedding is also very common in subtidal and intertidal zones where it is produced as a result of alternating high and low turbulence (Reinick and Wunderlich, 1968).

The top part of the Nura Nura Member in the western Saint George Range, around Millajiddee homestead, consists of approximately 10 m of massive, fine to very fine-grained, very well sorted sandstone containing faint, planar cross-bedding. These features indicate a high degree of winnowing of the sediment, and this is normally attributed to wave action in shallow-marine sediments. Consequently this deposit is tentatively interpreted as a beach or sand-bar deposit. The position of this part of the section in the vertical sequence (see below) suggests that it represents a barrier-bar deposit.

The overlying middle Poole Sandstone is fairly uniform throughout the entire Noonkanbah Sheet area, being composed of fine and very fine-grained, thin-bedded sandstone with abundant straight-crested, symmetrical ripple marks interbedded with fossil-root-filled beds. Crowe and Towner (in press) have shown from measurements of the ripple marks that they were probably formed by waves, indicating deposition in shallow water. The close association of the ripple-marked beds with fossil roots and the absence of a marine fauna and other sedimentary structures commonly found in shallow-water marine sediments suggests that the deposit is at least partly continental. Van Straaten (1954) has described probable lagoonal deposits in the Devonian of Belgium which are similar to the rocks of the middle Poole Sandstone, and in particular he discusses the abundance of wave-formed ripple marks, and points out that these structures, although actively formed in the tidal-flat environment, in fact stand little chance of preservation due to physical and organic reworking of the sediment. In the lagoonal environment, however, wave ripples stand a much better chance of being preserved due to the "discontinuous upward growth of the deposits" (van Straaten, 1954). As wave-formed ripple marks are very abundant in the middle Poole Sandstone, it is tentatively suggested that they were formed in a lagoonal environment. This suggestion gains credence when the whole sequence is considered in the vertical sense.

Visher (1965) has shown how, in a typical regressive marine sequence, the environment changes upwards from shallow marine to littoral to dune-barrier-bar and eventually to lagoonal. Although the dune phase was not identified in the western Saint George Range it is suggested that the deposits of the Nura Nura Member and the middle Poole Sandstone represent such a regressive sequence.

Towards the middle of the Saint George Range the Nura Nura Member could not easily be differentiated from the overlying middle Poole Sandstone as the lithologies of both units are similar. However, on the air-photographs of this area, the characteristic darker tone of the Nura Nura Member is clearly visible, allowing the member to be identified. Because the lithology of the Nura Nura Member in this area is similar to that of the middle Poole Sandstone, their depositional environments are also thought to be similar.

EASTERN SAINT GEORGE RANGE AREA

In the eastern Saint George Range the Nura Nura Member overlies the Millajiddee Member of the Grant Formation with a planar angular unconformity. At the base it consists of a poorly bedded, fine to medium-grained quartz wacke which contains abundant vertical burrows similar to those in the western part of the range. Other similarities with the western part of the range include the presence of the flaser bedding and lenses of intraformational mud-pellet conglomerate; however, fossils are absent in the east. Ascending the sequence, the lithology changes to well-rounded, well-sorted, medium and thin-bedded, medium-grained quartz arenite and quartz wacke, above which there is an erosional contact with the upper part of the member about 12 m above the base.

The upper 10 m of the member consists of a series of stacked, large-scale trough co-sets (each about 2 m thick) in which the grain size fines upwards. In each fining-upward cycle there is a conglomeratic base (both intraformational and extraformational) containing wood fragments and a top part with asymmetrical ripple marks. Superimposed on the fining-upward cycles is an overall upward graduation to coarser grained, well-sorted sediments. The Nura Nura Member is conformably overlain by the typically fine-grained, ripple-marked sediments of the middle Poole Sandstone, described above.

Lithologically, the lower part of the Nura Nura Member in the eastern Saint George Range is similar to the lower part of the section in the western part of the range except that it does not contain fossils and there is no basal conglomerate. It is consequently interpreted as a shallow-water deposit. In the upper part, the abundant trough cross-bedding and fining-upwards cycles are characteristic of lateral accretion by channels, and these cyclic sediments are interpreted as point-bar deposits (Allen, 1964). Point-bar deposits are laid down by meandering channels and can occur in an intertidal environment; however, the overall upward increase in grain size and sorting of the whole unit suggests that the Nura Nura Member at this locality represents a regressive marine sequence (see Visher, 1965). Moreover, the upward increase in grain size of the upper part of the member and the erosional contact at the base of this part suggest a regressive sequence of the deltaic type (see Selley, 1970).

MOUNT HUTTON

The Nura Nura Member is well exposed around the bases of Mounts Hutton and Amy, where it unconformably overlies slumped Grant Formation. In several places the member is absent but it reaches a thickness of 7 m on the west of Mount Hutton. This exposure is shown diagrammatically in Figure 27 and is described below.

The basal part of the member consists of large-scale, trough cross-bedded sandstone containing fossil root impressions. The cross-bedding indicates deposition from currents, and the roots indicate a continental environment, so it is suggested that these beds are fluviatile deposits.

The sequence passes either gradationally or abruptly upwards into massive, poorly sorted, medium-grained quartz wacke containing very abundant downward-bifurcating root impressions. These massive beds are interpreted as fossil soils, as they contain abundant root impressions. Lying either disconformably or conformably above these beds is ripple-marked sandstone, typical of the middle Poole Sandstone, except that at this locality it also contains scattered root impressions.

The interpreted fossil soil horizon in the Nura Nura Member interfingers laterally with poorly laminated mudstone, lacking fossil roots (see Fig. 27) but containing fossil leaves and scattered coarse sand grains. Because the fossil soil interfingers with this mudstone, it is evident that the mudstone beds must have been deposited at the same time that the soil was supporting vegetation. It must also be of similar lateral extent to the body of water in which it was deposited (5-10 m) and the absence of current structures in the mudstone indicates that deposition took place from suspension. The presence of fossil leaves supports this interpretation, as leaves need quiet conditions to be preserved. The scattered coarse grains of sand were probably carried into the water body by wind or on vegetation rafts.

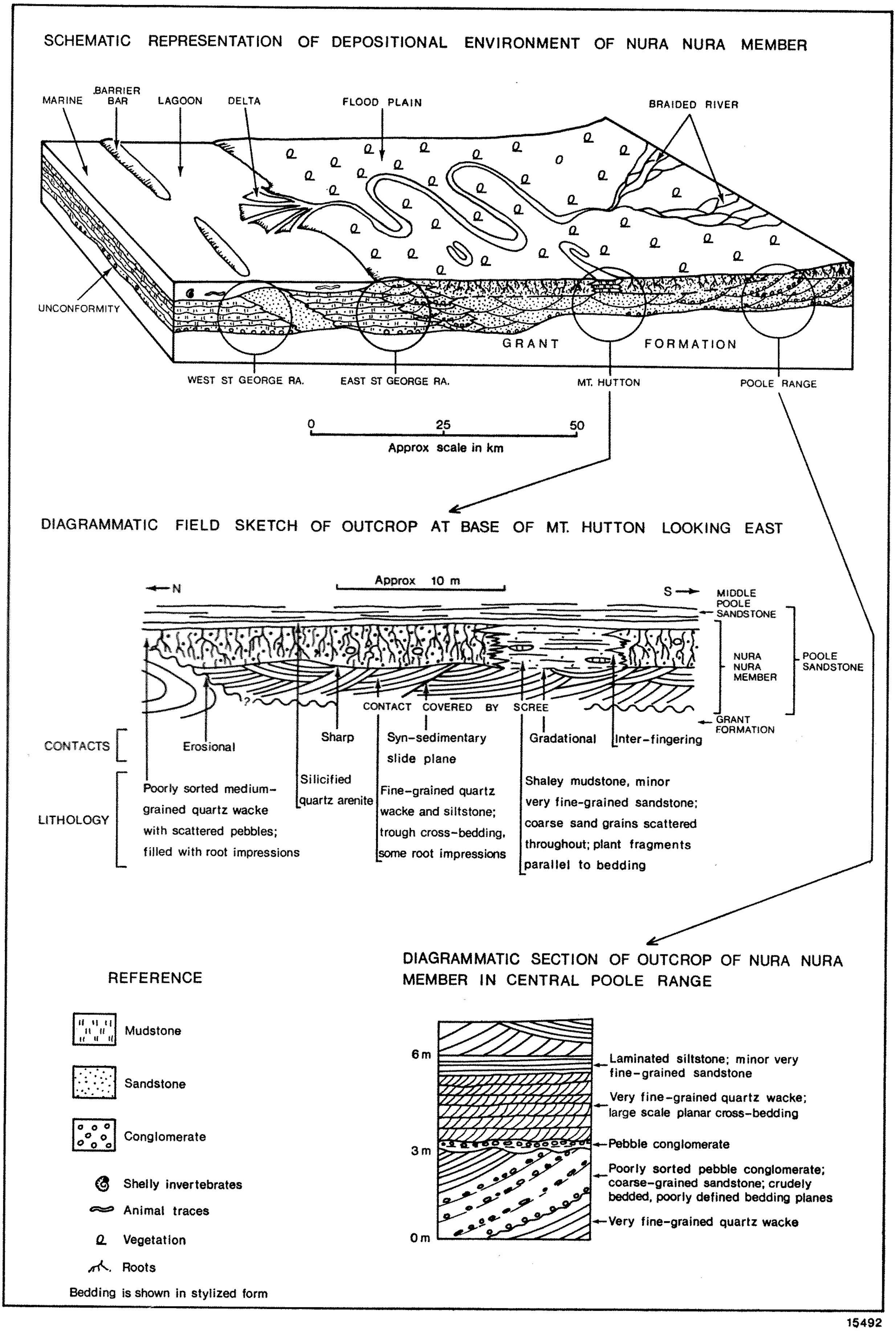


Figure 27. Schematic representation of depositional environment of Nura Nura Member.

The deposits of modern abandoned channel fills (Allen, 1964) are very similar to the mudstone body described above, and provide the best modern analogue for such a feature. Channel-fill deposits are formed when a river abandons part of its course and the resulting lake silts up with overbank deposits (e.g. ox-bow lakes). We therefore interpret a fluviatile environment of deposition for the Nura Nura Member at Mount Hutton and suggest that the rivers were of the meandering type, since abandoned channels of the type described are most commonly found in such regimes (Reineck and Singh, 1973).

POOLE RANGE AREA

In the Poole Range, the Nura Nura Member consists mainly of poorly sorted cross-bedded quartz wacke with occasional root impressions, indicating deposition in a fluvial environment. At one locality, overturned foresets are present. From laboratory experiments, McKee and others (1962) have shown that overturned foresets are formed by deposition of normal foresets followed by later disruption produced by strong, heavily laden currents. At another locality near the centre of the range, the member consists of a fining-upward sequence of large and small-scale, trough and planar cross-bedded, conglomeratic sandstone with unidirectional current readings. The style of the cross-bedding in this sequence is shown in Figure 27, which also shows the rather poor sorting of the sediment, and inclined conglomeratic foresets.

The section shown in Figure 27 is thought to be a braided-river deposit, as it bears a close resemblance to the typical braided-river sequence shown by Reineck and Singh (1973). This interpretation is supported by the evidence of high-velocity currents in the area (see above) as braiding of a river occurs where either the channel slope or the discharge is high. When combined with the suggestion of meandering-river deposition in the Mount Hutton area the information from the Poole Range tends to suggest that the latter locality was higher in the river profile.

Just to the north of the Poole Range, at Mount Thorlan, the lithology of the Nura Nura Member is different, consisting of graded beds of sandstone and siltstone which contain abundant fossil roots. Other structures are obscured by the disruption due to root growth, so it is difficult to interpret the environment of deposition of this locality, apart from saying that the deposits represent a fossil soil. Throughout the Poole Range area the Nura Nura Member is conformably overlain by typical middle Poole Sandstone.

CONCLUSIONS

The interpretations outlined above, though partly tentative, are strengthened when considered together. Figure 27 shows our reconstruction of the depositional environment of the Nura Nura Member and illustrates the relationships between the various facies and interpretations. The model shows the transition from fluviatile deposits in the east to shallow-water marine deposits in the west. This suggests that the late Sakmarian land surface sloped towards the west, although this may be an over-simplification because no data are available to the north and south of the belt of outcrop.

REFERENCES

Allen, J. R. L., 1964, Studies in fluviatile sedimentation: six cyclothems from the Lower Old Red Sandstone, Anglo-Welsh Basin: Sedimentology, v. 3, p. 163-198.

Crowe, R. W. A., and Towner, R. R., 1976, Permian stratigraphic nomenclature, Noonkanbah Sheet area: West. Australia Geol. Survey Ann. Rept. 1975, p. 56-58.

——— in press, The stratigraphy, sedimentology and environment of deposition of the Permian of the Noonkanbah Sheet area, Canning Basin, Western Australia: Australia Bur. Mineral Resources Rec. (unpublished).

Glenister, B. F., and Furnish, W. M., 1961, The Permian ammonoids of Australia: Jour. Paleontology, v. 35, p. 673.

Guppy, D. J., Lindner, A. W., Rattigan, J. H., and Casey, J. N., 1952, The stratigraphy of the Mesozoic and Permian sediments of the Desert Basin, Western Australia: Int. Geol. Congress XIX (Gondwanaland Symposium), Alger., 1952, p. 107.

——— 1958, The geology of the Fitzroy Basin, Western Australia: Australia Bur. Mineral Resources Bull. 36.

McKee, E. D., Reynolds, M. A., and Baker, C. H. Jr., 1962, Experiments on intraformational recumbent folds in crossbedded sand: U.S. Geol. Survey Prof. Paper 450 D, p. 155-160.

Reineck, H.-E., and Singh, I. B., 1973, Depositional sedimentary environments; with reference to terrigenous clastics: Heidelberg, Springer-Verlag.

Reineck, H.-E., and Wunderlich, F., 1968, Classification and origin of flaser and lenticular bedding: Sedimentology, v. 11, p. 99-104.

Selley, R. C., 1970, Ancient sedimentary environments: London, Chapman and Hall, Ltd.

van Straaten, L. M. J. U., 1954, Sedimentology of Recent tidal flat deposits and Psammites du Condroz (Devonian): Geologie en Mijnbouw, v. 16, p. 25-47.

Visher, G. S., 1965, Use of vertical profile in environmental reconstruction: Am. Assoc. Petroleum Geologists, v. 49, p. 41-61.

Wade, A., 1937, The geological succession in the West Kimberley District of Western Australia: Australian Assoc. Adv. Sci. Rept. 23, p. 93.

EMERGED PLEISTOCENE MARINE TERRACES ON CAPE RANGE, WESTERN AUSTRALIA

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

ABSTRACT

Four emerged, marine erosion terraces are preserved on the western flank of the Cape Range Anticline. From oldest to youngest they are named the Muiron, Milyering, Jurabi, and Tantabiddi Terraces. The related old shoreline cliffs are named Muiron, Milyering, Jurabi, and Tantabiddi Scarps, and the respective terrace deposits are named the Muiron and Milyering Members of the Exmouth Sandstone and the Jurabi and Tantabiddi Members of the Bundera Calcarenite.

The terraces, which are distinctly warped, are believed to have formed during Quaternary interglacial high sea-level stands. The warping indicates significant Quaternary tectonism in the Cape Range area.

INTRODUCTION

Four emerged post-Miocene marine erosion terraces, at distinctly different elevations, were mapped on the western side of the Cape Range peninsula during 1975. The terraces, with associated shoreline cliffs, have a total elevation difference of some 50 m. Both constructional and erosional terraces have been recognized in the area, but in this paper we will use the term terrace only for the erosional surfaces that have been cut into the Miocene bedrock in step-like fashion. The sediments that were laid down on a terrace during or soon after its formation are called terrace deposits.

The terraces were first described by Condit (1935, p. 865) who commented: "The slopes rise in several successive steps as elevated sea cliffs and wave-cut terraces ranging from about 20 feet above sea level up to 180 feet. The lowest forms a continuous coralline bench one-half to one mile wide". Raggatt (1936, p. 166), Condit's co-worker, described them as follows: "The relics of wave-cut terraces at several levels, so beautifully exhibited on the west coast of North-west Cape, are eloquent testimony of the fact that the land has been rising in the recent past". Condon and others (1953, 2nd edn. 1955) recognized only the lowermost of these terraces, which is covered by the Bundera Calcarenite, and they mapped the older terrace deposits as Miocene Tulki Limestone and Pilgramunna Formation.

The initial mapping suggested that the terraces, believed to be of Pleistocene age, are gently warped. Significant Quaternary tectonism, indicated by the warping, has rarely been demonstrated in Western Australia, and to determine the amount of deformation we surveyed eight profiles across the terraces, and mapped them at 1 : 40 000 scale.

Field survey readings were taken relative to high water mark on the beach, as this was the only available datum. High water mark was taken to be 1.2 m above Mean Low Water Springs level at Norwegian Bay, which is in turn 0.4 m above the Learmonth datum (Aust. Nat. Tide Tables, 1975, p. 18). All elevations in this paper are given relative to Norwegian Bay Mean Low Water Springs level. The survey lines were not closed, and no bench marks were available to tie into, so the accuracy of surveying is unknown and the results may not be very accurate. Checking of the surveyed elevations against parallax bar readings, 20 m-interval contour maps, and field data, suggested that results were reliable except for line D, to which minor adjustments were made.

Apart from these surveying limitations, accuracy is not possible because of uncertainties in pinpointing geologically significant levels in the field, as discussed below.

Marine erosion terraces form at or near low water mark (Fairbridge, 1961), but there may be considerable surface irregularities in such terraces (e.g. lines A and F—Milyering Terrace), and they may also slope seaward because of a rise in sea level during formation. From our observations along the shores of the Cape Range peninsula we believe that more accurate indicators of sea-level stands are available, in the form of *in situ* corals in reefal deposits and the transition from littoral to eolian deposits in clastic sequences. Another reason for using these two parameters as indicators of sea level instead of the terraces, is that terrace elevations can only be measured at a few spots on the second youngest terrace and not at all on the youngest one.

The sediments forming in the modern offshore reefs and lagoons on the west side of the peninsula are believed to be very similar to the younger terrace deposits. As the present-day reefs in the area can be seen to grow as high as low water mark, we have taken the uppermost occurrence of *in situ* corals in the terrace deposits as indicators of low water level at the time of deposition of the reefal sediments. Where we have done this, it is assumed that the corals in question did grow up to low water level and also that we observed the uppermost occurrence. It would be surprising if these assumptions held true with an accuracy of better than a metre.

The transition from littoral to eolian deposits in a clastic sequence has been taken to coincide with high water mark. In the older terrace deposits it is quite easy to recognize this transition, but again it is not possible to pick the contact with an accuracy of better than about a metre. A walk along a recent beach backed by dunes makes this difficulty clear.

DESCRIPTION OF TERRACES AND TERRACE DEPOSITS

The terraces on the western side of the Cape Range peninsula are recognizable from Vlaming Head in the north to Wealjugoo Hill in the south, a total distance of about 90 km. They have been carved out by the sea in the Miocene Tulki Limestone, Pilgramunna Formation, and Vlaming Sandstone. This last unit was discarded by Condon (1968, p. 40) who considered the Vlaming Sandstone as part of the Exmouth Sandstone, but we find it to be a valid mappable unit.

Figure 28 shows diagrammatically the relationships of the terraces and the nomenclature we propose, Figure 29 shows their distribution, and Figures 30 and 31 show the area around Yardie Creek homestead where the terraces are well developed.

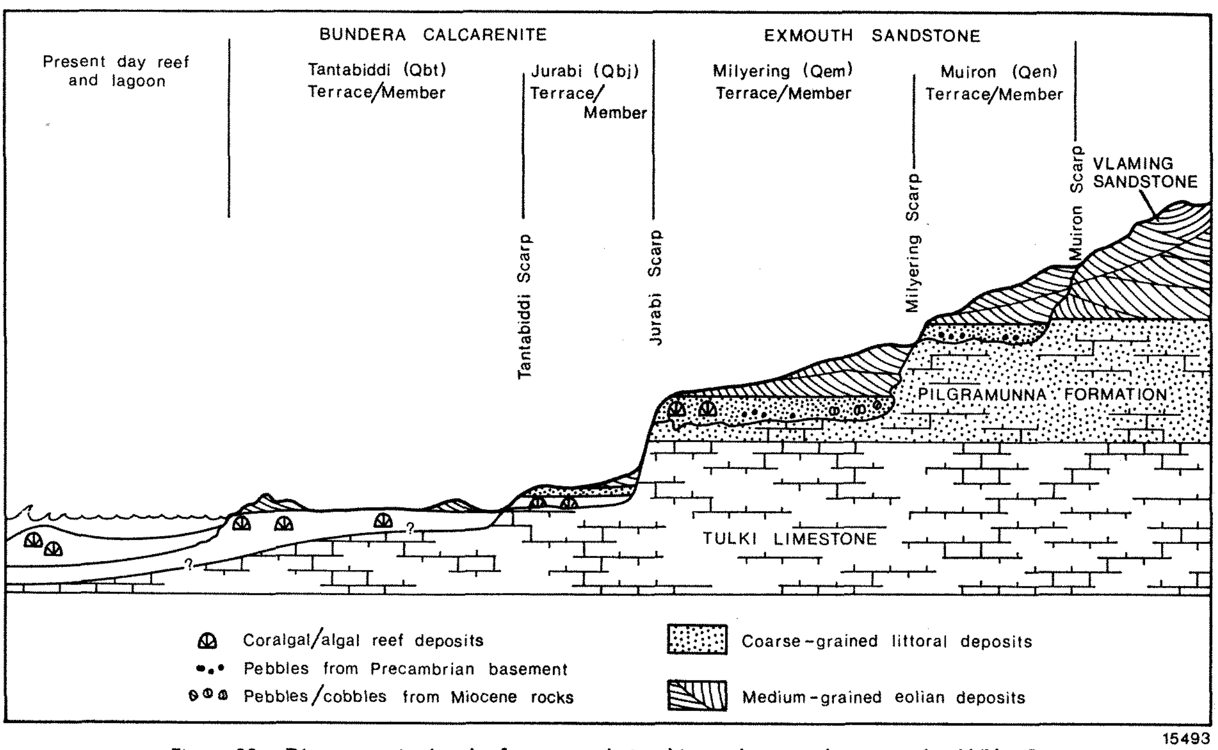


Figure 28. Diagrammatic sketch of terrace relationships and nomenclature used ; V/H~5.

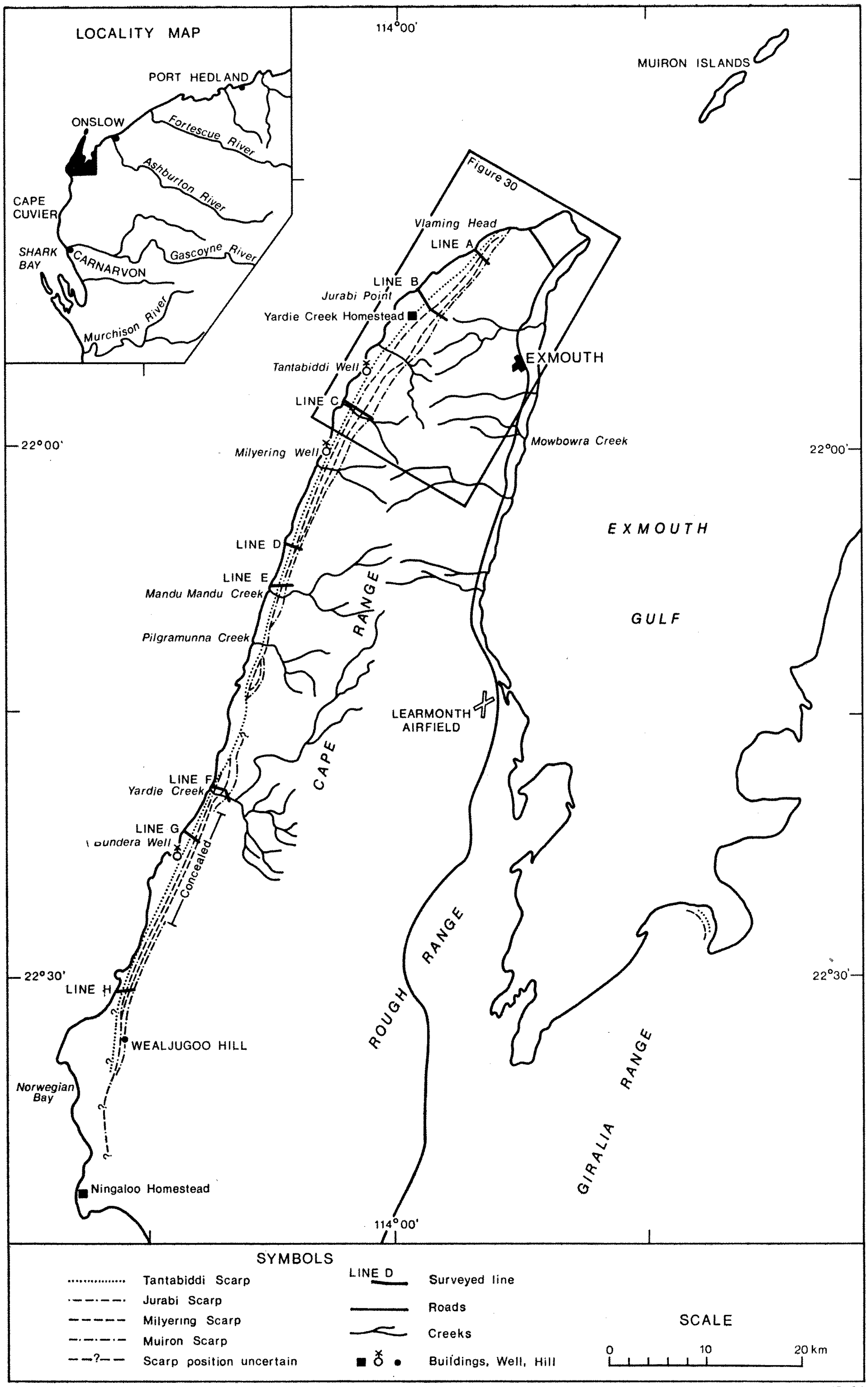


Figure 29. Shoreline scarps on the western side of Cape Range and on the Giralia Range.

To the south of Wealjugoo Hill the terraces may well exist but if so, they are completely obscured by extensive overlapping eolian deposits of various ages but very similar rock types. This concealment of the terraces also occurs in parts of the studied area, such as just north of Mandu Mandu Creek (Fig. 32E) and approximately 10 km north of Yardie Creek. Where this overlapping has occurred, it is difficult or impossible to map the various units which elsewhere are clearly recognizable.

On the eastern side of the Cape Range peninsula only the youngest terrace deposits have been recognized, but a distinct scarp has not formed. The likely reason for the absence of older terraces is that the eastern side of the peninsula is not as exposed to waves as the western side so that terraces and shoreline cliffs probably did not form.

The relative ages of the terraces and their deposits have been deduced from their position and preservation. The poorly preserved highest terrace is the oldest, and the lowest terrace, on which sedimentation still takes place, is the youngest. In descending order the terraces are here named Muiron, Milyering, Jurabi, and Tantabiddi Terrace, and the related scarps Muiron, Milyering, Jurabi, and Tantabiddi Scarps. The deposits on the two oldest terraces are named Muiron and Milyering Members of the Exmouth Sandstone, and those on the two youngest terraces the Jurabi and Tantabiddi Members of the Bundera Calcarenite. Formal definitions of these new stratigraphic names are given in the Appendix.

In places an older terrace has been completely eroded during the cutting of a younger terrace. North of Yardie Creek for example, the Tantabiddi Terrace cuts across both the Jurabi and Milyering Terraces. Where this has happened, a single scarp up to 20 m high is present, and is clearly visible from the coast road (Fig. 32F).

MUIRON TERRACE

The Muiron Terrace and its scarp and deposits have been extensively dissected and are discontinuously preserved. On a small scale (1-2 m) the terrace is smooth to irregular. Occasional grooves and pot-holes or shallow karst features have been noted, and at one locality the underlying Pilgramunna Formation has been extensively bored by organisms. Larger scale irregularities, such as occur in the Milyering Terrace, have not been seen but this is probably due to poor preservation.

The terrace deposits, which form the Muiron Member of the Exmouth Sandstone, consist in most places of up to several metres of calcareous quartz arenite which ranges from coarse-grained sand to pebbly granule conglomerate. This coarse-grained basal unit formed in a littoral environment, and grades up into well-sorted, mostly medium-grained quartzose calcarenite of eolian origin. Only where drainage patterns outline their shape can the dunes that formed the eolian part of the Muiron Member still be recognised (e.g. north side of Yardie Creek). Elsewhere the Muiron Member is too dissected for any of the original morphology to be preserved.

MILYERING TERRACE

The Milyering Terrace and its scarp and deposits are also extensively dissected, and in places the terrace has been exhumed through the stripping of its cover. The terrace is smooth to irregular on a small scale (1-10 m), and at a few places, e.g. line A, the terrace is deeply grooved. The grooves (Fig. 32A) may be as deep as 2.5 m, and they have a preferred orientation of 110°, which is determined by joints in the underlying Tulki Limestone. On the southern side of Yardie Creek the terrace is exposed in a cliff for some 250 m. At this locality the terrace slopes east towards the old shoreline, with a 4° angle over a distance of about 150 m. This shoreward slope is due to the stripping of a bedding plane in the underlying Tulki Limestone which dips gently to the east. Slopes of a similar scale have also been noted elsewhere.

The terrace deposits, which form the Milyering Member of the Exmouth Sandstone, consist at the base of minor algal boundstone and conglomerate which are overlain by and/or grade laterally into coarse-grained to pebbly calcareous quartz arenite and quartzose calcarenite. The algal boundstone contains rare colonial corals, gastropods, and bivalves, and appears to be restricted to areas that are deeply grooved. Along line A the boundstone grades laterally into conglomerate which fills many of the grooves in the terrace (Fig. 32A). The cobbles and boulders in the conglomerate are of local derivation, and consist of fragments of Tulki Limestone and Pilgramunna Formation. The pebble fraction, however, consists mainly of various types of quartz, chert, banded iron-formation, ?acid volcanics, tourmaline-quartz rock, and feldspar. This assemblage is identical in its components to the material carried by the Ashburton River where it flows into the sea near Onslow. Though conglomerate is rare in the Milyering Member, scattered pebbles of the Ashburton River assemblage are common in the coarse-grained basal part of the unit. The only fossils seen in this clastic part of the basal Milyering Member are rare irregular echinoids and large foraminifers. Low to medium-angle (5-15°) cross-bedding is locally preserved in this unit. As in the case of the Muiron Member, the coarse-grained basal part of the sequence is believed to have formed in a littoral environment. This grades upwards into well-sorted, mostly medium-grained, quartzose calcarenite of eolian origin. Although strongly dissected, the dune shape of this eolian part of the Milyering Member is still recognizable in places (Fig. 31), and large-scale, high-angle cross-bedding dipping toward the old shoreline is occasionally visible. This relationship is well exposed along line D, where the cross-bedded eolianite abuts against the very jagged shoreline cliff (Fig. 32D).

JURABI TERRACE

The Jurabi Terrace is extensively preserved and its scarp and sediments are dissected only by sizeable creeks. The terrace is poorly exposed but appears to be smooth to irregular on a small scale.

The terrace deposits, which form the Jurabi Member of the Bundera Calcarenite, consist of algal and coralgal boundstone and calciclastic sediments. Boundstone is the most common rock type exposed where the Tantabiddi Scarp cuts into Jurabi Terrace deposits, but clastic deposits predominate at the top of the member. This may represent a lateral change from a reef facies to a back-reef lagoon, as is the case along the present-day shore. At Mandu Mandu Creek the coralgal reef is laterally replaced by a limestone pebble to cobble conglomerate, but elsewhere the calciclastic deposits appear to contain little if any recognizable detritus from the Miocene rocks. Only minor occurrences of eolianite have been mapped as part of the Jurabi Member.

Locally an unnamed, poorly developed terrace, a few metres higher than the surface of the Tantabiddi terrace deposits, has been carved into the Jurabi Member. It is best preserved on line H.

TANTABIDDI TERRACE

The Tantabiddi Terrace is nowhere exposed, as sediments are still accumulating on it, and only negligible dissection of scarp and sediments has taken place.

The terrace deposits which form the Tantabiddi Member of the Bundera Calcarenite, consist of coral and coralgal boundstone and associated calciclastic deposits. The reefal boundstone is best exposed in low cliffs along the present shore and in intertidal platforms, but *?in situ* corals have been found up to 1.8 km inland. These reefal deposits grade laterally, and probably also vertically, into calcarenite and calcirudite, which are believed, on the basis of a comparison with present-day offshore deposits, to have formed in lagoonal and littoral environments. These shallow-marine carbonates are in part overlain by eolianites, the oldest of which are lithified and contain karst features.

54809—(5)

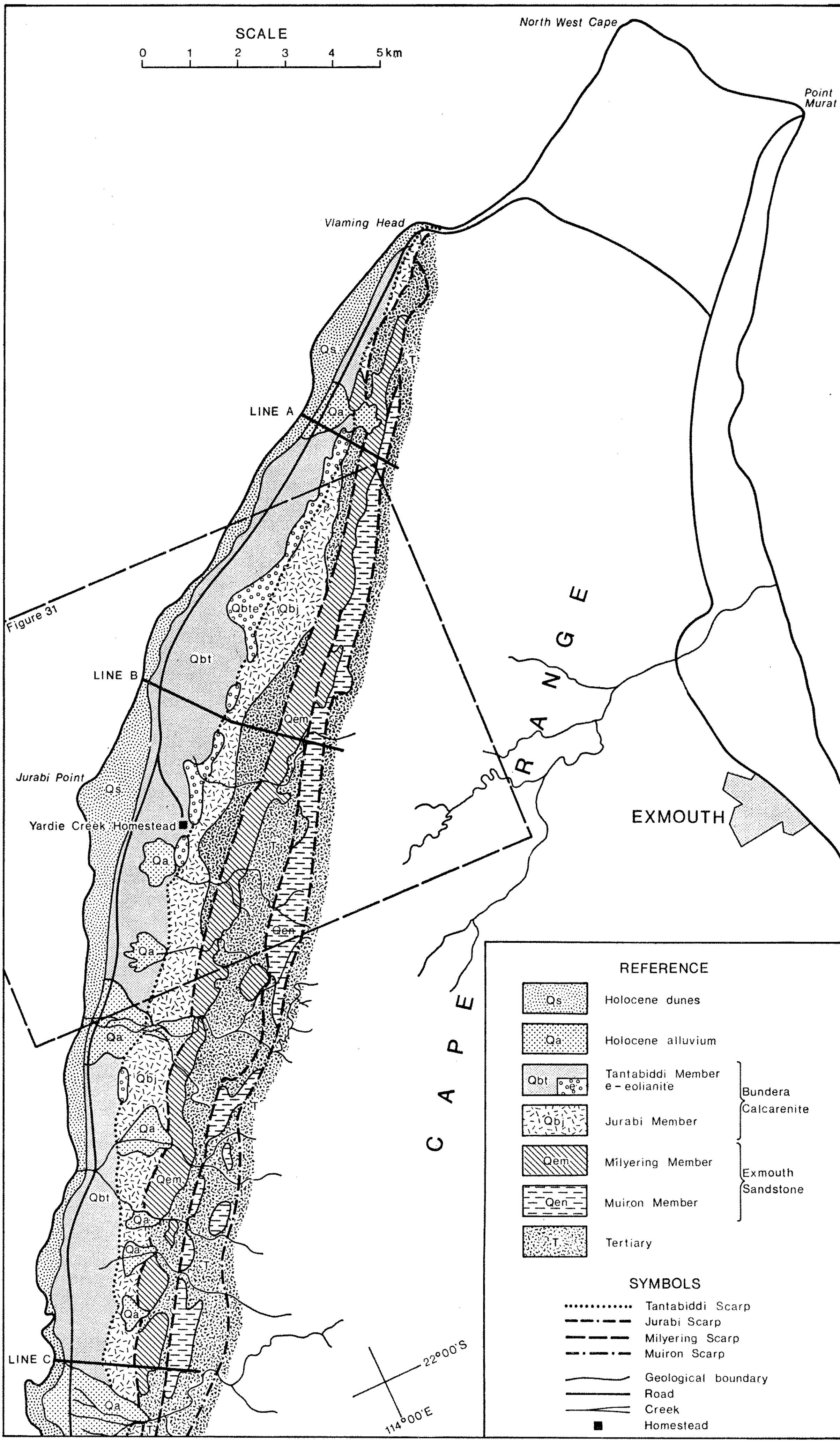


Figure 30. Shoreline scarps and terrace deposits on the northwestern part of the Cape Range peninsula.

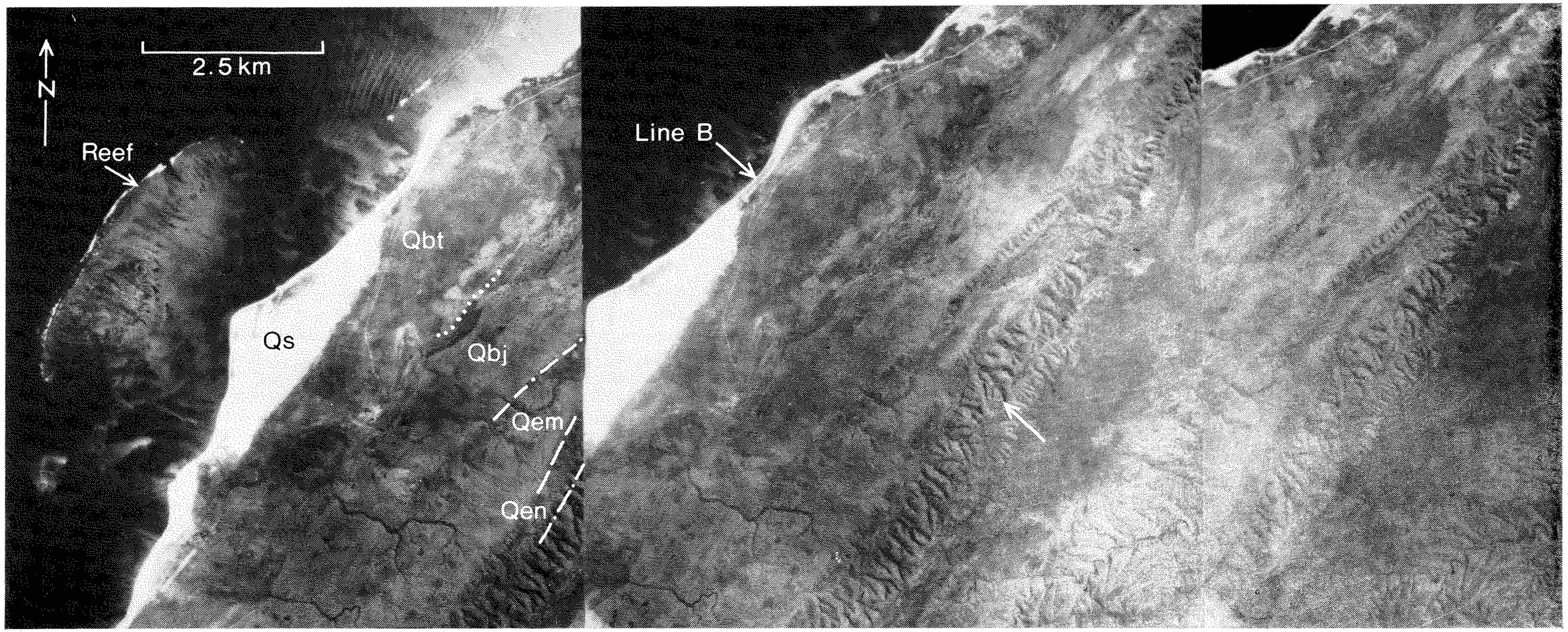


Figure 31. Stereoscopic triplet of part of Figure 30. Photographs Onslow (1963) ; run 15, Nos. 5264–66.

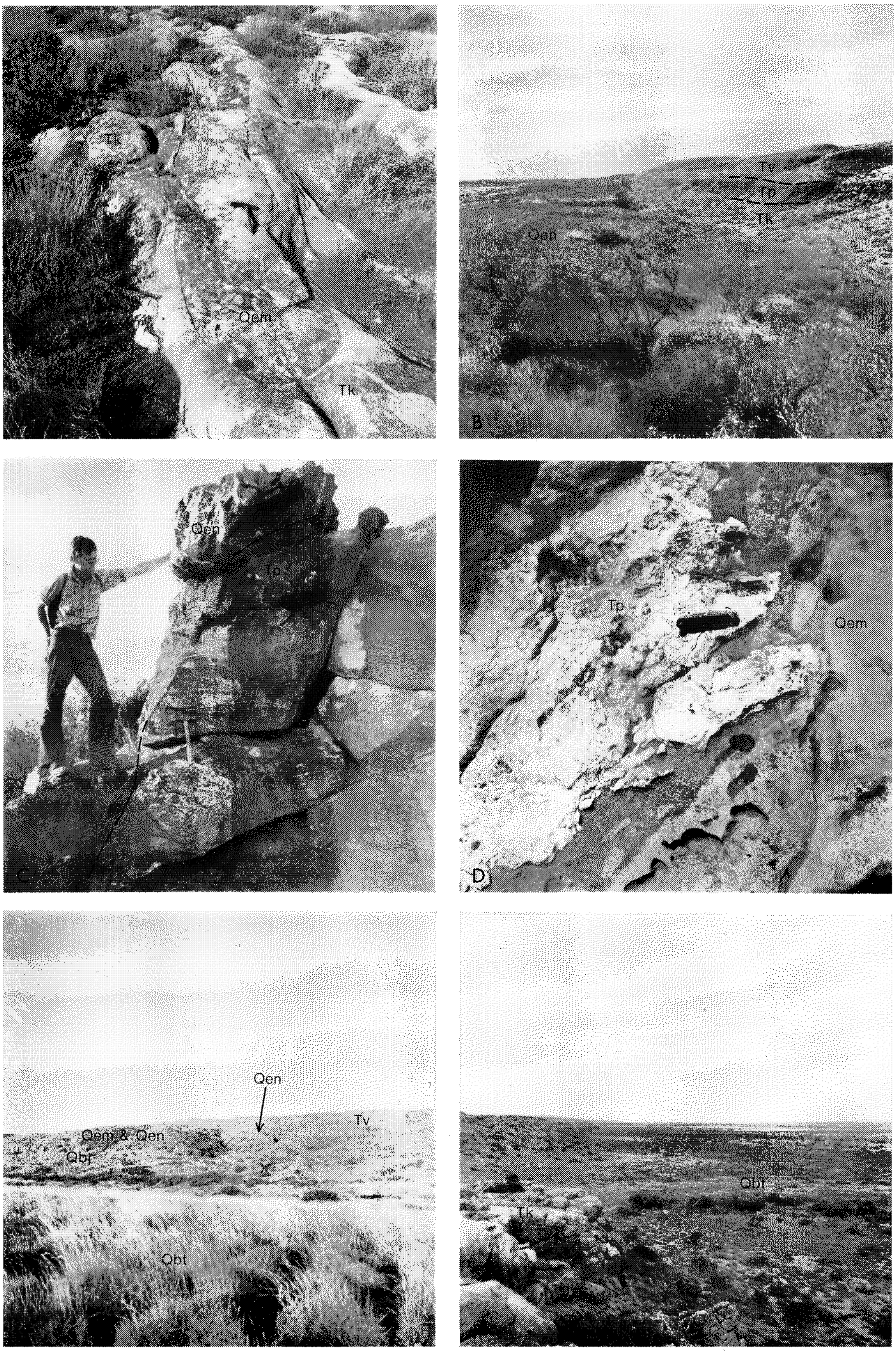

Tk
Qem
Tk
Tv
Tp
Tk
Qen
B
Qen
Tp
C
Tp
Qem
D
Qen
Qem & Qen
Tv
Qbf
Qbt
Tk
Qbt

Figure 32. (opposite).

A. Conglomerate-filled groove cut into Tulki Limestone, at base of Milyering Member. Conglomerate contains both local and Precambrian components ; Line A.
B. Ridge of Muiron Member eolianite abutting in the middle distance against the Muiron Scarp which is cut in Pilgramunna Formation ; 1 km south of Line B, looking north.
C. Muiron Member eolianite abutting against Muiron Scarp, cut in cross-bedded Pilgramunna Formation, outcrop partly cleaned with HCl ; Line A.
D. Milyering Member eolianite abutting against Milyering Scar p, here a very jagged cliff of light-coloured Pilgramunna Formation ; Line D.
E. View of the range from the top of a Tantabiddi Member dune deposit. Tantabiddi Scarp in foreground. Jurabi Terrace and Scarp distinct in left half of photo, Milyering Member eolianite covering Milyering Scarp half way up the hill and overlapping onto Muiron Member and Vlaming Sandstone; Line E.
F. Tantabiddi Scarp in Tulki Limestone ; about 7 km north of Yardie Creek looking south.

WARPING OF TERRACES

The surveying confirmed the initial impression that there has been significant deformation of these terraces. The results shown in Figures 33 and 34 and in Table 21 demonstrate clearly that the Muiron, Milyering, and Jurabi Terraces have been warped since their formation. The data are inconclusive for the Tantabiddi Terrace.

In Figure 34 the Muiron Terrace level cuts across the base of the Pilgramunna Formation. This is because the terraces do not everywhere cut the same distance into the flank of the Cape Range Anticline.

TABLE 21. LISTING OF SURVEYED ELEVATIONS
Datum is Mean Low Water Springs level at Norwegian Bay

	Data Set No. Surveyed Lines	A	B	C	D	E	F	G	H
	1 Contact Pilgramunna-Vlaming	52	74	....	78	(73)	(95)	76	(72)
	2 Base of Pilgramunna	(25)	(47)	≲9 (W) 62 (E)	42	(38)	(65)	39·5	(42)
EXMOUTH Muiron Mem. Qen	3 Contact littoral eolian ≧ HWM Qen	c	57·4	?48	57	61·6	(58)	55·8	62·5
	4 Base of littoral, = terrace level ?≲ LWM Qen	c	46·9	?46·3	55	57·5	51·5	54·6	57·3
EXMOUTH Milyering Mem. Qem	5 Contact littoral/eolian ≧ HWM Qem	19·8	33·3	31·4	46·6 (W) 42·6 (E)	42·1	?39·1 (W) 48·8 (E)	(38·2)	37·6
	6 Base of littoral, = terrace level ?≲ LWM Qem	14·2	29·5	24·9	40·1 (W) 38·0 (E)	36·0	35·6 (W) 29·6 (E)	34	32·2
	7 Interval between HWM (littoral-eolian contact) for Qen and Qem	?	24·1	(16·6)	14·4	19·5	(18)	(17·6)	24·9
	8 Interval between Qem HWM and max. ht. Qbj reef	?	24·5	22·3	25·1	24·2	23·9	(25·3)	23·3
BUNDERA Jurabi Mem. Qbj	9 Contact littoral/eolian ≧ HWM Qbj	c	10·3	a	c	?22	18·9	a	18·5
	10 *in situ* coral = ?max. height of reef ≲ LWM Qbj	c	8·8	9·1	19·5	17·9	15·2+	12·8	14·3
	11 Terrace level Qbj ?≲ LWM Qbj	c	c	c	c	c	12·4	10·2	c
BUNDERA Tantibiddi Mem. Qbt	12 Plain level = ?slightly above LWM Qbt	1·2	2·3	3·5	5·5	3–4	3	3–6	3–5
	13 *in situ* coral = ?max. height of reef ≲ LWM Qbt	c	2·3	c	5·5	c	c	c	c
	14 Distances between survey lines in km — Vlaming Head	4·5	7	14	15	4·5	22	5·5	18

≲ approximately equivalent to or lower than.
≧ approximately equivalent to or higher than.
HWM = High Water Mark.
LWM = Low Water Mark.
(W) west side of relevant part of section.
(E) east side of relevant part of section.

a absent.
c concealed.
( ) estimated level ; concealed, not surveyed, or extrapolated.
? level + or — 2 m ; hard to place in field.
+ level effected by erosion, probably originaly higher.

In addition to the elevations of the four terraces, Table 21 also shows the elevation of the high water-mark indicators in the Muiron and Milyering Members, the low water-mark indicator in the Jurabi Member, and the vertical separation of these sea-level indicators. As argued before, these are better indices of sea-level stands, i.e. horizontal planes, than the terraces, and are therefore more suitable for establishing the amount of deformation.

The figures for the Muiron and Milyering Members show that their respective high water-mark indicators are significantly farther apart at the northern and southern ends of the area than in the middle. This indicates that when the Milyering Terrace formed, the Muiron Terrace had already been warped slightly downward in the middle of the area. After the cutting of the Milyering Terrace, movement reversed and the middle part of the area rose relative to the southern and especially to the northern part.

There is also evidence that, apart from the very gentle north-south warping, some tilting perpendicular to this direction has taken place.

On line D the Milyering Terrace can be seen in the field to have a gentle easterly dip. The surveyed elevations in the littoral/eolian contact in the Milyering Member (Table 21; surveying accurate in this part of line D) indicate a similar eastward dip of this water-level indicator. Although this indicator is difficult to pick accurately, a difference of 2 m over a distance of 130 m seems significant, and we believe it indicates eastward tilt of the terrace.

The Tantabiddi Terrace and its deposits are not obviously warped within the study area. However, it might be possible to establish warping, if elevations were obtained on coral-reef deposits in the Tantabiddi Member, which occur intermittently along the coast as far south as Cape Cuvier and as far east as Onslow.

A quick inspection of the Cape Cuvier and Rough Range Anticlines produced no conclusive evidence of any pre-Tantabiddi terraces, although steps in the elevation of eolianites in both areas may indicate buried terraces. On the northern point of the Giralia Range, the Tantabiddi Scarp and an older stripped terrace, which is thought to correlate with the Jurabi Terrace, are present. It is too poorly preserved for any warping, if present, to be obvious.

AGE OF TERRACES

The terraces have been cut into the folded Middle Miocene rocks of the Cape Range Anticline, and they are therefore post-Middle Miocene and probably post-Miocene, in age. Fossils collected did not permit a more accurate dating.

The warping of the terraces proves that there has been significant tectonism in the area since their formation, and it indicates the possibility that they formed due to intermittent uplift combined with a relatively stable sea level. In this interpretation the terraces would have formed during periods of tectonic quiescence which were

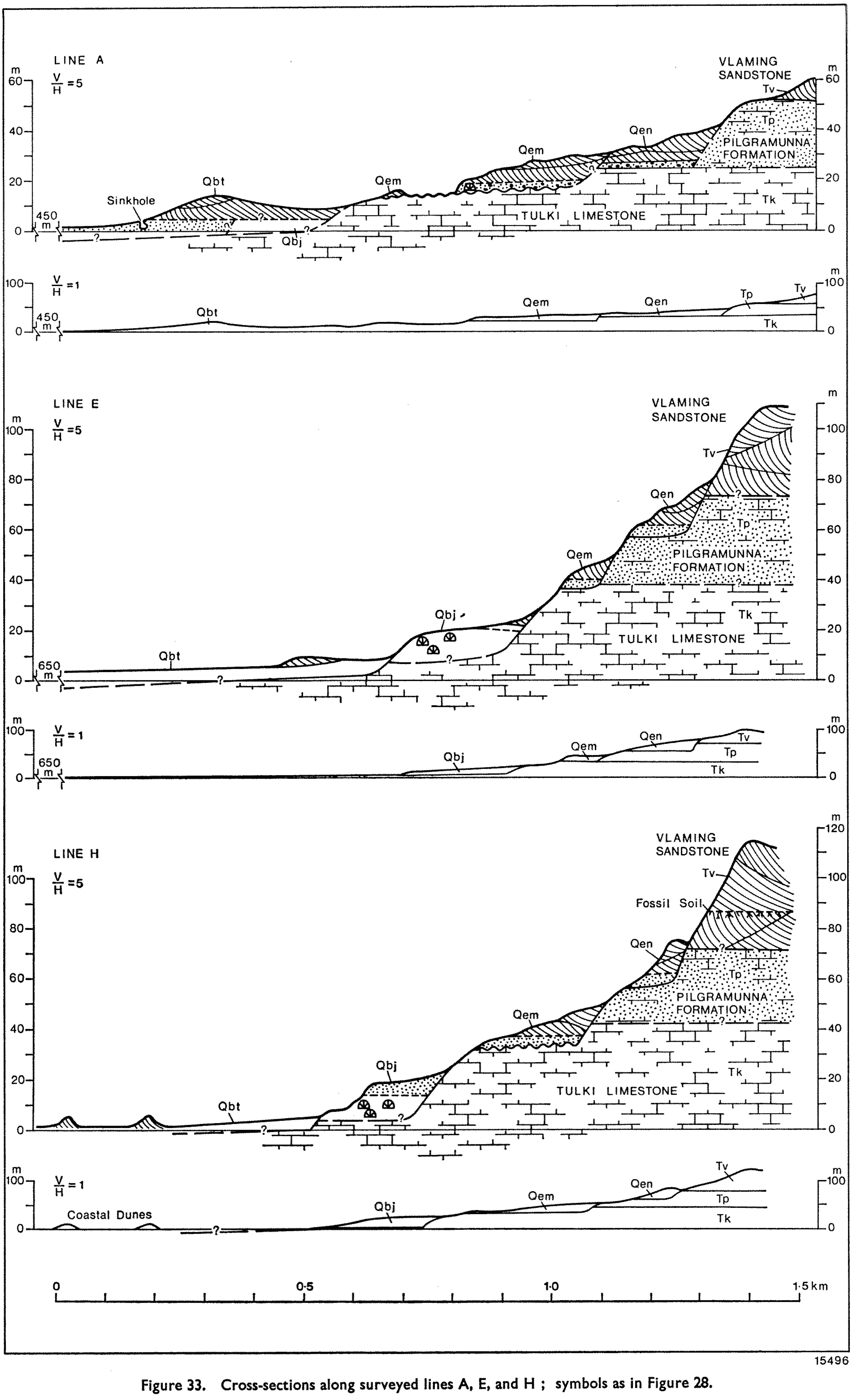


Figure 33. Cross-sections along surveyed lines A, E, and H ; symbols as in Figure 28.

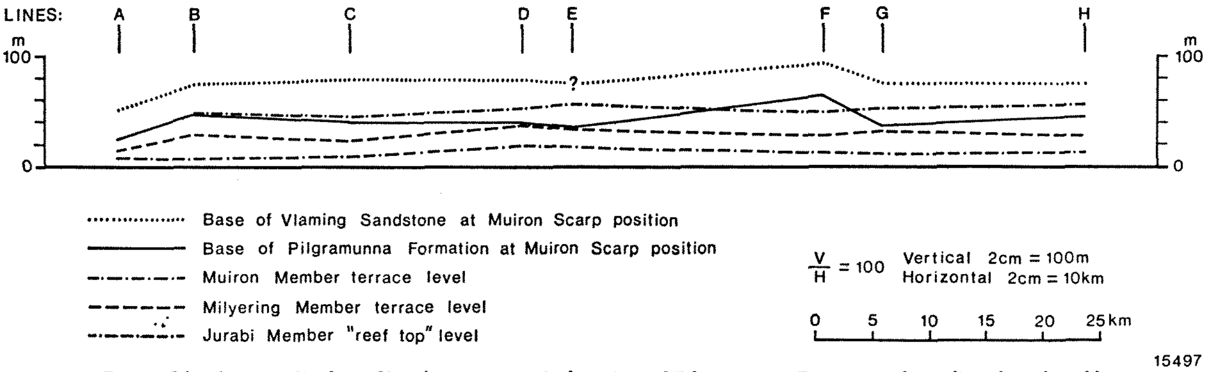


Figure 34. Longitudinal profile of terraces and elevation of Pilgramunna Formation from line A to line H.

separated by periods of uplift. An alternative interpretation is that the terraces formed during eustatic high sea-level stands of the interglacial periods of the Quaternary, and that they were simultaneously warped by fairly continuous deformation. We feel that the gentle warping of the terraces is more suggestive of continuous rather than abrupt and intermittent deformation, and tentatively interpret the terraces as having formed during successive Quaternary high sea-level stands. On the basis of this interpretation their age can be estimated by correlation of the terraces with known Quaternary high sea-level stands. For this purpose we made use of a curve published by Fairbridge (1961, p. 131) and modified by G. H. Low (unpublished).

The Tantabiddi Member, which covers the youngest terrace, is thought to have formed during the later part of the Riss-Würm interglacial, and it may be a correlative of the Bibra Formation in the Shark Bay area, which Logan and others (1970, p. 70) consider as older than 40 000 years. The Jurabi Terrace is believed to have formed during an early Riss-Würm high sea-level stand. The Milyering and Muiron Terraces, which must be considerably older because of their elevation and poor preservation, may have formed during the two main high sea-level stands of the Mindel-Riss interglacial.

CONCLUSIONS

The distinct warping of these terraces of probable Pleistocene age indicates that significant folding has occurred during the Pleistocene, and it seems likely that folding is still continuing. The amount of Pleistocene deformation suggests that the Cape Range structure, as exposed, may be a very young structure that formed in a few million years.

Reliable dating of the terrace deposits and a study of the offshore Cainozoic sediments are now required to confirm these conclusions.

ACKNOWLEDGEMENTS

The air-photographs of Onslow (Fig. 31) are published with permission of the Surveyor General, Department of Lands and Surveys, Perth.

We thank Mr. K. Graham, the Exmouth Shire Clerk, for the loan of surveying equipment, and Dr. P. G. Quilty, formerly of Wapet, for helpful discussions.

REFERENCES

Australian National Tide Tables 1975: Canberra, Aust. Govt. Pub. Service.

Condit, D. D., 1935, Oil possibilities in Northwest district, Western Australia: Econ. Geol., v. 30, p. 860-878.

Condon, M. A., 1968, The geology of the Carnarvon Basin, Western Australia—Part 3: Post-Permian stratigraphy; structure; economic geology: Australia Bur. Mineral Resources Bull. 77, Part 3, p. 1-68.

Condon, M. A., Johnstone, D., and Perry, W. J., 1953, The Cape Range structure, Western Australia—Part 1: Stratigraphy and structure: Australia Bur. Mineral Resources Bull. 21, Part 1, p. 1-42; (2nd edn., 1955, p. 1-48).

Fairbridge, R. W., 1961, Eustatic changes in sea level: *in* Physics and chemistry of the Earth, v. 4, p. 99-185, Pergamon Press.

Frye, J. C., and Willman, H. B., 1962, Morphostratigraphic units in Pleistocene stratigraphy—Note 27, Stratigraphic Commission: Am. Assoc. Petroleum Geologists Bull. 46, p. 112-113.

Logan, B. W., Read, J. F., and Davies, G. R., 1970, History of carbonate sedimentation, Quaternary Epoch, Shark Bay, Western Australia, *in* Carbonate sedimentation and environments, Shark Bay, Western Australia: Am. Assoc. Petroleum Geologists, Memoir 13, p. 38-84.

Raggatt, H. G., 1936, Geology of North-West Basin, Western Australia, with particular reference to the stratigraphy of the Permo-Carboniferous: Royal Soc. New South Wales Jour. and Proc., v. 70, p. 100-174.

APPENDIX—DEFINITION OF NEW STRATIGRAPHIC NAMES

The stratigraphic relationships on the western side of the Cape Range, as interpreted by us, differ considerably from the interpretation by Condon and others (1953, 1955) and Condon (1968). It is therefore necessary to revise the nomenclature.

The Exmouth Sandstone is divided into the Muiron and Milyering Members, which are lithologically very similar, but which can be easily recognized in the study area because of their occurrence on different terraces.

The Bundera Calcarenite is hereby redefined to incorporate lithologically similar deposits which have previously been mostly mapped as Tulki Limestone, but which disconformably overlie this Miocene unit. The redefined Bundera Calcarenite is divided into the Jurabi and Tantabiddi Members. The two members are lithologically similar, and can only be differentiated where their relationships are not obscured by overlapping younger eolianites.

Occurrence on a specific terrace, i.e. morphology and not lithology, is the most important criterion for recognizing these members. In other words, these units are not purely lithostratigraphic units, but like so many Quaternary map units, they are morphostratigraphic units in the sense of Frye and Willman (1962).

MUIRON MEMBER OF EXMOUTH SANDSTONE

Derivation of name: Muiron Islands, Onslow 1 : 250 000 Sheet area.

Distribution: Western side of Cape Range peninsula.

Type section: 22° 06′ 30″S, 113° 54′ E, about 150 m northwest of Vlaming Sandstone type locality.

Lithology: Calcareous quartz sandstone to pebbly granule conglomerate overlain by medium-grained well-sorted quartzose calcarenite.

Thickness: Up to about 25 m.

Relationships: Disconformably overlies the Miocene units of the Cape Range Anticline. Disconformably overlain by Milyering Member or younger eolianites.

Age: ?Pleistocene.

Previous usage: Condon and others (1953, 1955) included these deposits in the Pilgramunna Formation.

MILYERING MEMBER OF EXMOUTH SANDSTONE

Derivation of name: Milyering Well, Ningaloo 1 : 250 000 Sheet area.

Distribution: Western side of Cape Range peninsula.

Type section: 22° 06′ 25″S, 113° 53′ 50″E, about 400 m north-northwest of Vlaming Sandstone type locality.

Lithology: Calcareous quartz sandstone to pebbly granule conglomerate grading to quartzose calcarenite; minor conglomerate and algal boundstone. Overlain by well-sorted quartzose calcarenite.

Thickness: Up to about 30 m.

Relationships: Disconformably overlies the Muiron Member and the Miocene units of the Cape Range. Disconformably overlain by younger eolianites.

Age: ?Pleistocene.

Previous usage: Condon and others (1953, 1955) included these deposits in the Pilgramunna Formation.

JURABI MEMBER OF BUNDERA CALCARENITE

Derivation of name: Jurabi Point, Onslow 1 : 250 000 Sheet area.

Distribution: Western side of Cape Range peninsula.

Type section: 22° 06′ 20″S, 113° 53′ 40″E, about 800 m north-northwest of Vlaming Sandstone type locality.

Lithology: Algal or coralgal boundstone, calcarenite, and minor limestone conglomerate.

Thickness: Up to 20 m.

Relationships: Disconformably overlies the Exmouth Sandstone and the Miocene units of the Cape Range Anticline. Disconformably overlain by Tantabiddi Member.

Age: ?Pleistocene.

Previous usage: Condon and others (1953, 1955) included these deposits in the Tulki Limestone.

TANTABIDDI MEMBER OF BUNDERA CALCARENITE

Derivation of name: Tantabiddi Well, Ningaloo 1 : 250 000 Sheet area.

Distribution: Occurs along the coast at least from Cape Cuvier in the south to Onslow in the east.

Type section: 21° 50′ 10″S, 114° 04′ 18″E, in sinkhole on the western side of indurated dune; approximately 100 m south of track into road material quarry.

Lithology: Coral and coralgal boundstone, calcarenite to calcirudite.

Thickness: Up to about 20 m.

Relationships: Disconformably overlies Jurabi Member, Exmouth Sandstone, and Miocene units of Cape Range Anticline.

Age: Pleistocene to Holocene.

Previous usage: Condon and others (1953, 1955) mapped these deposits as Bundera Calcarenite, or, in a few places, as Tulki Limestone, or as Exmouth Sandstone.

STRATIGRAPHY, SEDIMENTATION, AND STRUCTURE IN THE WESTERN AND CENTRAL PART OF THE BANGEMALL BASIN, WESTERN AUSTRALIA

by A. T. Brakel and P. C. Muhling

ABSTRACT

The Bangemall Basin is a folded, Middle Proterozoic sedimentary basin with an arcuate east-west elongation, discordantly overlying the older tectonic units of the Western Australian Shield.

A regional facies change in the Bangemall Group occurs in the central part of the basin near the 119° E meridian and is the result of an easterly lensing out of dolomite, chert, and sandstone units. It partly corresponds to a major northeasterly trending zone of faulting and basement arches. Correlation of much of the eastern succession with the formations to the west and north is uncertain.

In the western portion of the basin most of the lower units were deposited in a shallow marine environment, but local, discrete lenses of coarse-grained, terrestrial alluvial fan deposits occur on the basal unconformity. These lower units of dolomite, lutite, and sandstone are characterized by lensing, interfingering, and lateral gradations. Near the top of these units is the Discovery Chert, representing a period of stable conditions over most of the western region. The rest of the sequence was laid down in deeper water and consists of laterally extensive lutites with interbedded sandstone sheets, two of which persist for distances of over 175 km.

In the central part of the basin the succession is simpler, with laterally persistant lutites and a prominent sandstone. The lower lutite rests on the basal uncomformity or is separated from it by locally developed sandstones and conglomerates.

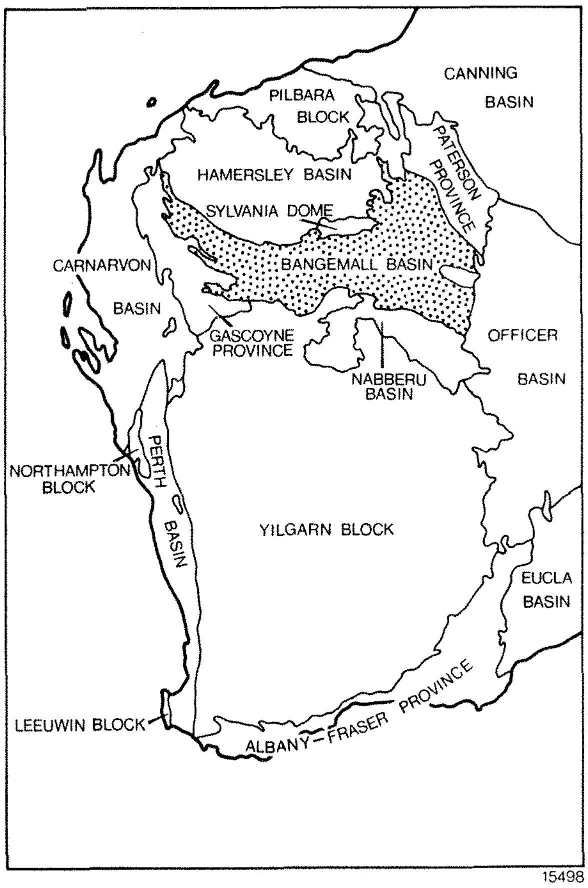
Along the northern margin of the basin there is a thick dolomite-bearing sequence, equivalent to all the shallow water formations and some of the deeper water formations of the western succession.

Basic sills and dykes are common. The only confirmed felsic volcanic rock is a rhyolite near the zone of the regional facies change.

Folding has occurred on two arcuate trends, one concentric with the pre-Bangemall platform to the north, the other continuous with trends in pre-Bangemall rocks to the south. Variations in deformation style and orientation permit definition of structural provinces. Deformation has been by fragmentation of the basement along pre-existing structures, and the relative complexity of sedimentation and structure records the continuing instability of the basement blocks.

INTRODUCTION

The Bangemall Basin is a Middle Proterozoic sedimentary basin containing folded and slightly metamorphosed rocks of the Bangemall Group. The basin overlies older Proterozoic and Archaean units, and together with them forms the northern half of the Western Australian Shield (Fig. 35). The northern margin of the Bangemall Group overlies the Hamersley Basin, as well as localized deposits of Bresnahan Group sandstone and conglomerate, and some Archaean inliers. The Hamersley Basin rocks are metamorphosed in their southern extent, and west of the Bangemall Basin are intruded by Proterozoic granitic rocks; they appear to pass into the igneous and metamorphic rocks of the Gascoyne Province southwest of the Bangemall Basin. Thus the Bangemall Group seems to be a younger cover straddling the transition from older cratonized sedimentary basin to mobile belt. A Lower Proterozoic sequence in the Nabberu Basin extends eastwards from the Gascoyne Province between the Bangemall Basin and the Archaean rocks of the Yilgarn Block (Barnett, 1975; Hall and Goode, 1975; Horwitz, 1975). Stratigraphic relationships in the eastern portion of the Bangemall Basin, not discussed here, are dealt with by Williams and others (1976).



15498

Figure 35. Regional setting of the Bangemall Basin.

Isotopic Sr/Rb age determinations on a black shale and felsic rocks in the Bangemall Group gave isochrons of 1 080 ± 80 m.y. (Compston and Arriens, 1968) and 1 096 ± 41 m.y. (Gee and others, 1976). Walter (1972) notes that a stromatolite which occurs in the Irregully Formation at the base of the group has an age range of 1 350 ± 50 to 950 ± 50 m.y.

Previous detailed geological mapping of the Bangemall Basin has been carried out by de la Hunty (1964), Daniels and MacLeod (1965), Daniels (1968, 1969, and 1970), and MacLeod (1970). Stratigraphic subdivision was first undertaken in the western region by Halligan and Daniels (1964) and modified by Daniels (1966a), who recognized the regional facies change between the northern and western areas of the basin. Daniels (1969) drew attention to the effect on sedimentation of north-easterly-trending basement structures in the Bangemall Group, and the increasing intensity of folding from north to south in the basin. Recent mapping in the centre of the basin has discovered another regional facies change and delineated distinct structural provinces.

Dolerite sills are common throughout the Bangemall Basin, and intruded before or during the main period of folding of the Bangemall Group. Dykes of dolerite occur either as feeders to the sills, or as later intrusions that transect the sills and the folds.

Localities referred to in the text are shown in Figure 36.

REGIONAL FACIES DISTRIBUTION

Figure 37 is a generalized geological map of the Bangemall Basin, west of the 120° E meridian. Three major facies provinces each with distinctive litho-stratigraphic assemblages are recognized in the basin. The western facies has the thickest and most varied succession. The transition between the western and northern facies is the result of both rapid lensing out of some units from the west and changes in lithology along strike of others. The western and northern facies share the same upper three formations.

The change from the western to the eastern facies is due to the easterly lensing out of dolomite, chert, and sandstone units and the persistence of shale and siltstone beds. The eastern and northern facies provinces are juxtaposed by faults. Relationships between facies are shown diagrammatically in Figure 38.

WESTERN FACIES

The stratigraphy of this facies is mostly after Daniels (1966a), although it is now recognized that two additional units (Mount Augustus Sandstone and Tringadee Formation) are locally developed on the basal unconformity. Furthermore, the Jillawarra Formation is a new formation recognized immediately below the Discovery Chert, and the basal sandstone member of Daniels' Kurabuka Formation is separated out as the Mount Vernon Sandstone. The new stratigraphic units will be defined in Muhling and others (in prep.).

Thicknesses of formations in the Edmund region are given by Daniels (1969). Further work is in progress to establish formational thicknesses in other areas for later publication.

MOUNT AUGUSTUS SANDSTONE AND TRINGADEE FORMATION

Although apparently at the same stratigraphic level, there is no physical continuity between these two basal conglomeratic units. The Tringadee Formation, with a maximum thickness of at least 1 000 m, is conformably overlain by the Irregully Formation. The top of the Mount Augustus Sandstone is not exposed but is also probably conformable. The Mount Augustus Sandstone, estimated to be over 600 m thick at Mount Augustus, may be equivalent to the much thinner Yilgatherra Member at the base of the Irregully Formation in the Edmund Sheet area, because the Yilgatherra Member is similar in lithology and stratigraphic position.

The Mount Augustus Sandstone and the Tringadee Formation both consist of coarse, often pebbly sandstone and lenses of pebble, cobble, and boulder conglomerate. The clasts are mainly vein quartz, but granitic and metamorphic clasts are also widespread. Siltstone and fine-grained sandstone lenses are rare. Some sandstone in the Tringadee Formation is feldspathic. Tangential cross-stratification is common in the Mount Augustus Sandstone and indicates palaeocurrents from the northwest. No gross vertical grain-size variation through the formations or parts of the formations occurs. These rocks are considered to have been deposited subaerially by braided streams. The isolated developments on the unconformity suggest that they were discrete alluvial fans, originating in response to the down-warping of the basin. The upper portion of the Tringadee Formation contains some dolomite members, indicating alternations between terrestrial and marine conditions.

IRREGULLY FORMATION

Except where previously indicated, the Irregully Formation is the lowest formation of the Bangemall Group. It consists mainly of microcrystalline dolomite, shale, and mudstone, with minor chert, sandstone, conglomerate, and breccia. The dolomite is finely laminated or massively bedded, and stromatolites and algal bands have been found in places. Hematite and goethite cubes, presumably after pyrite, are locally abundant. Some desiccation cracks are present. In the Edmund and Wyloo Sheet areas Daniels (1965) records irregular sheets of sedimentary breccia, thought to be the result of local intraformational erosion. In the southwestern limb of the Candolle Syncline, the formation consists of shale and mudstone and only minor dolomite. The unit appears to be absent in the Cobra Synclinorium and in the regions around Edmund homestead and south of Mount Egerton.

The formation was deposited in shallow lagoonal and tidal flat conditions.

KIANGI CREEK FORMATION

The Kiangi Creek Formation, which generally overlies the Irregully Formation, consists of interbedded quartz arenite and shale. The arenite is medium grained, has a siliceous cement, and contains up to 20 per cent feldspar in places. Tourmaline is a common accessory. Most sandstone beds exceed 1 m in thickness and do not show cross-stratification, but in some beds this structure is abundant. The silica cement may be due to secondary surficial silicification. In general, the shale content of the formation increases from west to east, although rapid variations are common.

The formation interfingers with the Irregully Formation such that the two are laterally equivalent in part, and in some areas the Kiangi Creek Formation overlies the basal unconformity. Interbedded sandstone and dolomite occur at higher levels, for example, north and west of Mount Egerton and between Glen Ross Creek and the Ethel River.

The Kiangi Creek Formation appears to have been deposited in a near-shore marine environment, chiefly as shoals and barrier islands.

JILLAWARRA FORMATION

This newly named formation, with an estimated thickness of 1 400 m near Jillawarra bore, lies between the Kiangi Creek Formation and the Discovery Chert. It consists dominantly of grey, brown, and black silty shales and silty mudstones, together with minor chert, dolomite, and sandstone. Some chert beds resemble the Discovery Chert in appearance. The shales are commonly siliceous and chert-like in outcrop, a feature probably due to surface silicification. Crystal casts after pyrite, and possibly halite and gypsum are abundant in some beds.

The formation interfingers with the arenites of the Kiangi Creek Formation. The base of the formation is taken to be the top of the highest major sandstone underlying the shale interval. The unit apparently thins to the west and is absent in most of the Edmund Sheet area.

The sediments are interpreted as shelf muds laid down on the seaward side of the Kiangi Creek Formation sands, and the water was at times stagnant and hypersaline.

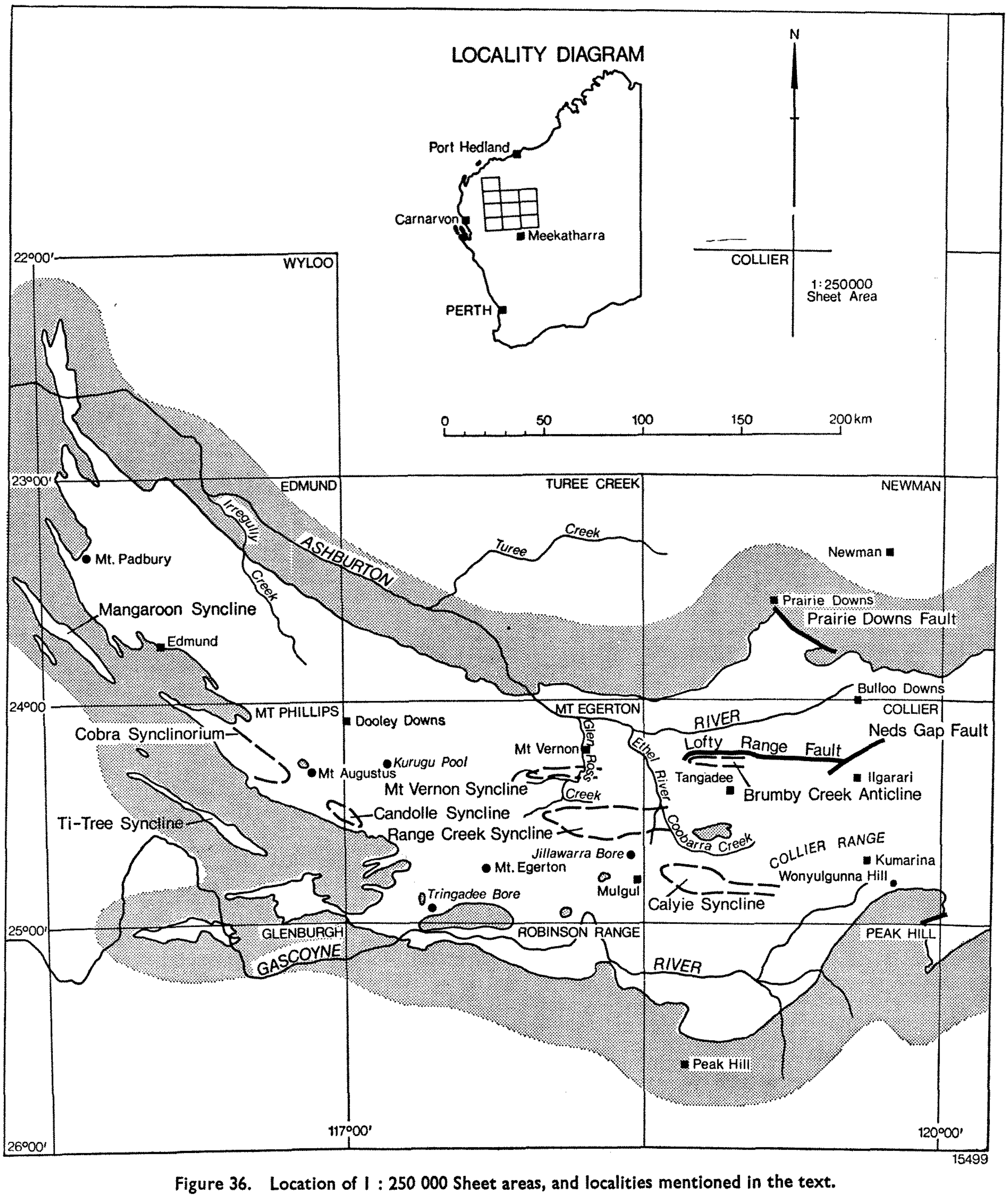


Figure 36. Location of 1 : 250 000 Sheet areas, and localities mentioned in the text.

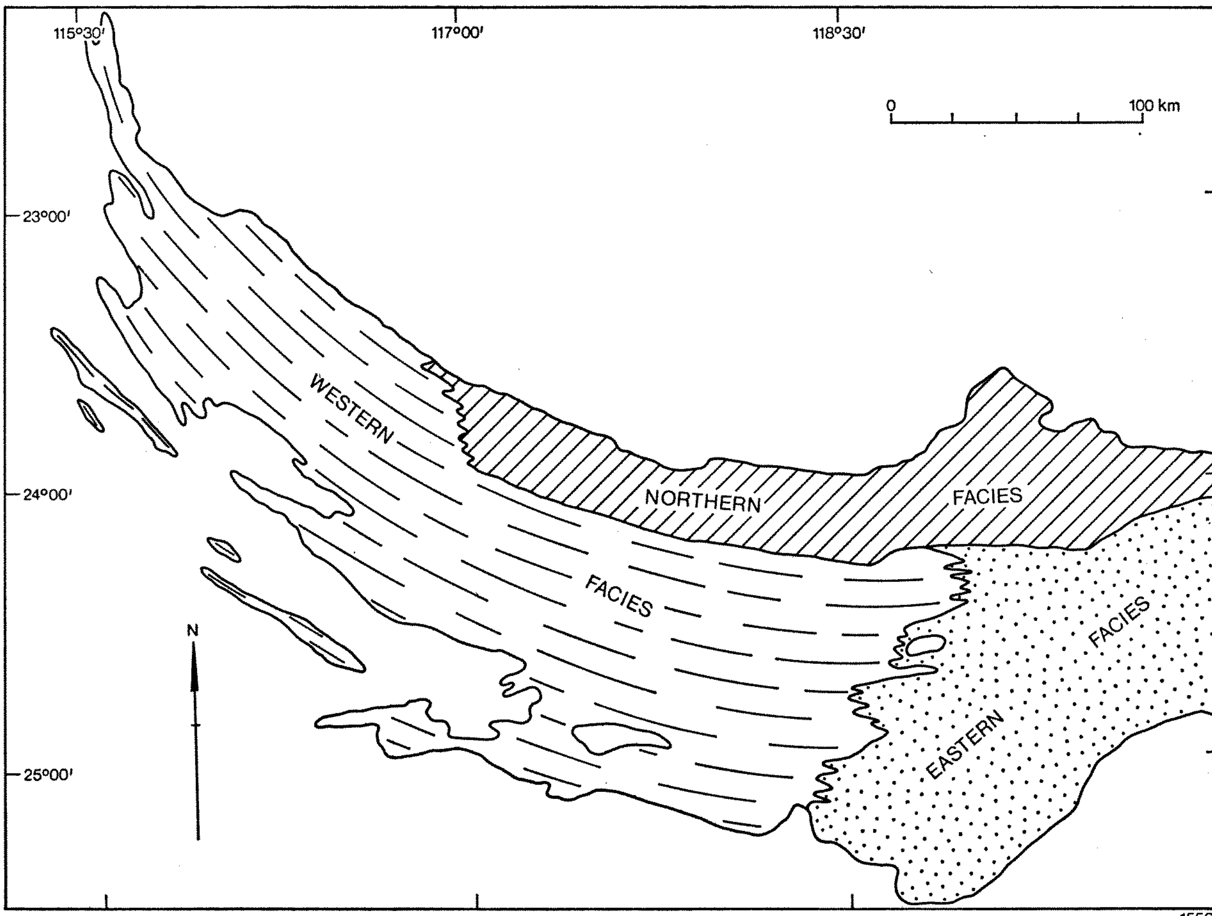


Figure 37. Facies provinces in the western and central Bangemall Basin.

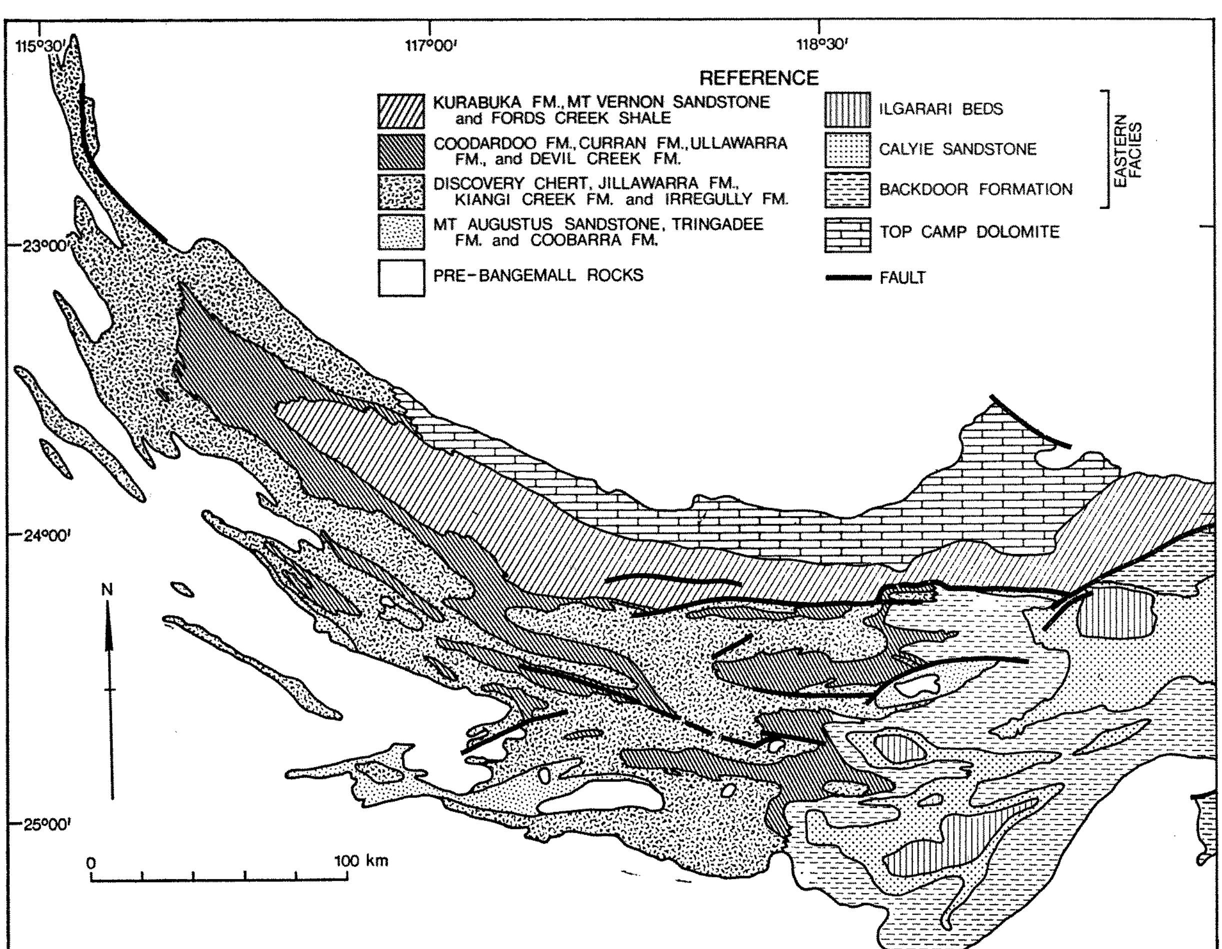


Figure 38. Generalized geological map of the Bangemall Basin west of the 120°E meridian.

DISCOVERY CHERT

The Discovery Chert, conformably overlying the Jillawarra Formation, is a distinctive, remarkably persistent chert unit which forms the best marker horizon in the Bangemall Group. On the northern margin of the basin in the Edumund Sheet area it overlies the Irregully Formation and lenses out eastwards. It consists of black, massive chert with diffuse light-coloured laminations that are either planar, wavy, or contorted. A streaky texture visible with a hand lens is characteristic. The bedding is generally 10 to 30 cm apart and is wavy, containing irregular depressions and swells. Crystal casts after pyrite are common. Possible gypsum casts are also present. A search for acritarch microfossils revealed black spherical bodies, 5 to 10 μ in diameter, possibly of organic origin. Iron oxide replacement prevented separation and positive identification of these spheres.

The upper and lower contacts are usually transitional over a thickness of about 3 m, the beds becoming thinner and less siliceous away from the chert. Daniels (1969) records some sharp lower contacts in the Edumund Sheet area, as well as a regional colour variation from black to grey and maroon to white.

The Discovery Chert is the first unit in the basin which does not show major facies variations. At this time the sedimentation pattern became simpler and tectonic conditions were relatively quiet. However, slump structures have been found in places and may indicate some seismic activity. The environment seems to have been that of shallow, stagnant, and at times hypersaline water in which silica was precipitated chemically in anaerobic conditions.

DEVIL CREEK FORMATION

The Devil Creek Formation is a dolomite and silty shale unit conformably overlying the Discovery Chert. The dolomite is similar to that of the Irregully Formation, but minor lenses of dolarenite and dolorudite occur. A 1 cm thick oolite band was seen 6 km west of Kurugu Pool. Stromatolites have been recorded (Daniels, 1966a).

The proportion of dolomite to shale varies, both vertically and laterally, and the dolomite itself may form discrete lenses. Dolomite is locally absent, for example in the Mount Vernon Syncline, so that the remaining lutite sequence is indistinguishable from the overlying Ullawarra Formation.

Hematite cubes after pyrite are widespread, and rare unaltered pyrite cubes have been found. Nodules up to 2 cm in diameter consisting of small cubes and octahedra after pyrite are also present.

Cross-stratified beds are a common but minor feature. They contain abundant medium and small-scale (Conybeare and Crook, 1968), shallow, interfering, trough-shaped, cross-strata (pi and nu-cross-stratification), some planar alpha-cross-stratification, climbing ripples (kappa and lambda-cross-stratification), and scoured surfaces.

The laminated dolomite is thought to have been precipitated on the floors of lagoons, originally as calcium carbonate, and the interbedded shale laid down during times of clastic sediment input. A tidal mudflat environment is possible, but because desiccation cracks and interfering sets of ripple marks have not been observed, deposition in the restricted waters of lagoons is more likely. The cross-stratified and coarser-grained dolomite beds point to a transient high-energy environment where the wave base impinged on the sediment-water interface, such as a shallow-water shoal.

ULLAWARRA FORMATION

Conformably overlying the Devil Creek Formation and in part laterally equivalent to it, is the Ullawarra Formation, which is composed of shale, mudstone, quartzose siltstone, and fine-grained sandstone, as well as minor bands of dolomite and chert. Alternating thin-bedded maroon and white shales are common. Load casts are abundant. Laminated or massive siltstone is present in beds up to about 0.5 m thick. Cubic crystal casts occur sporadically, but are not as abundant as in older formations. Alpha and kappa-cross-stratification occur in some of the quartzose siltstone beds. This rock may grade into fine-grained sandstone.

The environment of deposition ranged from that envisaged for the Devil Creek Formation, but with a greater influx of clastic sediment, to deeper water conditions. The quartzose siltstone and sandstone could represent offshore shoals. However, the upper portion of the unit may have been laid down completely in a deeper water open marine setting.

CURRAN FORMATION

The Curran Formation is a distinctive pale-weathering unit of shale, mudstone, and chert, extending over a distance of 85 km and overlying the Ullawarra Formation. At its most easterly point it is cut off by a fault north of the Mount Vernon Syncline. At the time of its deposition conditions were fairly stable and uniform.

COODARDOO FORMATION

The overlying Coodardoo Formation in the Edmund Sheet area is a well-bedded greywacke with beds of shaley siltstone near the top (Daniels, 1969). The base is a transition zone 20 m thick, consisting of alternating beds of dark grey-green to black shale and thin greywacke with abundant sole marks. In the Mount Egerton Sheet area, however, the Coodardoo Formation consists of poorly to moderately sorted quartz arenite and minor wacke. The formation has a sheet-like form at least 175 km long, and is better sorted to the east. It disappears from the sequence by lensing.

The sands were introduced into the basin from the northwest by turbidity flows and in part transported farther east by bottom traction currents. Daniels (1966a) considers that the land to the north was gradually elevated at this time, resulting in a change in conditions from those of the Curran Formation.

FORDS CREEK SHALE

The Fords Creek Shale which conformably overlies the Coodardoo Formation is a thick sequence of green micaceous shale and silty mudstone, with minor amounts of interbedded quartz arenite, chert, and greywacke. Groove casts, bounce casts, flute casts, current bedding, ripple marks, and slump structures have been recorded.

Deposition was on an open marine shelf, chiefly as fine-grained material settling out of suspension. The arenite intercalations appear to be traction current deposits, although they may have been emplaced by turbidity flows and subsequently reworked by bottom currents. In the Edmund Sheet area palaeocurrents indicate a provenance to the north (Daniels, 1966a).

MOUNT VERNON SANDSTONE

Formerly regarded as the basal member of the Kurabuka Formation, this unit has been elevated to formation status. It is about 300 m thick north of Mount Vernon homestead and forms a sheet with an east-west extent of over 300 km. At the top of the underlying Fords Creek Shale is a transition zone in which thin arenite members of the shale sequence increase upwards in frequency and thickness. The bulk of the sandstone is a well-sorted, medium-grained quartz arenite. Siltstone fragments, some as large as 10 cm in length, are locally abundant. Pi and omikron-cross-stratification commonly in herringbone arrangement, ripple marks, flute casts, groove casts, and bounce casts are common. Herringbone cross-stratification is generally regarded as an indicator of tidal activity.

The evidence points to deposition in a near-shore, high-energy regime, such as a barrier bar system lying parallel to the coast.

KURABUKA FORMATION

The youngest unit in the western facies is the Kurabuka Formation which consists chiefly of greenish-white and dark-grey shale and mudstone. Near its base, interbedded cherty siliceous shale is common. In the upper portion of the formation there are some carbonate bands a few centimetres thick.

The deposit may represent a lagoonal facies developed next to the Mount Vernon Sandstone. Temporary changes in water circulation and sediment input would have resulted in the siliceous shale and carbonate bands. During storms or exceptionally high tides, siltstone fragments could have been washed out to be incorporated in the sands of the barrier bar system.

The sequence from the Fords Creek Shale upwards is thus seen as a progradational one which could portray the last stage of the infilling of the basin before the end of marine deposition.

NORTHERN FACIES

TOP CAMP DOLOMITE

This basal sequence of the Bangemall Group along the northern margin of the basin consists of over 2 000 m of dolomite, green shale, siltstone, chert, and sandstone. Dolomite beds, some with stromatolites, occur at several levels. Some of the bedded cherts appear to be silicified lutites. The sandstones are dominantly fine grained, well bedded, and have internal lamination. Bedding surfaces commonly show current lineations, flute and groove moulds, load casts, and ripple marks. Intraformational conglomerate and slump structures have been noted.

South of Prairie Downs a thick wedge of arkose and conglomerate with jaspilite boulders, known as the Prairie Downs Beds (Halligan and Daniels, 1964), occurs within the Top Camp Dolomite. A nearby derivation from the north and northeast is postulated (Daniels, 1966b). The wedge thickens to the northeast and a disconformity has been recorded at its base. It appears this deposit originated as an alluvial fan related to contemporaneous tectonic activity on the Prairie Downs Fault.

North of Bulloo Downs the dolomite unit is absent, its place being taken by a succession of shale, sandstone, and rare dolomite overlying the basal unconformity. Although extensive Cainozoic deposits largely obscure the bed-rock, these rocks are thought to be equivalent to the Top Camp Dolomite, in which the dolomite members lens out to the east.

FORDS CREEK SHALE, MOUNT VERNON SANDSTONE, AND KURABUKA FORMATION

Along the regional axis of the basin, the northern facies shares the same upper three formations as the western facies, so that the Top Camp Dolomite is equivalent to the Coodardoo Formation and all the units below it.

In the Bulloo Downs area fine-grained laminated dolomite beds, some extensively stained by manganese, are present in the Fords Creek Shale. The upper portion of the Fords Creek Shale in the eastern Lofty Range grades into the Mount Vernon Sandstone through a 450 m thick transition zone represented largely by fine-grained sandstone and coarse-grained siltstone. Some thin glauconitic sandstone beds occur.

EASTERN FACIES

Four formations are recognized in this facies.

COOBARRA FORMATION

This thick accumulation of coarse-grained sandstone and conglomerate, analogous to the Mount Augustus Sandstone and Tringadee Formation, unconformably overlies a basement inlier of sheared granitic rocks. In its northwest extent, conglomerate makes up about half of this formation, but elsewhere sandstone predominates. The conglomerate contains well-rounded pebbles, cobbles, and boulders of vein quartz, together with clasts of jaspilite-bearing conglomerate that may be derived from the Lower Proterozoic Labouchere Formation (Barnett, 1975) on the southern margin of the Bangemall Basin. Other clasts include sandstone of intraformational derivation. The sandstones of the formation are medium to coarse-grained, moderately to well-sorted, pebbly quartz arenites. Cross-stratification is common.

Bedding trends in the formation are continuous with those in the adjoining Kiangi Creek Formation to the west, and the two units are equivalent in part (Fig. 39). The upper beds of the Kiangi Creek Formation overlie the western portion of the Coobarra Formation and consist of fine-grained, laminated dolomite, dolomitic sandstone, medium-grained quartz arenite, and minor siltstone and shale. The eastern portion of the Coobarra Formation is overlain by the Backdoor Formation. The base of the lowest siltstone or shale member of an overlying formation marks the top of the Coobarra Formation.

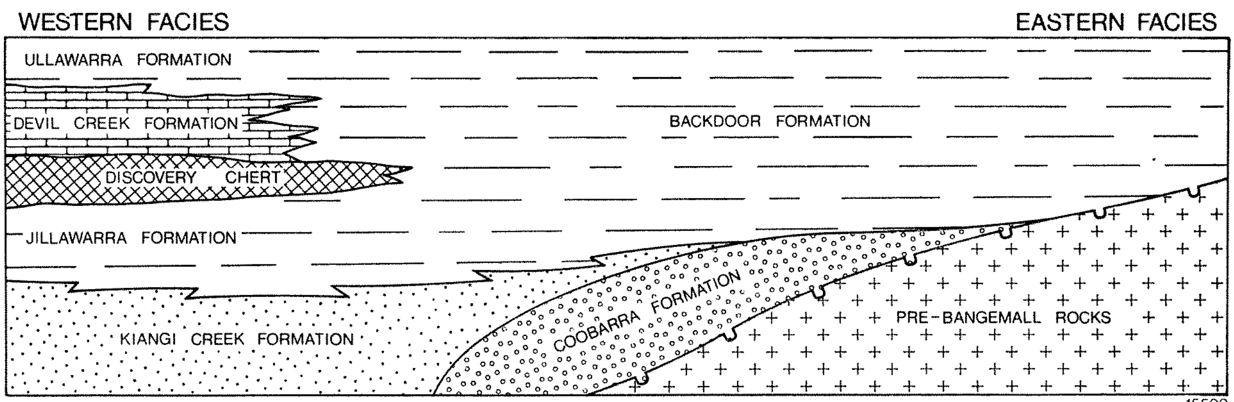


Figure 39. Diagrammatic section showing east-west facies changes in the Coobarra Creek district. Not to scale.

The Coobarra Formation originated as a terrestrial alluvial fan, in which the proportion of gravel and the grain size of the sand decreased away from the source area. Where the fan entered the sea, reworking of the material by wave action in beach and near-shore conditions resulted in sorting of the sand to produce the Kiangi Creek Formation. Piedmont deposition was ended by a marine transgression.

A rhyolite flow about 30 m thick occurs near the base of the sequence in the northwestern part of the outcrop area. The rock is very fine grained, has prominent flow banding, and contains pseudomorphs of beta quartz. This is the only confirmed outcrop of felsic volcanic rock discovered in the Bangemall Group.

*BACKDOOR FORMATION**

This lowest, laterally extensive formation of the eastern facies consists of shale and siltstone, with lesser amounts of chert, claystone, and lenses of dolomite and sandstone. Cubic crystal casts after pyrite are locally abundant. The siltstones are either laminated or massive and are of two types: a soft, earthy rock with a similar composition to the shale; and a hard, grey-white, siliceous, quartzose to feldspathic type which grades into fine-grained sandstone. Some of the chert is similar in appearance to the Discovery Chert and the chert beds in the Jillawarra Formation. A black, planar-bedded, silicified, cherty shale occurs at the top of the formation in the central part of the basin.

South of Kumarina, this formation lies on the basal unconformity, but at Wonyulgunna Hill a medium-grained quartz arenite occurs. Generally, in the transition area between the eastern and western facies the formation overlies the Devil Creek Formation. However, where the Devil Creek Formation and the Discovery Chert lens out, the lutite sequence extends down to the Jillawarra Formation level, and in the Coobarra Creek district overlies the Kiangi Creek and Coobarra Formations.

---

* Name requires approval.

The sequence was deposited in a marine shelf environment, which was shallow enough to allow the formation of carbonates in places.

CALYIE SANDSTONE

Overlying the Backdoor Formation is the Calyie Sandstone, a prominent sandstone unit over 1 000 m thick. Beds are up to 3 m in thickness and are uniform in composition and grain size. Current grooving, ripple marks, and cross-stratification are present. Pyrite casts are present but uncommon, and fragments of siltstone are widespread. The rock is usually a medium-grained quartz arenite but both finer and coarser-grained feldspathic beds also occur, as well as interbeds of shale and siltstone. In the Kumarina area a glauconitic sandstone bed 10 m thick forms the base of the unit. The upper and lower limits of the formation are respectively regarded as the youngest and oldest laterally persistent sandstone member in this stratigraphic interval.

The unit forms a regionally uniform sheet about 150 km long in the area dealt with here, but it extends at least another 220 km farther east. It is considered to be a marine deposit.

ILGARARI BEDS

This is the top unit of the eastern facies, and consists chiefly of earthy white and brownish shale, siltstone, claystone, and fine-grained sandstone. Less commonly it is a hard, white quartz siltstone which grades into a fine-grained cross-stratified sandstone. In the area about 12 km east of Ilgarari thick manganese staining occurs in places on outcrops. The unit forms poor outcrops and its top has been eroded. It is thought to be a marine deposit.

CORRELATION OF EASTERN FACIES

The bottom portion of the Backdoor Formation is equivalent to the Jillawarra and Ullawarra Formations of the western facies, so that deposition was also contemporaneous with the Discovery Chert and Devil Creek Formation of the western facies. The relative stratigraphic position of the younger rocks of the eastern facies is uncertain. The Calyie Sandstone may be equivalent to either the Mount Vernon Sandstone or the Coodardoo Formation.

In the first case, the Fords Creek Shale correlates with the higher beds of the Backdoor Formation while the Kurabuka Formation is represented by the Ilgarari Beds. This necessitates major facies changes close to the Lofty Range and Neds Gap Faults. Green, fissile shales and mudstones are common in the Fords Creek Shale north of the Lofty Range, but this rock type is uncommon in the Backdoor Formation where grey, less fissile rocks predominate. The Calyie Sandstone east of Neds Gap Fault is thinner than the Mount Vernon Sandstone to the west and has no corresponding transition zone of fine-grained sandstone and coarse-grained siltstone at its base. The Kurabuka Formation is largely made up of greenish shale, mudstone, and chert, whereas the Ilgarari Beds contain white and brownish shale, mudstone, and fine-grained sandstone. Green rocks are rare in the latter unit, and have not been found at a depth of 60 m in the copper mine at Ilgarari.

Alternatively the Calyie Sandstone can be analogous to the stratigraphically lower Coodardoo Formation. It may therefore have been deposited in response to the same regional tectonic conditions, although the two formations were never physically continuous. The Ilgarari Beds then correlate with the basal portion of the Fords Creek Shale, and the black, planar-bedded chert at the top of the Backdoor Formation could be equivalent to the Curran Formation. However, there are also difficulties with this interpretation. There is no corresponding sandstone unit in the northern facies sequence, so that the thinning of the sandstone already noted north of Ilgarari would have to proceed to zero in the entire region north of the Lofty Range Fault. Another difficulty is the juxtaposition of the Calyie Sandstone with the Mount Vernon Sandstone across the Neds Gap Fault which would be a remarkable coincidence considering the large displacement required.

At present, the evidence for either view is inconclusive.

STRUCTURE AND TECTONICS

The Hamersley Basin is known to have been stabilized before deposition of the Bangemall Group, and in discussing basement—cover relationships, the informal term "Hamersley craton" is used here for the crustal block of Hamersley Basin rocks that form a basement to the Bangemall Group.

Two major fold trends are present in the Bangemall Basin. The dominant trend is arcuate from southeast to easterly, and is parallel to the major lithological and structural trend in the Hamersley craton (Daniels, 1966b). The other trend is a northeast to easterly arcuate trend which is roughly parallel to the northern margin of the Yilgarn Block (Fig. 40). Dips in the Bangemall Basin vary from horizontal to vertical, and even slightly overturned. Fold styles are essentially concentric, with well-developed, broad synclines and poorly developed cuspate anticlines. Slaty cleavage is only sporadically developed and metamorphism is minimal.

Regional variations in the intensity and orientation of folds outline four major structural provinces (Fig. 41). It is postulated that these provinces relate directly to the nature of the underlying basement.

NORTHERN PROVINCE

The Bangemall Basin is broadly synclinorial. The southern flank, which contains numerous folds, contrasts with the gently dipping northern flank. The northern province includes this northern limb which is a relatively undeformed apron around the periphery of the Hamersley craton.

WESTERN PROVINCE

This province extends in width from the synclinorial axis to the southern margin of the basin. It is characterized by relatively tight folds that have the typical southeasterly trend of Edmundian folds. Slaty cleavage is more common than in the other provinces. There is no diminution in intensity of folding at the southern margin, and some of the folds are slightly overturned to the north. The outliers of Bangemall Group in the Ti-tree and Mangaroon folds are tight synclinal keels.

Typically the folds are doubly plunging with lengths along the axes of about 20 to 75 km. The terminations of these folds usually occur in northeasterly trending zones. Palaeogeomorphic highs of basement rock are exposed through the Bangemall Group and form marked indentations in its southern margin, and some of these basement highs are the loci of basal conglomeratic beds. All these features together delineate northeasterly trending regional arches.

EASTERN PROVINCE

In the southeastern part of the basin, folding is gentle and is characterized by irregular-shaped domes and basins having a dominant east-northeast direction. Major faults are absent and the structural style indicates a stable basement.

INTERMEDIATE PROVINCE BETWEEN EASTERN AND WESTERN PROVINCES

This province is characterized by elongate folding with a principal direction that is distinctly arcuate from northeast to easterly. The boundaries of this intermediate province are defined by northeasterly trending lineaments which persist well to the northeast beyond the intermediate zone. The eastern boundary against the eastern province is marked by the Tangadee Lineament, which is expressed by two important features. Firstly there is a line of basement inliers that were highs during initial Bangemall Group sedimentation, and which influenced the formation of wedges of basal conglomerate and sandstone. Secondly there is a line of east-southeasterly or easterly trending faults arranged *en echelon*. One of these faults is arcuate, being convex to the north, and has a south-side-up movement. However, the northernmost faults on this line are parallel to the lineament and cut the easterly trending folds.

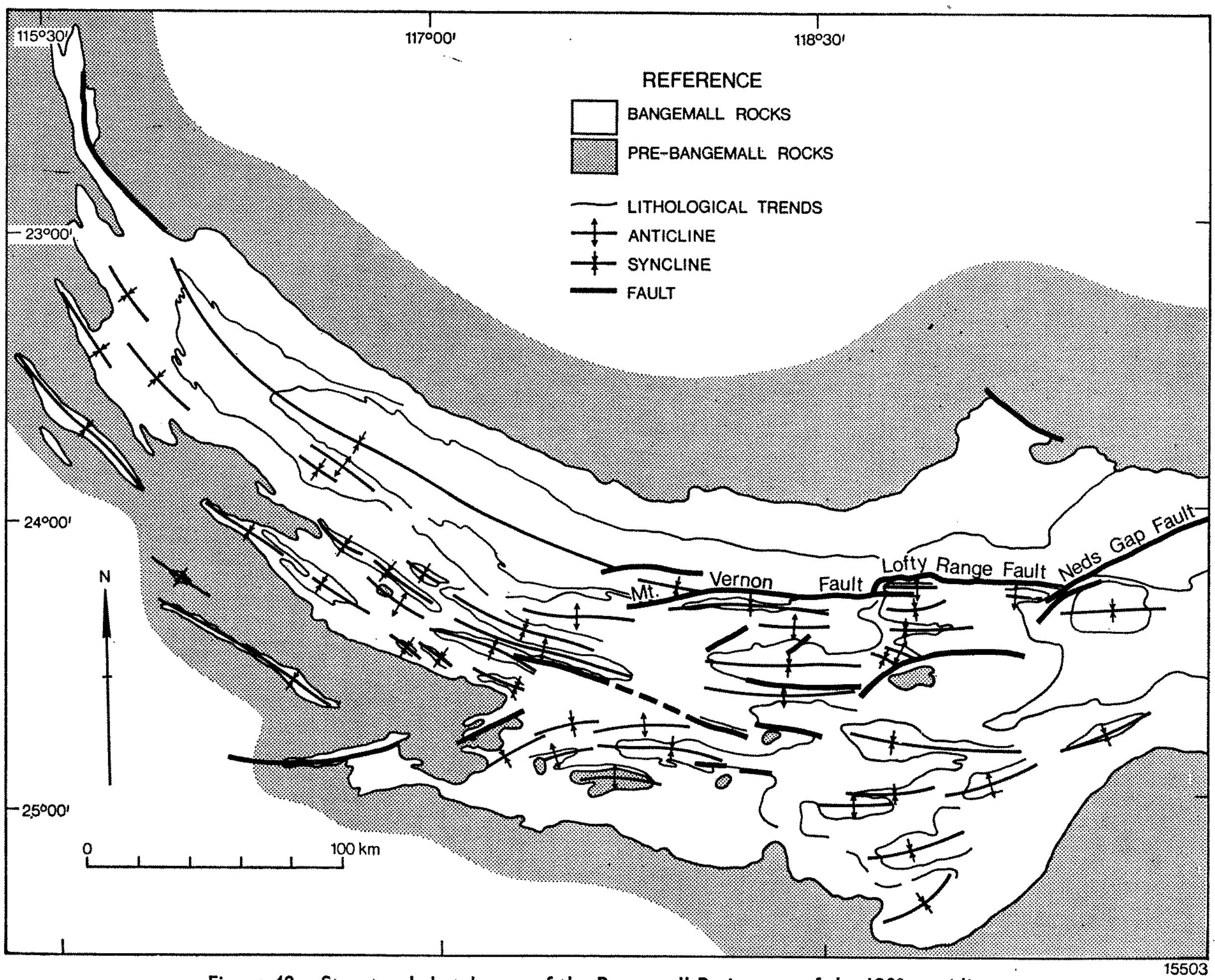


Figure 40. Structural sketch map of the Bangemall Basin west of the 120° meridian.

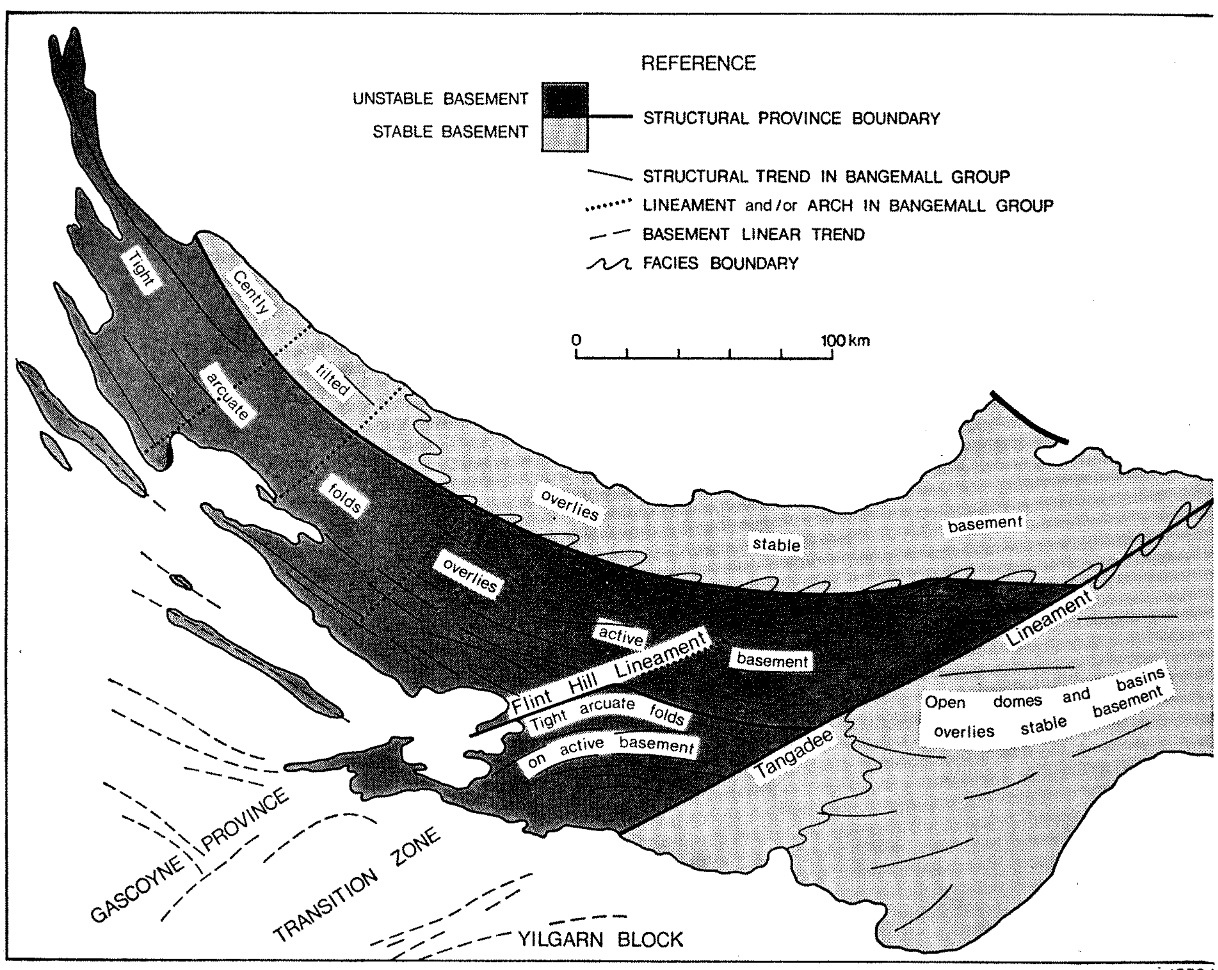


Figure 41. Structural provinces of the western and central Bangemall Basin.

The boundary of the transitional zone with the western province is called the Flint Hill Lineament. Apart from being a conspicuous photolineament, it is a line of structural mismatch whereby the southeasterly trending folds of the western province are replaced by northeasterly trending folds. Easterly trending faults in the central part of the basin and north of the intermediate province cut the axial trend of the east-southeasterly trending folds, and some of these faults are known to be south-side-up thrusts.

The age relationship of the northeasterly trending folds and the more typical southeasterly trend is uncertain and no superposition has been recognized. However, the deformation styles, which are notable for the paucity of cleavage make this relationship inconclusive. There is no marked mismatch of stratigraphy across the Flint Hill Lineament so that it is not interpreted as a sinistral wrench fault that dragged easterly trending folds into a northeasterly direction. Instead the regional fold patterns suggest synchronous formation of folds of all trends by independently behaving basement segments.

RELATION OF STRUCTURAL PROVINCES TO BASEMENT

A notable feature of fold trends in most of the Bangemall Basin, and especially the western province, is the parallelism with earlier Ophthalmian fold trends in the Hamersley craton (Daniels, 1966b), and those in the Gascoyne Province. A basement control to the Edmundian folding is therefore indicated. The transitional boundary between the northern and western structural provinces in the overlying Bangemall Group may reflect the position of the southern margin of the buried Hamersley craton.

Similarly, the northeast trend of the eastern province parallels the structural trend in the northern periphery of the Yilgarn Block, and a similar basement control is indicated. However, the irregular style of folding suggests an interaction with the trend of the western province.

The nature of the boundary between the Gascoyne Province and the Yilgarn Block is not properly understood at present, but it appears that on approaching the Yilgarn Block, the southeast trends of the Gascoyne Province are intersected by northeast trends that parallel those in the Yilgarn Block. The transitional zone is a migmatite complex about 70 km wide, trending northeast. The boundaries of this zone, when extrapolated into the Bangemall Basin correspond with the boundaries of the intermediate province, namely the Flint Hill and Tangadee Lineaments.

The structural provinces in the Bangemall Basin therefore appear to reflect movement of basement blocks, which formed by segmentation along the buried boundaries of the Hamersley craton, Gascoyne Province, and Yilgarn Block.

RELATION OF SEDIMENTATION TO TECTONICS

There is a correlation between the major sedimentary facies boundaries and structural province boundaries. Thus the change from the western to the eastern facies corresponds roughly to the Tangadee Lineament. Similarly, the northern facies corresponds largely with the northern structural province and the western facies occurs wholly within the western province.

Furthermore, there is a relationship between the complexity of sedimentation and the degree of deformation. Thus the stratigraphically simple northern facies is little deformed, whereas the western facies, which shows complex relationships between many stratigraphic units, is more strongly deformed. These regional variations in the style of sedimentation were therefore controlled by the stabilities of the individual basement segments.

CONCLUSIONS

The sedimentary history of the Bangemall Basin is one of progressive extension of the area of deposition accompanied by a marine transgression from west to east. Possible entrances for the sea were to the northwest through the Wyloo Sheet area and to the west across the Gascoyne Mobile Belt.

Early deposition was restricted to the region west of the 119°E meridian. Alluvial fans advanced into the basin from local topographic high points, and there was a gentle seaward gradient from the shoreline with a very broad intertidal and shallow lagoonal zone, in which the Irregully Formation and lower Top Camp Dolomite were laid down. The Kiangi Creek Formation originated as sandy shoals and islands near the basin axis. As the area of deposition extended, these zones migrated outwards, especially towards the south, and laminated muds of the Jillawarra Formation settled out of suspension in the deeper water. Lateral movements of province boundaries resulted in complex interfingering of the various sediments. The more pronounced and fluctuating migration of the southern margin can be attributed to a more tectonically active segment of basement rocks underlying this region. If the interpretation of some crystal casts as evaporite minerals is correct, there were periods when the water in the basin was restricted and hypersaline. During such a stagnant period, when tectonic conditions were quiet, the Discovery Chert was precipitated in shallow water, perhaps on a tidal flat over most of the existing basin area. Carbonates and muds of the Devil Creek Formation were deposited in lagoonal and shoal environments, while farther out to sea, muds of the Ullawarra Formation were laid down. The absence of medium-grained quartz sand in the shoal zone at this time reflects a lack of supply due to tectonic inactivity in the hinterland. Meanwhile, the sea was transgressing eastwards. Here fine-grained sediments were deposited on a fairly stable basement and the environment was generally unsuitable for the formation of carbonates except locally. Later sedimentation in the west took place on an open marine shelf and resulted in laterally extensive lutite formations in which green shales are conspicuous. At times, such as when the Curran Formation was deposited, tectonic conditions were quiet. On other occasions tectonic movements affected the basin hinterland and renewed the supply of sand, causing sheets of the material to cover large areas. At least one of these sheets was introduced into the basin by turbidity flows, and all show signs of working by bottom traction currents. Subsequently, barrier bar and lagoonal environments appear to have prevailed, and this shallowing of the basin could have been a prelude to the end of deposition.

After sedimentation ceased, the intrusion of dolerites and the movements of the Edmundian Fold Period took place. In the older crust activity on the boundaries of the basement tectonic units increased. Those segments which had shown greatest instability during sedimentation were again the most active, and the folding in the sedimentary cover overlying them was consequently most intense.

REFERENCES

Barnett, J. C., 1975, Some probable Lower Proterozoic sediments in the Mount Padbury area: West. Australia Geol. Survey Ann. Rept. 1974, p. 52-54.

Compston, W., and Arriens, P. A., 1968, The Precambrian geochronology of Australia: Canadian Jour. of Earth Sciences, v. 5, p. 561-583.

Conybeare, C. E. B., and Crook, K. A. W., 1968, Manual of sedimentary structures: Australia Bur. Mineral Resources Bull. 102, p. 32.

Daniels, J. L., 1965, Breccias associated with the Proterozoic Bangemall Group, North West Division: West. Australia Geol. Survey Ann. Rept. 1964, p. 34-36.

——— 1966a, Revised stratigraphy, palaeocurrent system and palaeogeography of the Proterozoic Bangemall Group: West. Australia Geol. Survey Ann. Rept. 1965, p. 48-56.

——— 1966b, The Proterozoic geology of the North-West Division of Western Australia: Australasian Inst. Mining Metall. Proc. No. 219, p. 38-46.

——— 1968, Turee Creek, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

———1969, Edmund, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

——— 1970, Wyloo, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Daniels, J. L., and MacLeod, W. N., 1965, Newman, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

de la Hunty, L. E., 1964, Balfour Downs, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Gee, R. D., de Laeter, J. R., and Drake, J. R., 1976, Geology and geochronology of altered rhyolite from the lower part of the Bangemall Group near Tangadee: West. Australia Geol. Survey Ann. Rept. 1975, p. 112.

Glaessner, M. F., Preiss, W. V., and Walter, M. R., 1969, Precambrian columnar stromatolites in Australia. Morphological and stratigraphic analysis: Science, v. 164, p. 1056-1058.

Hall, W. D. M., and Goode, A. D. T., 1975, The Nabberu Basin: A newly discovered Lower Proterozoic Basin in Western Australia: Geol. Soc. Australia, First Australian Geol. Convention, Abs., p. 88-89.

Halligan, R., and Daniels, J. L., 1964, Precambrian geology of the Ashburton Valley region, North-West Division: West. Australia Geol. Survey Ann. Rept. 1963, p. 38-46.

Horwitz, R. C., 1975, Provisional geological map at 1:2 500 000 of the Northeast Margin of the Yilgarn Block, Western Australia: Australia C.S.I.R.O. Mineral Investig. Rept. No. F.P. 10.

MacLeod, W. N., 1970, Peak Hill, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Muhling, P. C., Brakel, A. T., and Davidson, W. A., in prep., Mount Egerton, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Walter, M. R., 1972, Stromatolites and the biostratigraphy of the Australian Precambrian and Cambrian: Palaeont. Assoc. Spec. Papers in Palaeontology, No. 11, 190 p.

Williams, I. R., Brakel, A. T., Chin, R. J., and Williams, S. J., 1976, The stratigraphy of the eastern Bangemall Basin and the Paterson Province: West. Australia Geol. Survey Ann. Rept. 1975, p. 79.

THE STRATIGRAPHY OF THE EASTERN BANGEMALL BASIN AND THE PATERSON PROVINCE

by I. R. Williams, A. T. Brakel, R. J. Chin, and S. J. Williams

ABSTRACT

Stratigraphic reappraisals of the Paterson Province and northeast part of the Bangemall Basin, east of the Hamersley Basin and Pilbara Block, Western Australia, have produced important changes in the interpretation of the Proterozoic sequences of the region.

The oldest rocks of the area are the gneisses, schists, and igneous rocks of the Rudall Metamorphic Complex which forms the core of the Paterson Province. This metamorphic domain is unconformably overlain by the Yeneena Group, a moderately to strongly folded and faulted, mixed sedimentary succession of ?Lower or Middle Proterozoic age. Four formations, the basal Coolbro Sandstone, the Broadhurst Formation, the Choorun Formation, and the Isdell Formation are recognized within it in the Rudall Sheet area.

An unconformity is present between the Yeneena Group and the flat-lying to gently folded Middle Proterozoic Bangemall Group, which consists largely of sandstone. Two formations, the Skates Hills Formation and the McFadden Sandstone, comprise the Bangemall Group in its northeastern and eastern extent, while three formations, the Calyie Sandstone, the Backdoor Formation, and the Wonyulgunna Sandstone, believed to be facies equivalents, are present to the west.

The Bangemall Group—Yeneena Group boundary, regarded as the margin of the Bangemall Basin, can be traced southeasterly across the Rudall and Gunanya Sheet areas. An inlier of ?Lower Proterozoic sedimentary rocks is exposed in the southeast quadrant of the Trainor Sheet area. These older rocks may be correlatives of the Yeneena Group to the north or the Nabberu Basin rocks which lie to the south.

The McFadden Sandstone is unconformably overlain by small areas of the Proterozoic Durba Sandstone.

An isolated and uncorrelated, folded and faulted Proterozoic sedimentary sequence, the Karara Beds, is unconformable on the Rudall Metamorphic Complex and the Yeneena Group in the vicinity of Karara Well.

INTRODUCTION

This report outlines important stratigraphic reappraisals of the Proterozoic sedimentary sequences in the eastern part of the Bangemall Basin and the Paterson Province. The area, shown on Figure 42, lies largely in the southwestern part of the Great Sandy Desert and covers all of the Rudall, Gunanya, Trainor, and Buller 1:250 000 Sheet areas, and parts of the Paterson Range, Balfour Downs, Tabletop, Runton, Madley, and Stanley Sheet areas.

The significant changes to the 1973 edition of the Geological Map of Western Australia following recent mapping in this region are: the location of the northeastern margin of the Bangemall Group; the identification of a sedimentary sequence called the Yeneena Group, which unconformably underlies the Bangemall Group, and which forms the cover sequence of the Paterson Province; the extension of the Rudall Metamorphic Complex much farther to the southeast; the detection of an isolated sedimentary sequence of uncertain age but unconformable on the Yeneena Group in the Karara Well area; the recognition of a younger sandstone formation unconformably overlying the Bangemall Group at Durba Hills; and the discovery of an inlier of pre-Bangemall Group rocks in the southeast of the Trainor Sheet area. The derivation and detailed description of the type areas and sections for the Proterozoic units are given in the following Explanatory Notes, in preparation, belonging to the G.S.W.A. 1:250 000 Geological Series: Rudall (Chin and others), Runton (Crowe and Chin), Gunanya (I. Williams and S. Williams), and Trainor (Leech and Brakel).

The stratigraphy, as it is now understood, is shown in Table 22 and the regional distribution of the units is given on Figure 42.

TABLE 22. STRATIGRAPHY OF THE EASTERN BANGEMALL BASIN AND THE PATERSON PROVINCE

Buller 1:250 000	Trainor 1:250 000	Gunanya-Rudall 1:250 000	Tabletop-Runton 1:250 000
	Durba Sandstone	Durba Sandstone	
	unconformity	unconformity	
BANGEMALL GROUP: Calyie Sandstone	BANGEMALL GROUP: McFadden Sandstone	BANGEMALL GROUP: McFadden Sandstone	Karara Beds?
Backdoor Formation	Skates Hills Formation		
Wonyulgunna Sandstone			
	unconformity	unconformity	
	Unnamed ? Lower Proterozoic Formation	YENEENA GROUP: Isdell Formation	YENEENA GROUP
		Choorun Formation	
		Broadhurst Formation	
		Coolbro Sandstone	
		unconformity	unconformity
		RUDALL METAMORPHIC COMPLEX	RUDALL METAMORPHIC COMPLEX

RUDALL METAMORPHIC COMPLEX

The Rudall Metamorphic Complex forms the basement rocks in the Paterson Province. The complex extends for 100 km east-southeasterly through the Rudall, Gunanya, and Tabletop Sheet areas to the Runton Sheet area where it is unconformably overlain by Phanerozoic sedimentary rocks of the Canning Basin. A small inlier occurs in the McKay Range on the northern edge of the Gunanya Sheet area.

The complex is composed of two main lithological assemblages which are not distinguished on Figure 42. A gneissic assemblage is perhaps the oldest and consists largely of orthogneiss, gneissic amphibolite, and paragneiss. The gneisses have undergone retrograde metamorphism during a later period of metamorphism and deformation. This later period has also involved a second and possibly younger group of metasedimentary rocks including mainly quartzite and quartz-mica schist. Both assemblages have undergone polyphase deformation. Several periods of granitic, mafic, and ultramafic intrusions are evident.

YENEENA GROUP

The Rudall Metamorphic Complex is unconformably overlain by a thick ?Lower or Middle Proterozoic clastic and carbonate succession called the Yeneena Group. The unconformity is complexly folded and faulted, and along the western margin of the Rudall Metamorphic Complex thrusts, high-angle reverse faults, and fold axial planes in the Yeneena Group dip consistently northeast. The lower units of the Yeneena Group have undergone low-grade dynamic metamorphism. Both metamorphism and deformation decrease westwards in the Yeneena Group.

The group occupies the northwestern, northern, and central western parts of the Rudall Sheet area. It extends northwards across the western margin of the Paterson Range Sheet area and marginally into the Nullagine Sheet area (Hickman, 1975) where it unconformably overlies crystalline rocks and Lower Proterozoic sedimentary rocks in the Gregory Range area. The group also extends westwards into the Balfour Downs Sheet area (de la Hunty, 1964) where it unconformably overlies the Fortescue Group. On both sheets the unit has been called the Bocrabee Sandstone.

The Yeneena Group can also be traced southeastwards through the McKay Range, across the Gunanya Sheet area to the Lady Victoria Hills and into the Runton and Madley Sheet areas where it crops out in the Runton Range and Constance Headland.

A large inlier of folded and faulted Proterozoic rocks around the Telfer gold deposits in the Paterson Range Sheet area is believed to be equivalent to the higher formations in the Yeneena Group. In this area the succession has been intruded by granite at Mount Crofton which has been dated at 614 ± 42 m.y. (Trendall, 1974).

Four constituent formations are recognized in the Rudall Sheet area, but because of the discontinuous nature of the exposures, it is not possible to assign all the Yeneena Group rocks to formations.

COOLBRO SANDSTONE

The basal unit is the Coolbro Sandstone, a predominantly medium-grained quartz sandstone that is commonly cross-bedded. It contains at the base a discontinuous but locally conspicuous conglomerate unit with minor shale and siltstone beds. The clasts in the conglomerate are derived from the underlying metamorphic complex.

The Coolbro Sandstone is well exposed in the north central part of the Rudall Sheet area around Coolbro Creek and in the Throssell Range but it thins rapidly southwestward.

BROADHURST FORMATION

The Coolbro Sandstone is unconformably overlain by the poorly exposed Broadhurst Formation which consists of interbedded micaceous siltstone, mudstone, shale, graphitic shale, and fine-grained sandstone. Phyllite and graphitic shales occur in the vicinity of the Three Sisters Hills. The formation crops out in the Broadhurst Range and in the Three Sisters Hills area.

CHOORUN FORMATION

The Broadhurst Formation is comformably overlain by the Choorun Formation, a thick interbedded unit of fine to coarse-grained sandstone, micaceous siltstone, quartz pebble conglomerate, calcareous mudstone, and shaley dolomite. The formation occupies much of the central western part of the Rudall Sheet area and extends into the Balfour Downs Sheet area.

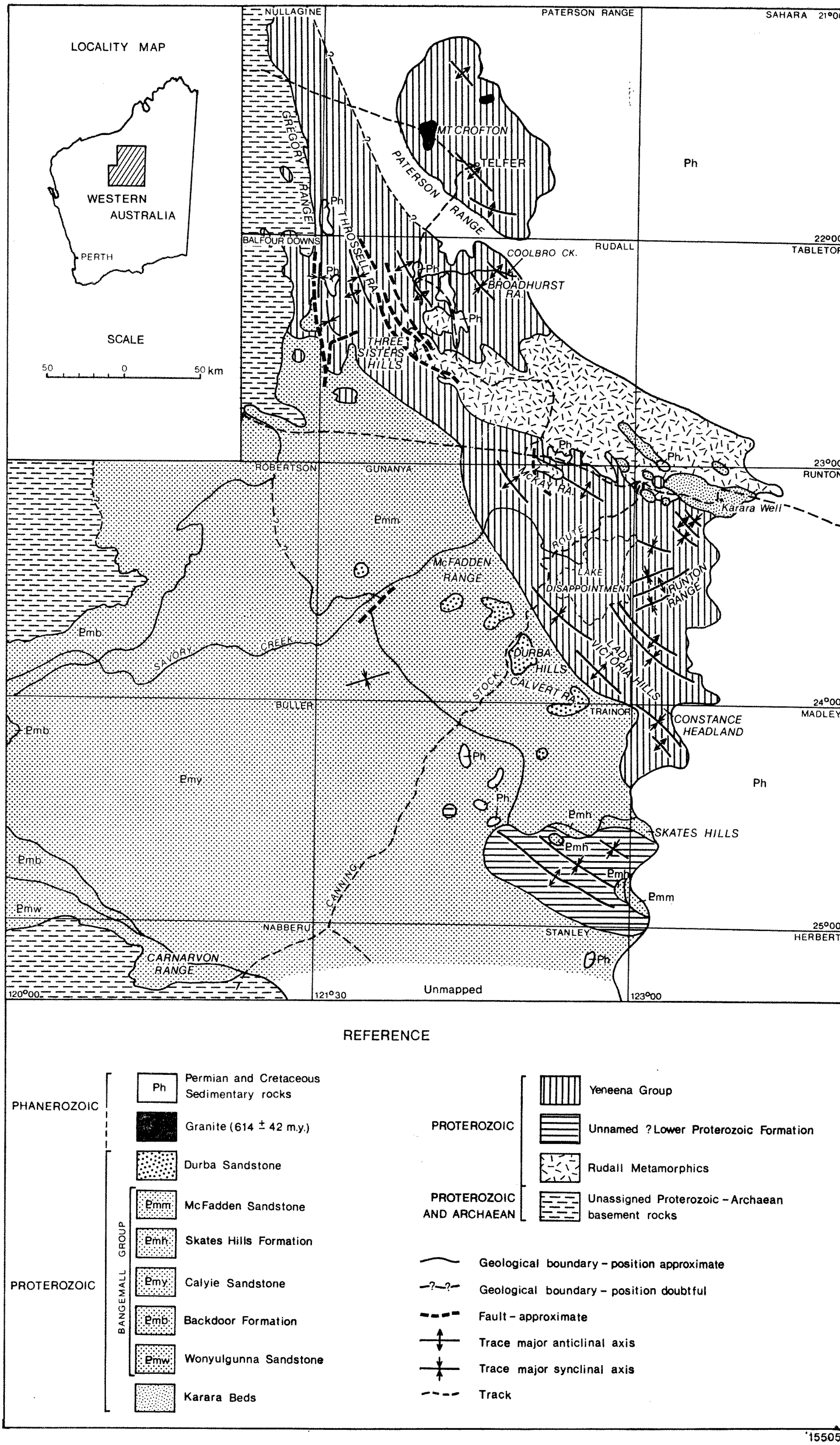


Figure 42. Solid geology of the eastern Bangemall Basin and Paterson Province.

54809—(6)

ISDELL FORMATION

The uppermost formation of the Yeneena Group in the Rudall Sheet area is the Isdell Formation. It is predominantly dolomite and dolomitic shale, with variable amounts of interbedded sandstone, siltstone, and minor pebble conglomerate. The clastic components increase westwards. The formation occurs in a major synclinal structure in the northwest and along the north central margin of the Rudall Sheet area. This formation, and possibly the upper part of the Choorun Formation, may be correlatives of the carbonate-clastic sequences in the Paterson Range Sheet area.

KARARA BEDS

Near Karara Well, in the Runton Sheet area, a sequence of folded conglomerate, sandstone, and minor siltstone and dolomite lies unconformably on both the Yeneena Group and the Rudall Metamorphic Complex. These are called the Karara Beds and occur in a number of scattered, disconnected outcrops in the adjacent corners of Rudall, Tabletop, Runton, and Gunanya Sheet areas. Their regional stratigraphic position is uncertain. They may correlate with the Bangemall Group, the Durba Sandstone, or rocks to the south in the Runton Sheet area at present placed in the Yeneena Group.

They may also constitute a completely separate sequence, represented by erosional or non-depositional periods elsewhere in the Proterozoic succession.

UNASSIGNED ?LOWER PROTEROZOIC ROCKS IN THE TRAINOR SHEET AREA

An unnamed ?Lower Proterozoic formation occurs as an inlier in the southeastern portion of the Trainor Sheet area, and adjacent part of the Madley Sheet area. It is a hard siliceous sandstone unit with some micaceous siltstone and shale lenses. The sandstones vary from massively bedded to laminated quartz arenites. Cross-bedding is widespread but not conspicuous in outcrop.

The formation is overlain by gently dipping Bangemall Group rocks. Along the northern margin of the inlier there is a strong angular unconformity between the Bangemall Group rocks and the older rocks. However, along the southern margin both units dip in the same direction, so that the contact, which is not exposed, appears to be disconformable.

The traces of the major fold axes are parallel to those in the Yeneena Group rocks farther north (Fig. 42). However, direct correlation is not possible at this stage and the rocks may be the time equivalent of part of the Nabberu Basin sequence to the south, or the Yeneena Group to the north.

BANGEMALL GROUP

The Middle Proterozoic Bangemall Group occupies over half the area under discussion and its extent can now be taken as the limit of the Bangemall Basin. Most of its constituent formations are not developed over the whole region because of lateral facies changes.

SKATES HILLS FORMATION

At the base of the Bangemall Group in the Skates Hills (Madley Sheet area) and parts of the southeastern Trainor Sheet area is a succession of conglomerate, interbedded sandstone, shale, and siltstone, and finally stromatolitic dolomite, termed the Skates Hills Formation. The unit varies in thickness and lenses out in places. The basal boulder-bearing cobble conglomerate is likewise lenticular. The formation rests unconformably on the unnamed ?Lower Proterozoic sandstone unit mentioned previously.

McFADDEN SANDSTONE

The Skates Hills Formation is conformably overlain by the McFadden Sandstone. This formation consists largely of quartzose and feldspathic arenite and wacke. It is characterized by flaggy, well-laminated beds, and cross-bedding sets up to 8 m thick. Pebble and granule-bearing rocks are common.

The McFadden Sandstone unconformably overlies the Yeneena Group along the northeastern margin of the Bangemall Basin. It is also unconformable on the ?Lower Proterozoic sandstone unit in the southeast quadrant of the Trainor Sheet area. Westwards, the unit loses its characteristic features and it appears to grade laterally into the Calyie Sandstone.

In the southwestern corner of the Gunanya Sheet area around Savory Creek it appears to overlie part of the Calyie Sandstone. The extent of the unit in the adjoining Robertson Sheet area is unknown. The formation is best developed in the McFadden Range and is unconformably overlain by the Durba Sandstone in the Durba Hills and Calvert Range.

CALYIE SANDSTONE

The western half of the Trainor Sheet area and most of the Buller Sheet area are occupied by a sandstone unit which is a continuation of the Calyie Sandstone defined on the adjacent Collier Sheet area (Brakel and Muhling, 1976). The unit consists mainly of flat-lying and gently dipping quartz arenite with minor siltstone and conglomerate lenses.

The formation grades into the McFadden Sandstone and disconformably overlies the ?Lower Proterozoic sandstone unit in the southeast Trainor Sheet area.

BACKDOOR FORMATION

The Backdoor Formation is a sequence of shale, siltstone, chert, and fine-grained sandstone that occurs in the western part of the area under discussion. It also crops out extensively in the Collier Sheet area (Brakel and Muhling, 1976). It conformably underlies the Calyie Sandstone but appears to lens out near the boundary of the Nabberu Sheet area. The shale and siltstone of the "Manganese Group" (de la Hunty, 1969) which conformably underlies the Calyie Sandstone in the centre of the Robertson Sheet area are presumed to correlate with the Backdoor Formation.

WONYULGUNNA SANDSTONE

The newly recognized Wonyulgunna Sandstone is a prominent ridge-forming unit which lies conformably beneath the Backdoor Formation.

It unconformably overlies a basement that consists of schist and metamorphosed banded iron-formation intruded by granite.

DURBA SANDSTONE

The Durba Sandstone is a flat-lying, massive quartz arenite which unconformably overlies the McFadden Sandstone in the Gunanya and Trainor Sheet areas. The formation occurs as a series of scattered outliers situated along a rough southeasterly trend which may represent a very shallow depositional basin aligned parallel to structural trends in the older rocks of the Paterson Province. Its age and correlation are uncertain. Lithologically similar sandstone is present within the Calyie Sandstone in the Buller Sheet area, so that the Durba Sandstone may belong to the Bangemall Group, the unconformity being only of local significance. Alternatively the deposit may be of post-Bangemall Group age, representing a last, brief, and limited return of deposition at the close of the Proterozoic sedimentation in the region.

PHANEROZOIC ROCKS

A number of scattered Permian outliers of the glacigene Paterson Formation occur in the Paterson Range, Rudall, and Trainor Sheet areas. The Paterson Range, southwest of Telfer, is the largest Permian outcrop area separated from the Canning Basin.

No Cretaceous rocks have been recognized beyond the main boundary of the Officer and Canning Basins.

CONCLUSIONS

The geological history of the region can be briefly summarized as follows.

The oldest rocks form the metamorphic and igneous Rudall Metamorphic Complex, in which polyphase deformation is recorded. The rocks involved are probably Lower Proterozoic in age, and may include reworked Archaean terrains.

The complex is unconformably overlain by the Yeneena Group, a sedimentary sequence which was laid down in a shallow marine shelf environment and consists largely of detritus derived from the Rudall Metamorphic Complex. Initial gravel and sand accumulation was followed by lower energy conditions indicated by alternating sand and mud, and finally carbonate, silt, sand, and gravel sedimentation. This sequence may have resulted from migrating, contemporaneously adjacent subenvironments instead of only gross temporal variation. It is likely that this probable Lower or Middle Proterozoic deposition extended over a large area beyond the present outcrop limits.

The unnamed ?Lower Proterozoic sandstone in the Trainor Sheet area may also have been deposited at this time in a near-shore location. The region was subsequently modified by tectonism which decreased in intensity to the southwest and imparted to the rocks a general northwesterly structural trend.

In the Karara Well area a sedimentary sequence, possibly developed in a discrete marine basin, was laid down after an interval of erosion had effected the Yeneena Group. The age of these sediments is uncertain.

To the southwest a marine transgression, which was part of that taking place over the area of the Bangemall Basin, led to the deposition of shelf sediments which were dominantly sand, except for some lenses of gravel and dolomite. An east to west lateral change in facies was present due to the nature of the detritus supplied to the basin and differing depositional environments, such as deeper water to the west. Later movements accompanied by dolerite intrusions, caused some mostly gentle folding. In the centre of the region a last short depositional episode represented by the Durba Sandstone occurred after some erosion of the Bangemall Group rocks, in what may have been a small, very shallow basin elongated parallel to the older structural trends. The constituent sand was quite likely reworked from the underlying sandstone.

The final Proterozoic activity took place in the northeastern district which underwent further tectonism and metamorphism accompanied by the emplacement of granites in the Paterson Range area at the close of Precambrian time. No further record of geological activity is preserved in the region until the Late Palaeozoic when widespread Permian glaciation took place.

An important result of the recent mapping is the discovery of the pre-Bangemall Group rocks along parts of the western margin of the Officer Basin. These strongly imply that the eastern limit of Precambrian outcrops also marks the real eastern edge of the structural Bangemall Basin, which would not, therefore, continue as an unbroken subsurface unit into Central Australia. Separate Middle Proterozoic basins under the Phanerozoic cover cannot be ruled out. A structural reason for the location of the western margin of the Officer Basin is also implied.

REFERENCES

Brakel, A. T., and Muhling, P. C., 1976, Stratigraphy, sedimentation, and structure in the western and central part of the Bangemall Basin: West. Australia Geol. Survey Ann. Rept. 1976, p. 70.

Chin, R. J., Williams, I. R., Williams, S. J., and Crowe, R.W.A., in prep., Explanatory notes on the Rudall 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. (unpublished).

Crowe, R. W. A., and Chin, R. J., in prep., Explanatory notes Runton, W.A. 1:250 000 Sheet: Australia Bur. Mineral Resources Rec. (unpublished).

de la Hunty, L. E., 1964, Balfour Downs, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

——— 1969, Robertson, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Hickman, A. H., 1975, Explanatory notes on the Nullagine 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1975/5 (unpublished).

Leech, R. E. J., and Brakel, A. T., in prep., Explanatory notes on the Trainor 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. (unpublished).

Trendall, A. F., 1974, The age of a granite near Mount Crofton, Paterson Range Sheet: West. Australia Geol. Survey Ann. Rept. 1973, p. 92-96.

Williams, I. R., and Williams, S. J., in prep., Explanatory notes on the Gunanya 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. (unpublished).

THE KALUWEERIE CONGLOMERATE: A PROTEROZOIC FLUVIATILE SEDIMENT FROM THE NORTHEAST YILGARN BLOCK, WESTERN AUSTRALIA

by P. D. Allchurch* and J. A. Bunting

ABSTRACT

An outlier of unmetamorphosed polymictic conglomerate and lithic arenite lying unconformably on Archaean granitic rocks, and considered to be Proterozoic in age, is interpreted as a fluviatile deposit. The sediments are immature and contain a variety of granitic and low-grade metamorphic rock fragments. The deposit is elongated east-west, is slightly sinuous, and was probably derived from the erosion of adjacent granitic rocks and the Booylgoo Range greenstone belt to the west.

The subhorizontal attitude of these beds and other probable Proterozoic outliers on the northeastern part of the Yilgarn Block, together with their lack of deformation illustrates the stability of the shield since Proterozoic times. It is suggested that the flatness of the shield surface relates to Proterozoic erosion and is not a more recent phenomenon.

INTRODUCTION

Outliers of Proterozoic sedimentary rocks from well within the area of the Archaean Yilgarn Block are rare and have not generally been recognized. The Kaluweerie Conglomerate is one such deposit. The purpose of this paper is to present a description of the rocks in the Kaluweerie Hill area, to discuss their depositional environment, and to compare them with other Proterozoic outliers in the region.

Kaluweerie Hill lies in the southwest corner of the Sir Samuel 1:250 000 Sheet area. It is approximately 620 km northeast of Perth and 140 km south of Wiluna.

---

*Australian Selection (Proprietary) Limited.

REGIONAL SETTING

The basement rocks of the area form part of the stable Archaean Yilgarn Block which consists of linear, arcuate belts of metavolcanic and metasedimentary rocks separated by large areas of granitic rocks. To the north and northeast this craton is bounded by Early and Middle Proterozoic sedimentary basins. A tongue of gently-dipping quartzite, shale, dolerite, and dolomite extends unconformably onto the Yilgarn Block as far south as Wiluna, and is the closest large area of confirmed Proterozoic sediment to the Kaluweerie area. Outliers of presumed Proterozoic sedimentary rocks also occur at Mount Lawrence Wells and Mount Yagahong (Fig. 43, insert).

The granitic rock in the vicinity of Kaluweerie Hill is mainly medium to coarse-grained adamellite, porphyritic in places, with a poorly developed foliation. Near-vertical quartz microdiorite dykes cut the adamellite. In places the dykes are distinctively vertically layered. They trend 080° and are thought to be equivalent to the Widgiemooltha Dyke Suite which is late Archaean or early Proterozoic in age. A series of quartz-filled fractures, of which Kaluweerie Hill is an example, also trend 080°, and the microdiorite dykes may be related to this fracture system. Associated with the quartz fractures is a peculiar epidote-quartz rock, which may have resulted from alteration of the adamellite during quartz deposition.

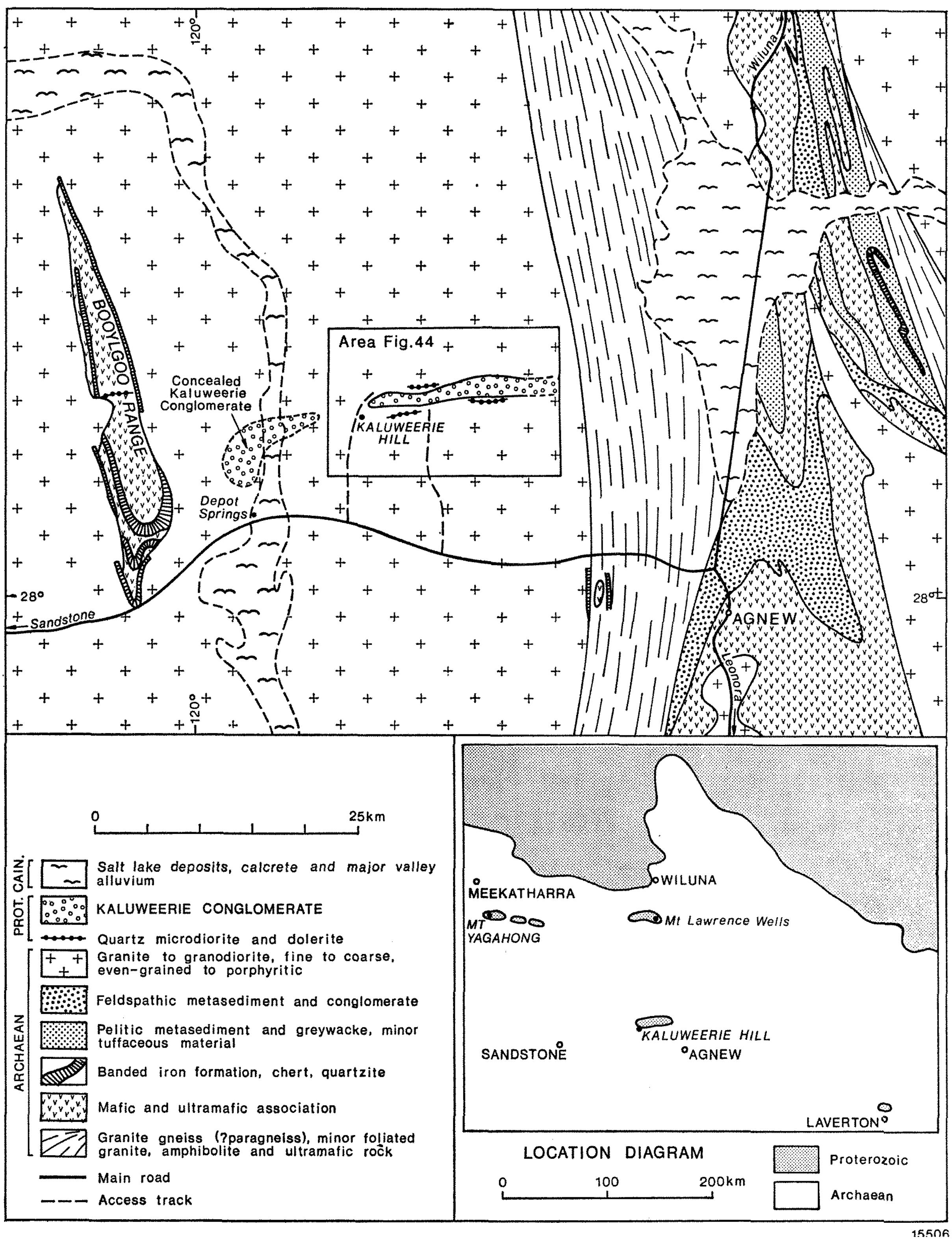


Figure 43. Regional geology, Agnew-Booylgoo Range area.

Between the adamellite and the Agnew-Wiluna greenstone belt to the east, is a poorly exposed north-trending belt of banded quartz-feldspar paragneiss with minor amphibolite, metamorphosed banded iron-formation, talc schist, and gneissic granite (Fig. 43).

THE KALUWEERIE CONGLOMERATE

The name Kaluweerie Conglomerate is proposed for a sequence of conglomerate and arenite that unconformably overlies Archaean granitic rocks and is overlain by Cainozoic superficial deposits. It is considered to be Proterozoic in age. Present exposure forms a sinuous belt trending roughly east-west, about 15 km long by 1.5 km wide (Fig. 44). The conglomerate has also been intersected in drillholes, through thin Cainozoic cover about 10 km west of the western outcrop limit. The name is taken from Kaluweerie Hill, 1 km south of the western end of the belt of outcrop. The type section is the hill at lat. 27°49′50″S, long. 120°11′40″E, 1.5 km north-northwest of Langford Well, where the maximum exposed thickness is about 25 m. In drillholes 10 km west-southwest of Kaluweerie Hill the conglomerate is 35 m thick.

LITHOLOGY

Two lithological types are present:—

(1) polymictic conglomerate and pebbly lithic arenite,

(2) fine to coarse-grained lithic arenite.

The conglomerate generally forms a lower unit, and arenite is dominant in the upper part of the occurrence.

Conglomerate

The conglomerate is a poorly sorted, well-indurated rock (Fig. 45A) in which grain size ranges from fine sand to boulders 60 cm across. Clay and silt fractions are absent or minor. In places there is a scarcity of clasts in the 2 mm to 10 mm range. The matrix/clast division is taken at 2 mm. Below this size the matrix is composed mainly of individual mineral grains, whereas in the coarser material rock fragments and composite grains are dominant.

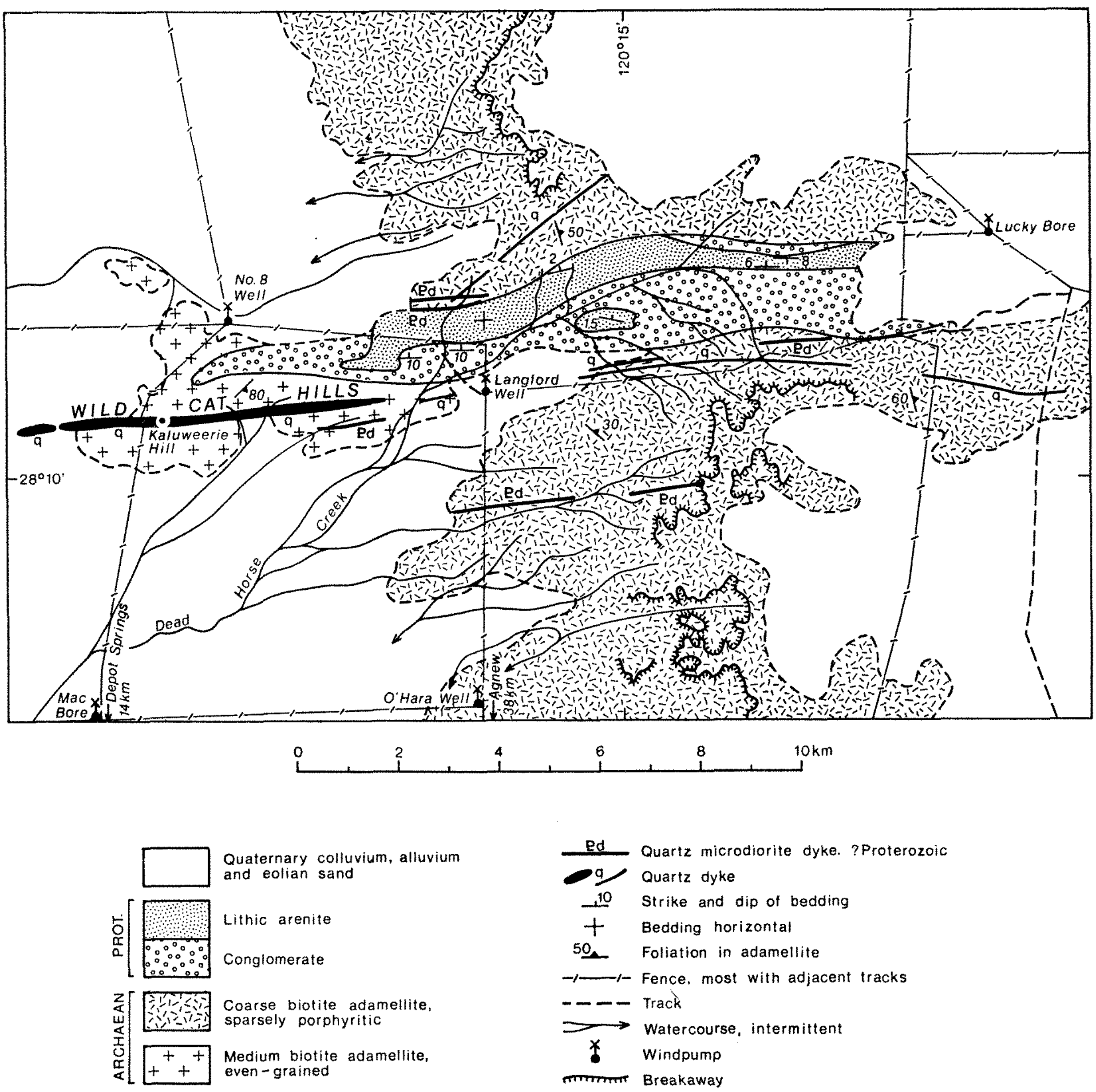


Figure 44. Geology of the Kaluweerie Hill area.

Clasts are variable in composition and include granitic rocks ranging from granite to tonalite, plus aplite, felsic gneiss, metabasalt, amphibolite, banded iron-formation, banded chert, chlorite schist, felsic volcanic rocks, metagabbro, metadolerite (including rare cobbles of porphyritic dolerite with feldspar phenocrysts up to 5 cm x 3 cm), and vein quartz. The clasts are generally subangular to rounded. Sphericity and shape depend largely on the rock type involved. High sphericity is characteristic of the granitic clasts and the more poorly foliated felsic volcanic and mafic rocks. Gneissic rocks, banded iron-formation, and chert form tabular clasts, whereas schistose rocks form elongate, bladed clasts.

The matrix of the conglomerate is moderately to poorly sorted and contains 50 to 60 per cent quartz, 15 to 20 per cent feldspar (mostly plagioclase with minor microcline and perthite), and 20 to 25 per cent chlorite, sericite, biotite, amphibole, and epidote. Carbonate, sphene, and iron oxide minerals account for about 5 per cent of the matrix. The constituent minerals are detrital except for minor secondary calcite around detrital carbonate grains (Fig. 45, C and D) and possibly the very fine white mica. Textures are similar to those in the arenite described below, but in places the scarcity of clay and silt allows for a closer packing of the larger grains (Fig. 45B). Lithification probably occurred by suturing of grain boundaries and remobilization of silica, suggesting a considerable depth of burial. Deep burial is also suggested by fracturing of plagioclase against quartz (Fig. 45E), kinking of chlorite and mica between compacted quartz grains, and a slight platy alignment of quartz grains parallel to bedding.

Lithic arenite

Lithic arenite is dominant towards the top of the succession but also occurs as lenses in the lower conglomeratic unit. In places there are gradations into conglomerate as the arenite becomes pebbly, and the matrix of the conglomerate is then indistinguishable from the arenite.

The arenite ranges from very fine grained to very coarse grained, with a tendency for finer material to occur near the top of the sequence. Sorting is moderate to good in the finer rocks, but becomes poorer in the coarse-grained varieties. In hand specimen the arenite is a hard, strongly lithified dark-grey to greenish-grey rock and apart from indistinct and irregular bedding (Fig. 45F) the rock is massive. It outwardly resembles basalt or dolerite, particularly in suboutcrop where it weathers to spherical boulders.

Typical arenite contains 50 to 70 per cent quartz, equal amounts of feldspar and mafic minerals, with minor detrital calcite, muscovite, sphene, and iron oxide minerals. Authigenic pyrite is interstitial to quartz (Fig. 46A). The mafic minerals are amphibole, epidote, biotite, and chlorite, both as individual detrital grains and as constituents in lithic fragments. Quartz and feldspar are very irregular in shape, and the close fitting of grains in some samples indicates considerable rearrangement and compaction. Clay matrix is usually a minor constituent, but may reach up to 10 per cent.

The very coarse lithic arenite contains a variety of lithic grains similar to those in the conglomerate, such as granite, felsic volcanic, dolerite, and chert, in addition to the normal medium-grained arenite lithology (Fig. 46, B, C, and D). Very fine-grained lithic arenite which occurs near the top of the exposed sequence in the type section consists of about 60 per cent quartz, 15 per cent epidote, 10 per cent green pleochroic amphibole, 10 per cent feldspar, and 5 per cent clay matrix and iron oxide. Possible local sources for the unusually large amount of epidote are the Archaean metavolcanic rocks, and the epidote-quartz rock associated with the quartz-filled fracture system.

About 1.5 km north-northwest of Lanfford Well, medium-grained lithic arenite contains irregular fragments of mudstone up to 5 cm long (Fig. 46, E and F), which probably indicates penecontemporaneous erosion of thin mud bands. At the margins of the fragments, grains of matrix quartz project into, and are in places enclosed by, the mudstone, indicating that the mudstone was plastic during deposition of the arenite.

DEPOSITIONAL FEATURES

Primary sedimentary structures within the conglomerate are poorly developed. Bedding is indistinct and irregular, and layers form discontinuous lenses and tongues (Fig. 45 F). Faint cross-bedding is present in some parts of the arenite. The generalized upward fining imparts an overall grading to the deposit. Graded beds are present but uncommon, and some examples show reverse grading. Within the conglomerate, discoidal pebbles tend to be aligned parallel to bedding, but the orientation of long axes within bedding planes appears to be random.

Dip measurements and the distribution of rock types indicate that the deposit forms a shallow asymmetrical synclinal trough elongated approximately east-west. This shape may be partly depositional and partly due to post-depositional compaction or minor tectonic warping. Dip of bedding planes is seldom more than 10°

DEPOSITIONAL ENVIRONMENT

Features such as coarseness, poor sorting, large proportion of feldspar, nature of the rock fragments, angularity of the sand fractions, and lack of clay and silt, indicate a local origin. The lack of well-defined bedding and the sinuous, elongate shape of the outcrop indicates a fluviatile environment, possibly in a partly confined channel. The rocks exposed form a topographic low between hills of vein quartz to the south and breakaways of granite to the north. The conglomerate shows some features characteristic of the rapid flow of water-lubricated material found in debris flow deposits close to areas of strong erosion (Reineck and Singh, 1973). The lack of preferred orientation of clasts is typical of such deposits, while the lack of attrition between sand-sized grains is shown by the high degree of angularity and the preservation of detrital epidote, amphibole, chlorite, and carbonate.

There may have been basement structural control of the river channel by the quartz and mafic dykes in the vicinity. The deposit hugs the northern side of the Wild Cat Hills quartz ridge from south of Lucky Bore to the point where it passes under the calcrete cover to the west—a distance of nearly 30 km. The quartz ridge is presently several tens of metres above the base of the conglomerate and was probably high ground during deposition of the conglomerate.

PROVENANCE

Banded iron-formation and ferruginous chert are absent from the Agnew-Wiluna greenstone belt to the east, and felsic volcanic rocks are uncommon. Although the Booylgoo Range has yet to be mapped in detail, it is known that banded iron-formation and chert form a major part of the sequence. The conglomerate therefore was probably derived from the west. The granitic clasts and the vein quartz fragments in the conglomerate, and the epidote in the arenite could all have been derived from the immediate area.

Further evidence for a western source is the scarcity of arenaceous layers in drillholes 8 to 10 km west-southwest of Kaluweerie Hill, where the sequence is dominantly pebbly. Thus, as well as fining upwards, there may also be lateral fining to the east. The vertical grading may represent a filling of the channel accompanied by a decrease in the amount of material being eroded from nearby uplands.

Figure 45. Petrographs and photomicrographs of the Kaluweerie Conglomerate (scale bar represents 1 mm except where stated otherwise).

A. 42869. Conglomerate, showing variety of clasts.

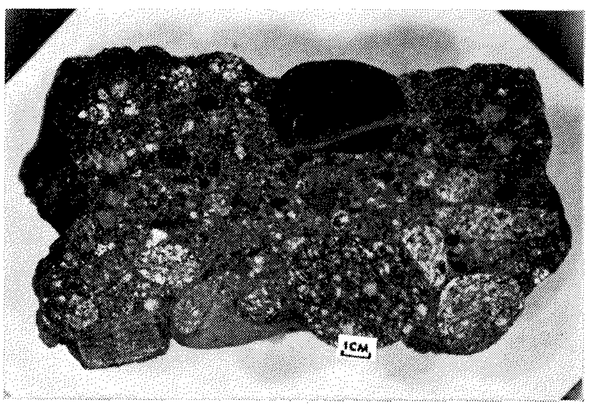
B. 42868. Conglomerate, matrix showing very close packing of detrital grains (plane polarized light).

C. 42871. Conglomerate matrix, showing detrital carbonate grain (carb) (plane polarized light).

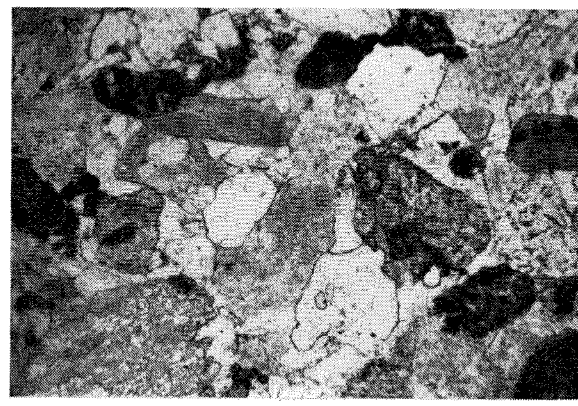
D. Same as C, showing secondary carbonate growth (Sc) (crossed nicols).

E. 42868. Conglomerate matrix, showing pressure (load) fractured plagioclase (Pl) (crossed nicols).

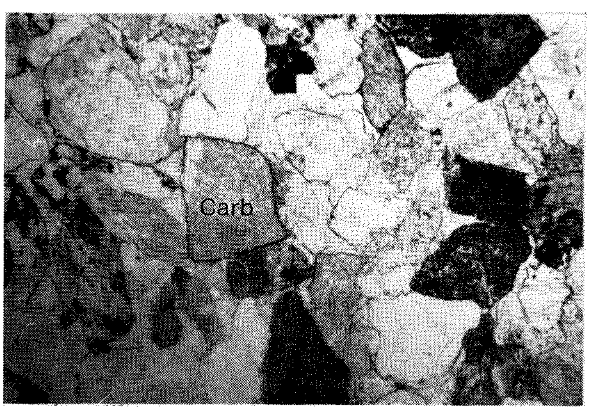
F. 42870. Irregular bedding with reverse grading in lithic arenite.



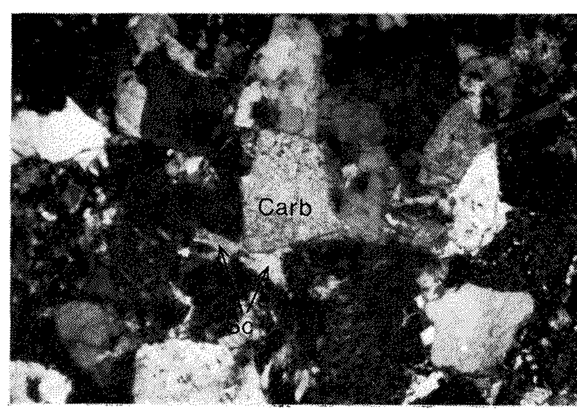
A



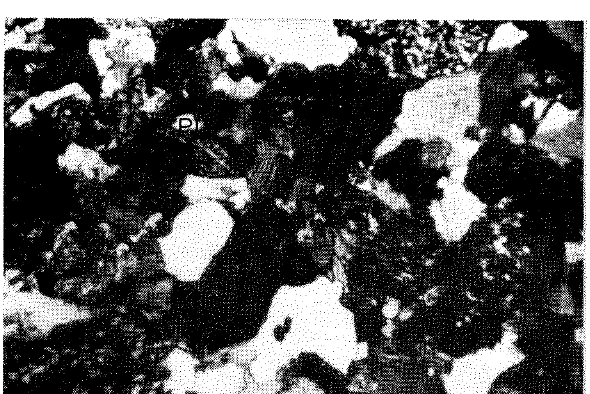
B



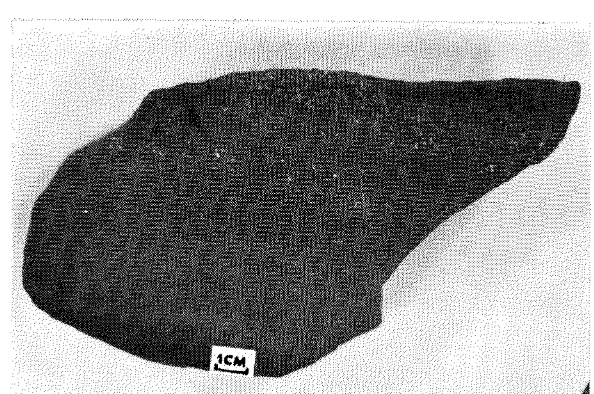
C



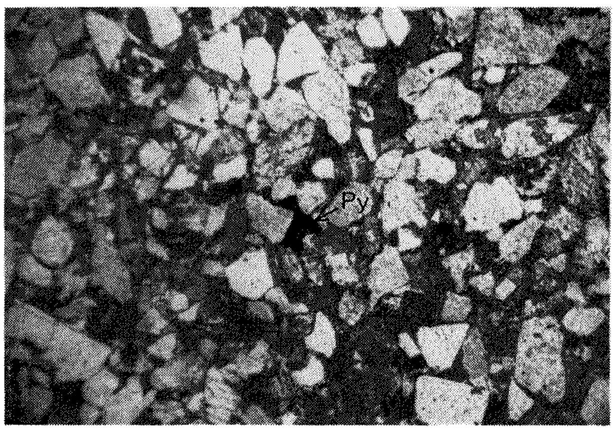
D



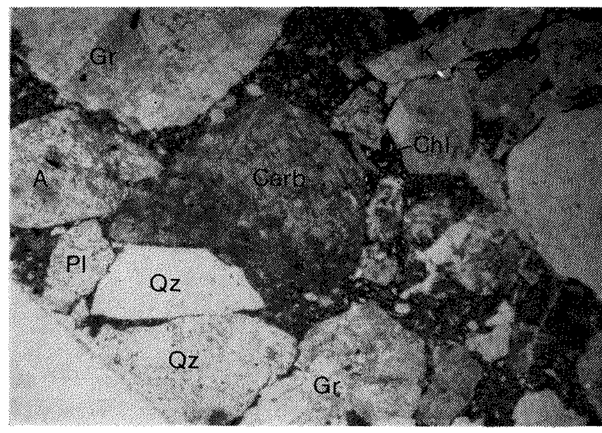
E



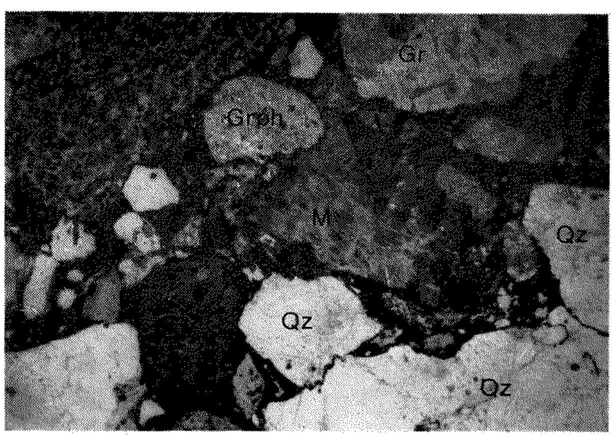
F



A

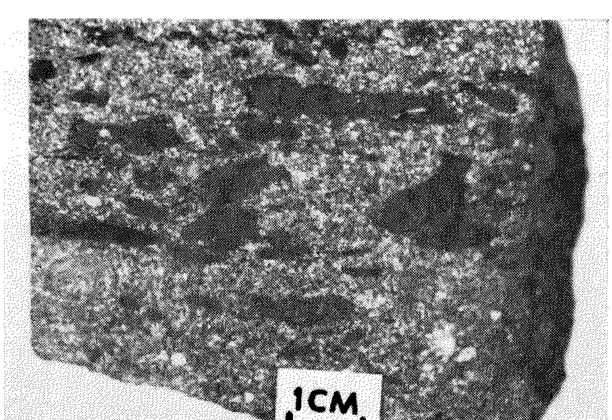


B



C


D



E

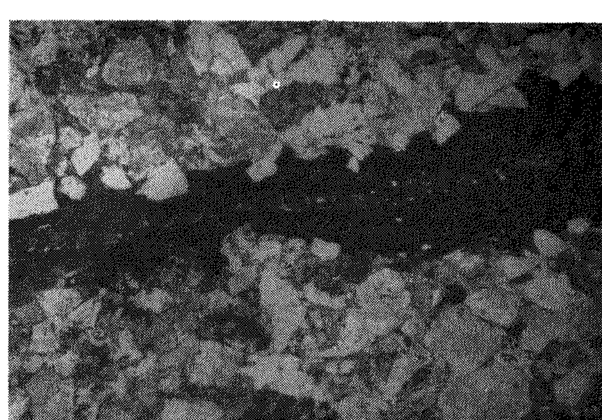

F

Figure 46. Petrographs and photomicrographs of the Kaluweerie Conglomerate (scale bar represents 1 mm except where stated otherwise).

A. 42862. Lithic arenite with ?authigenic pyrite (Py) (plane polarized light).

B & C. 42863. Variety of detrital grains in very coarse lithic arenite: Gr-granite, Carb-carbonate, Qz-quartz, Pl-plagioclase, K-alkali feldspar, A-aplite, Chl-chlorite, Fv-felsic volcanic, Grph-granophyre, M-muscovite, Do-metadolerite (plane polarized light).

D. 42863. Same as C, but with crossed nicols.

E. 42867. Mudstone intraclasts in lithic arenite.

F. 42867. Bedded mudstone intraclast in lithic arenite, showing penetration of quartz grains (plane polarized light).

OTHER POSSIBLE PROTEROZOIC OUTLIERS

Flat-lying, dominantly marine Proterozoic rocks occur west and northwest of Wiluna (140 km north of Kaluweerie Hill) as a southward projection onto the Yilgarn Block. The succession is described by Sofoulis and Mabbutt (1963) as consisting of basalt, argillaceous sediment, thin dolomite beds, and sandstone. An outlier of these rocks at Mount Yagahong is described by Sofoulis and Mabbutt as a sequence of basal conglomerate overlain by 6 m of basalt, 152 m of shale, and 30 m of upper basalt. However, Clarke (1916) and Gibson (1904) had previously considered the material overlying the basal conglomerate to be tuffaceous arkose which might be mistaken in hand specimen for fine-grained greenstone. Reexamination by the present authors of thin sections described by Gibson and Clark showed them to be very similar in mineralogy and texture to the fine and medium-grained lithic arenite from the Kaluweerie Hill area.

Field checking at Mount Yagahong and adjacent outliers revealed a sequence consisting of a basal conglomerate and lithic arenite similar in lithology to the Kaluweerie Conglomerate. It ranges in thickness from a few metres to more than 30 m and is overlain by about 120 m of dark-grey laminated shale and mudstone, which is in turn overlain by more than 40 m of arenite and lithic arenite. In most of the outliers only the basal unit is preserved.

The Proterozoic outlier at Mount Lawrence Wells (Fig. 43, inset) consists of 30 m of arkose unconformably overlying Archaean granite. The arkose contains blocks of white quartz and is overlain by 10 m of chert-breccia which is possibly a silicified dolomite.

A small area of conglomerate near Laverton is lithologically similar to that in the Kaluweerie Hill area and probably represents a similar continental environment. The variety of clasts is similar, with the addition of several boulders of limestone. The exposure, which is 3 m thick, overlies deformed Archaean conglomerate, although no contact is visible.

EVIDENCE OF AGE

Evidence for the Proterozoic age of the Kaluweerie Conglomerate is largely circumstantial. The exact contact with the underlying late Archaean granitic rocks is not exposed but must be unconformable because of the undeformed, unmetamorphosed, and subhorizontal nature of the sediments. The conglomerate is also younger than the post-granite mafic dykes which are generally regarded as being about 2 400 m.y. old.

In the field and in thin section the Kaluweerie Conglomerate is similar to the basal unit at Mount Yagahong, and is considered to be its stratigraphic equivalent. The age of the Mount Yagahong rocks has not been clearly established, but similarities between the upper part of the sequence and rocks within the main part of the Proterozoic basin to the northwest suggest an Early to Middle Proterozoic age. The stratigraphic relationship between Mount Lawrence Wells and the other outliers is not known.

The possibility that the conglomeratic outliers are Permian fluvioglacial deposits of the type that occurs in the Officer Basin to the east can be ruled out. Unlike the Kaluweerie Conglomerate the Permian conglomerates have a large proportion of clay and silt in the matrix and are probably tillites. Permian fluviatile conglomerates, which are not common, are characterized by a predominance of quartz clasts with minor exotic rock types. Furthermore, the Permian rocks are poorly indurated, usually strongly kaolinized, and generally lack authigenic pyrite and carbonate.

REGIONAL SIGNIFICANCE

Proterozoic rocks flanking the northern and northeastern edge of the Yilgarn Block are predominantly marine (Hall and Goode, 1975; Horwitz, 1975). They include ripple-marked sandstones and shales, dolomite, oolitic sandstone, and banded iron-formation, and minor conglomerate, intruded by basalt and dolerite sills. The presence of continental detrital sediments in the Kaluweerie Hill area, and possibly at Mount Yagahong and Laverton, indicates an eroding land mass in this part of the Yilgarn Block during Proterozoic times. The subhorizontal attitude of the beds and their lack of deformation illustrate the stability of the shield since then.

The presence of Proterozoic outliers at several places of similar elevation (about 500 m) on the northern Yilgarn Block, along with the uniform elevation of the Proterozoic unconformity along the northern margin of the block sugggest that the flatness of the shield is a relic of Proterozoic erosion and not related to more recent peneplanation. The coarse, immature continental deposits in the Kaluweerie Hill area and at Mount Yagahong may represent the last phase of high energy degradation of the Archaean rocks prior to peneplanation and marine transgression from the north.

URANIUM POTENTIAL

Carnotite uranium mineralization has been detected in rotary percussion drilling in weathered Kaluweerie Conglomerate west of Kaluweerie Hill. Although the conglomerate is adjacent to Cainozoic calcrete containing minor carnotite, it seems likely that the conglomerate mineralization is Proterozoic in age and possibly of placer type. Although of no economic significance here, potential for economic accumulations elsewhere in the region is evident.

The occurrence of uranium in the Kaluweerie Conglomerate suggests a source other than Archaean granites for the uranium deposits in Cainozoic calcretes. Although granite seems the likely ultimate source, concentration of uranium in basal Proterozoic platform sediments during erosion of the Yilgarn Block is a possible precursor to deposition in Cainozoic calcrete following erosion of the Proterozoic. It is noteworthy that the Yeelirrie uranium deposit lies in calcrete between Kaluweerie Hill and the Proterozoic outliers near Wiluna, in an area which was almost certainly covered by Proterozoic sediments.

REFERENCES

Clarke, E. de C., 1916, The geology and ore-deposits of Meekatharra, Murchison Goldfield: West. Australia Geol. Survey Bull. 68.

Gibson, C. G., 1904, The geology and mineral resources of a part of the Murchison Goldfield: West. Australia Geol. Survey Bull. 14, p. 44.

Hall, W. D. M., and Goode, A. D. T., 1975, The Nabberu Basin: a newly discovered Lower Proterozoic basin in Western Australia: Geol. Soc. Australia, First Australian Geol. Convention, Abs., p. 88-89.

Horwitz, R. C., 1975, Provisional geological map at 1:2 500 000 of the Northeast Margin of the Yilgarn Block, Western Australia: Australia C S I R O Mineral Investig. Rept. No. F.P.10.

Reineck, H. E., and Singh, I. B., 1973, Depositional sedimentary environments: Berlin, Springer-Verlag.

Sofoulis, J., and Mabbutt, J. A., 1963, Geology of the Wiluna-Meekatharra area, *in* Lands of the Wiluna-Meekatharra area, Western Australia, 1958: Australia C S I R O Land Res. Series No. 7, p. 93-106.

STRIATED AND FACETED BOULDERS FROM THE TUREE CREEK FORMATION – EVIDENCE FOR A POSSIBLE HURONION GLACIATION ON THE AUSTRALIAN CONTINENT

by A. F. Trendall

ABSTRACT

A small proportion of the fine-grained sandstone and acid volcanic clasts in a conglomerate with scattered boulders (a mixtite) near Meteorite Bore (lat. 22°50'30"S, long. 117°02'30"E) are faceted and striated in a manner strongly suggestive of a glacial origin. The mixtite occurs within the Turee Creek Formation of the Wyloo Group, which is the uppermost of three groups of the Mount Bruce Supergroup, the formal stratigraphic name applied to the contents of the Lower Proterozoic Hamersley Basin. The siltstone matrix of the boulders is strongly cleaved, concordantly with the structural position of the locality, but the clasts themselves do not appear to have been significantly deformed. The occurrence of possible glacigene rocks within a sedimentary sequence with an age about 2 000 m.y. on the Australian continent invites comparison with glacigene rocks of similar age in the Huronian of Canada and in the Transvaal Supergroup of southern Africa, but no confident correlation can be made on the basis of presently available data.

INTRODUCTION

In 1962, in the course of his field mapping in the southwestern part of the Mount Bruce 1:250 000 Sheet area, Mr. L. E. de la Hunty drew my attention to exposures of conglomerate, near Meteorite Bore, which he considered on lithological grounds might be glacigene. Through lack of more specific evidence this possibility was not mentioned in his published notes on the area (de la Hunty, 1965, p. 17), or in contemporaneous derivative work (MacLeod and others, 1963, p. 50; MacLeod, 1966, p. 56); nor has any reference to it been published subsequently.

In 1975 a convenient opportunity arose to revisit the exposures briefly. Mr. J. G. Blockley and I spent a short time searching for boulders which might provide stronger evidence of a glacial association; several were found and collected. A brief early record of these boulders, which is provided in this paper, seems justified by their possible significance both for the interpretation of the Proterozoic development of the northwestern part of the Australian continent, and for intercontinental Proterozoic correlation. During 1976 it is planned to revisit the locality to collect data for the more complete description which its potential importance warrants.

REGIONAL STATUS AND SETTING OF THE TUREE CREEK FORMATION

The Turee Creek Formation is the lowermost unit of the Wyloo Group, which is the uppermost of the three constituent groups of the Mount Bruce Supergroup (MacLeod, 1966) of the Hamersley Basin. This Proterozoic, initially intracratonic, basin occupied the area now lying between the approximate latitude and longitude limits 20 to 25°S and 116 to 122°E about 2 300 to 1 800 m.y. ago.

The name Wyloo Group was first published by MacLeod and others (1963), but they emphasized the provisional nature of their named subdivisions. Halligan and Daniels (1964) used virtually the same names, but for authority referred to de la Hunty's Explanatory Notes on the Mount Bruce Sheet area, then in press. However, de la Hunty (1965) stated that his subdivision, set out below, was provisional:

Wyloo Group
- Ashburton Formation
- Duck Creek Dolomite
- Mount McGrath Formation
- Beasley River Quartzite
- Turee Creek Formation

No type sections or areas were subsequently established for any of these units, and although their publication and widespread acceptance have conferred on them effective validity, this omission creates difficulties for subsequent stratigraphic work.

The stratigraphy of the two lower groups of the Mount Bruce Supergroup, the Fortescue Group and the Hamersley Group, is consistent with their deposition, largely as volcanogenic and chemogenic material respectively, in a developing intracratonic basin. The mainly terrigenous clastic material of the Wyloo Group is thought to have accumulated in a deeper arcuate trough which developed along the southern and western edges of the earlier basin, over a length of over 600 km (MacLeod, 1966). The Turee Creek Formation forms a recognizable unit over some 250 km of the southern part of this arc, as well as in a few synclinal outliers in the central part of the basin. It has been separately distinguished only in the Wyloo (Daniels, 1970), Mount Bruce (de la Hunty, 1965), and Turee Creek (Daniels, 1968) 1:250 000 Sheet areas. Its thickness in these areas is reported to range between about 37 m (120 ft) and "several thousand feet", and it is described as including a variable succession of greywacke, shale, dolomite, quartzite, and conglomerate (MacLeod, 1966).

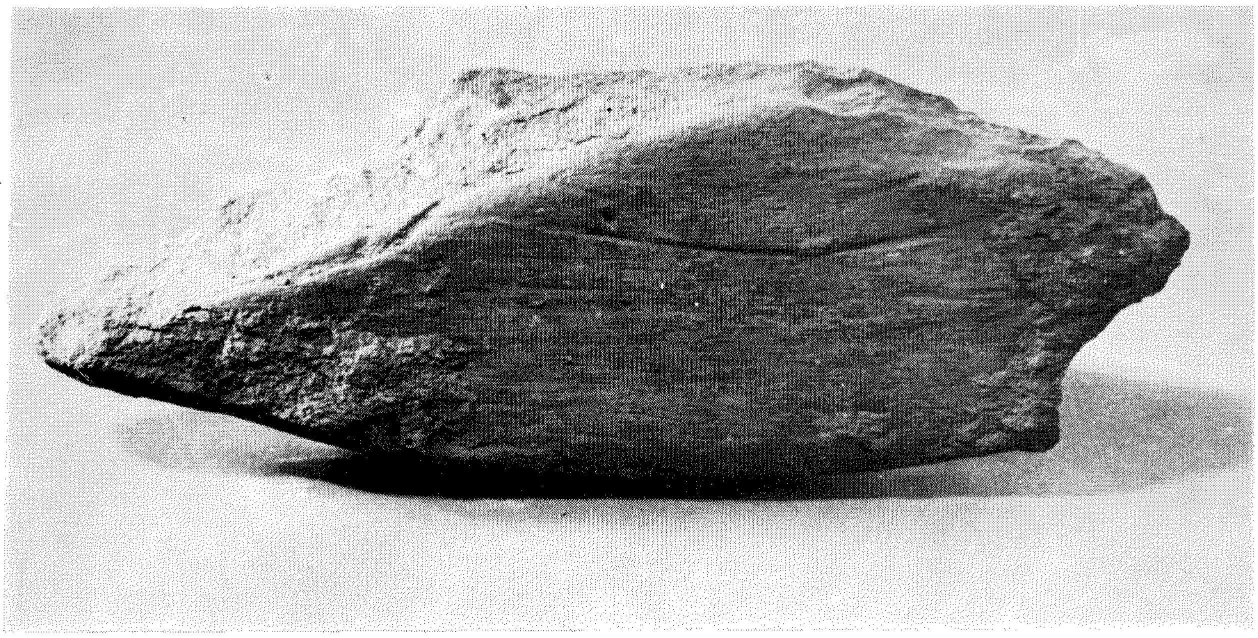
On a regional scale the contact between the Hamersley and Wyloo Groups along the southern and western edges of the basin is a line of general structural discordance. Despite this, wherever the top of the uppermost unit of the Hamersley Group, the Boolgeeda Iron Formation, is well exposed, there appears to be a conformable upward transition from its dark magnetic banded iron-formation into siltstone of the Turee Creek Formation. However, the recent denudational history of the area is such that only a small thickness of siltstone is ever visible in such situations, and an exposure gap invariably precludes certainty that no major stratigraphic discordance is present at some higher level within the Turee Creek Formation. Certainly at one locality along the contact between the Hamersley and Wyloo Groups both the Turee Creek Formation and the Boolgeeda Iron Formation are missing from the succession (Trendall and Blockley, 1970, p. 34), so that local discordance, or nonsequence, within the Turee Creek Formation would not be surprising.

MIXTITE NEAR METEORITE BORE

STRUCTURAL AND STRATIGRAPHIC SITUATION

Meteorite Bore lies near the southwestern corner of the Mount Bruce 1:250 000 Sheet area (de la Hunty, 1965), at lat. 22°50'30"S, long. 117°02'30"E, on the broad alluvial plain of the Beasley River. A low unnamed hill about 1 600 m long (east-west) and 800 m wide rises 10 to 20 m above the plain to the northeast of the bore, with its southwestern foot about 1 km distant.

Disregarding the Cainozoic alluvium and colluvium, the hill lies centrally within the mapped outcrop of the Turee Creek Formation, on the north-dipping southern limb of a westerly plunging syncline, known as the Hardey Syncline; this forms a continuously recognizable structure for a strike length of at least 50 km in this area (MacLeod, 1966). Although poor local exposure and the effect of deformation jointly prevent determination of the bedding dip, the probable outcrop width of the Turee Creek Formation of about 3 km, coupled with an expectation of steep dip from regional structural consideration, makes it likely that the formation is at least 1 km thick in this vicinity.



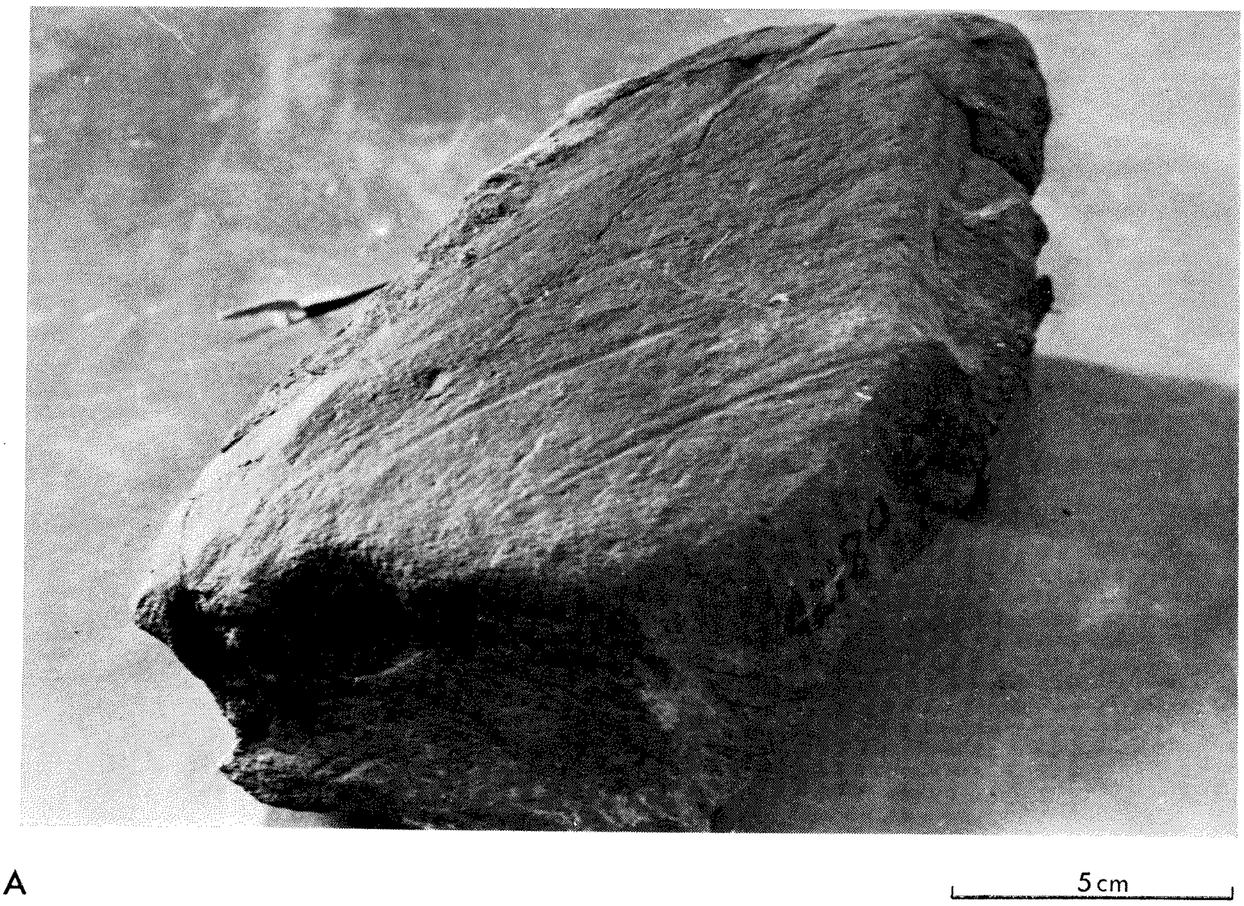
A

B

Figure 47. Two striated boulders from Meteorite Bore.

A. Small flat, striated clast of fine-grained sandstone, about 15 x 5 x 1 cm. The illustrated face bears a deep groove, curved through about 30°, superimposed on a set of straight, sub-parallel, finer striae along the mean direction of the curve. There is a deep equant indentation just above the deep curved groove near its left-hand end. Note that striae are parallel to the longest axis of the clast. Part of the upper left-hand edge appears tectonically fractured and slightly displaced. GSWA 42180A.

B. Part of a large boulder of fine-grained sandstone, about 20 x 25 x 15 cm. Although this boulder is well rounded, a shallow curved re-entrant face at one end, and its adjacent shoulders, are screened by short grooves in divergent directions along the direction of the face GSWA 42180G.



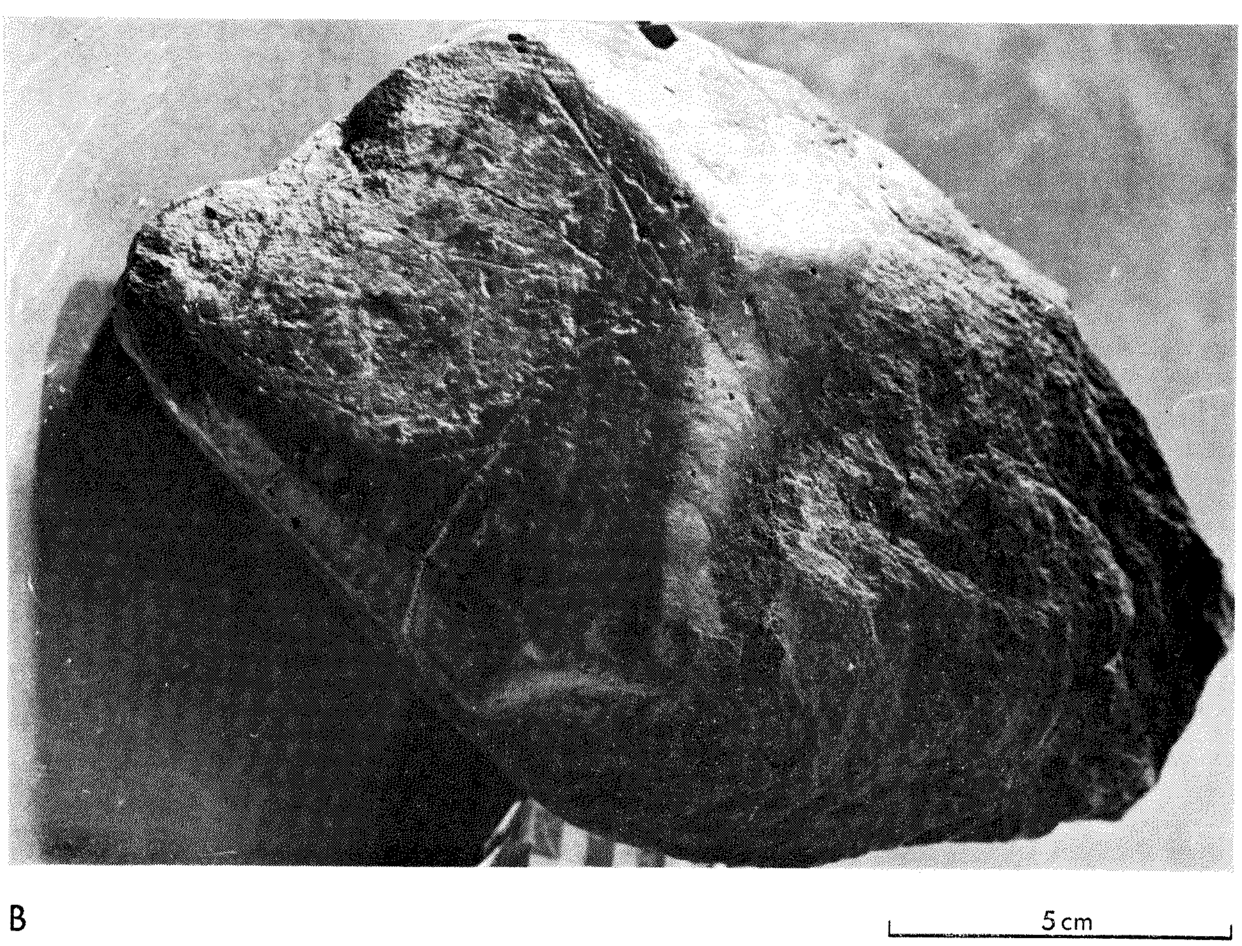


Figure 48. Two striated boulders from Meteorite Bore.

A. Flat, elongate boulder of fine-grained sandstone, about 20 x 10 x 5 cm. The illustrated top face has two deep, slightly curved, sub-parallel grooves with an asymmetric cross-section. GSWA 42180E.

B. Boulder of asphanitic, pale green, acid volcanic rock, about 15 x 10 x 7 cm. Three flat faceted faces met to define a corner in the upper centre of the photograph. The face below and to the left of this corner bears many short straight grooves in widely divergent directions. GSWA 42180B.

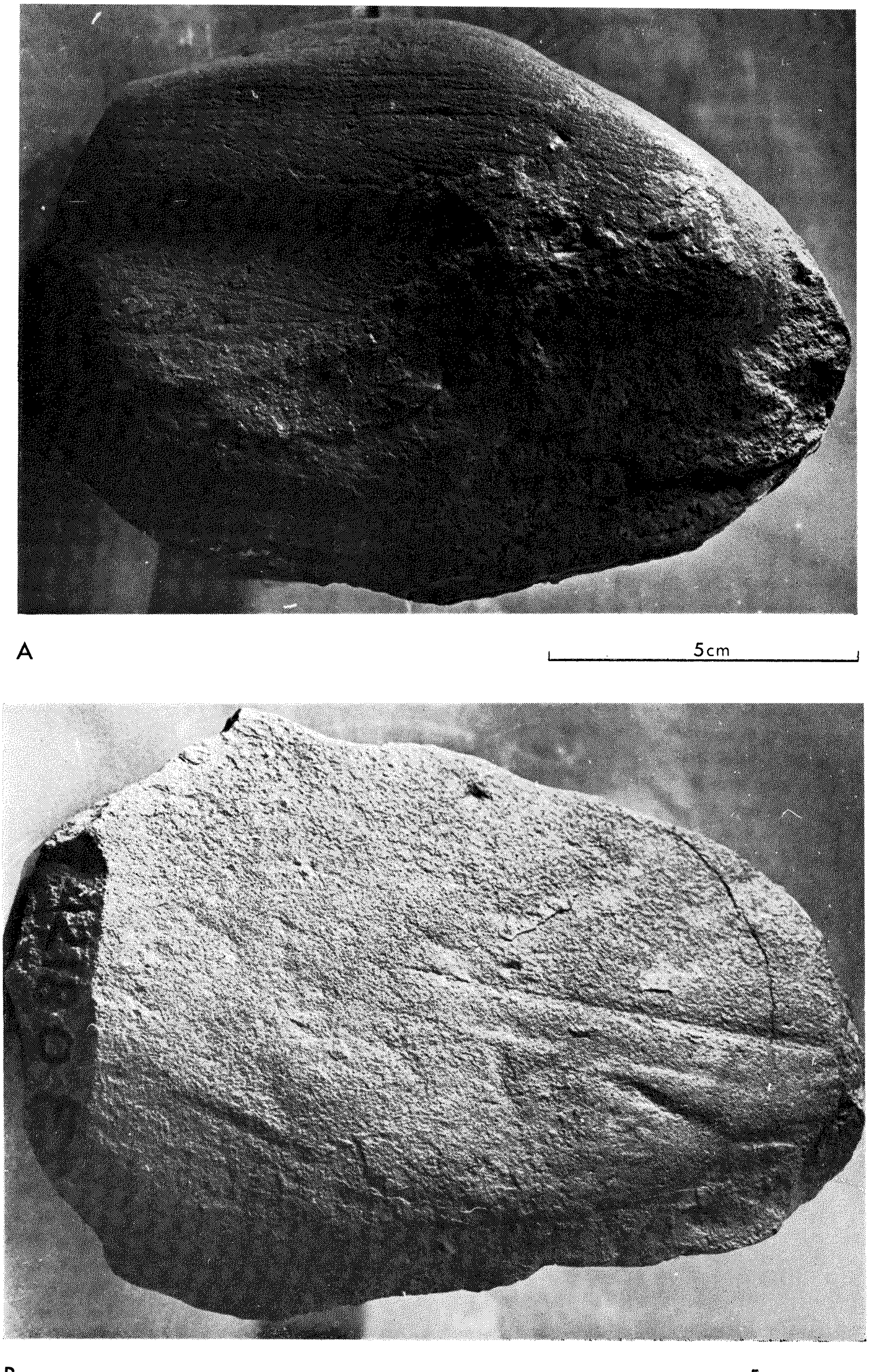


Figure 49. Two striated boulders from Meteorite Bore.

A. Flat, elongate boulder of fine-grained sandstone, about 14 x 10 x 4 cm. Many striae over the "stepped" face illustrated are generally sub-parallel, and are along the length of the clast, but a less well developed set cuts across these at about 30°, from upper left to lower right, GSWA 42180A.

B. Flat, elongate boulder of fine-grained sandstone, about 20 x 12 x 3 cm. By contrast with the many fine striae of boulder in A, above, the face shown bears only a few deep sub-parallel grooves. The longest of these is a multiple groove. GSWA 42180F.

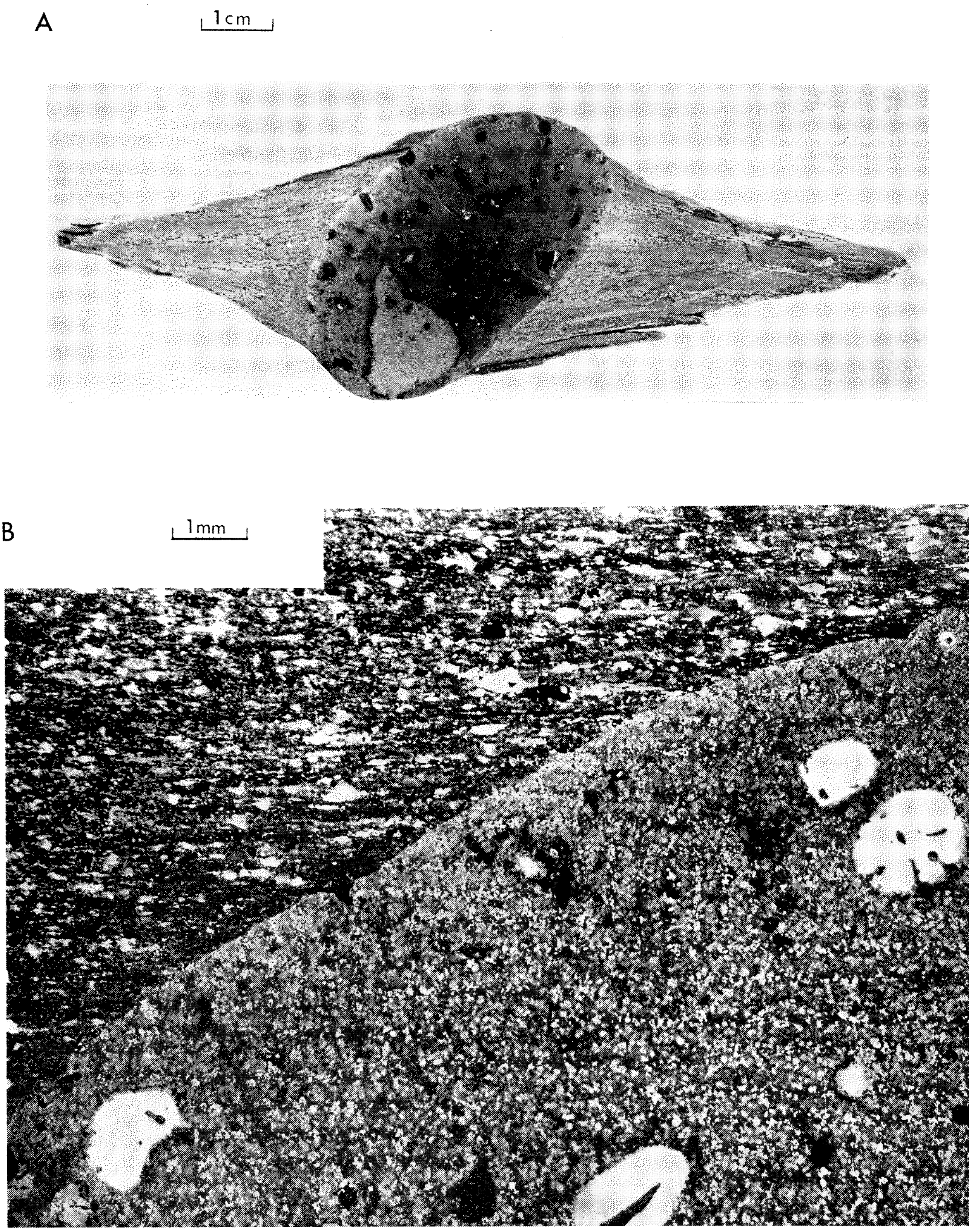


Figure 50. Cross-sectional appearance of a clast of porphyritic acid volcanic rock from Meteorite Bore. GSWA 42180A.

A. Sawn and smoothed cross-section showing the sharply defined edges of the rounded clast, with its adherent fringe of strongly cleaved siltstone.

B. Thin-section of a part of the boundary, showing the abrupt termination of the cleavage at the edge of the clast. Many sand-size grains of quartz lie within the matrix siltstone. Embayed phenocrysts of B-quartz lie in the undistorted mosaic of the clast, the margin of which is slightly modified.

LITHOLOGY AND STRUCTURAL EFFECTS

Mixtite (Schermerhorn, 1966) is well exposed over the slopes of the hill. Clasts, ranging from boulders over 1 m long down to pebbles a few millimetres across, are sparsely and randomly distributed in a matrix of greenish-brown siltstone; few, if any, of the clasts appear to be in direct contact. Primary bedding is not confidently identifiable, possibly due to a well-developed, near-vertical cleavage, penetrative in the matrix (Fig. 50), striking approximately east-west and clearly subparallel to the axial plane of the Hardey Syncline; however, east-west zones of apparently variable clast-type distribution may have a primary origin. The stress which imposed the strong penetrative cleavage of the matrix clearly had no structural effect on the more massive boulders (Fig. 50), but may have affected some of the others: the flat sandstone clast shown in Figure 47A appears to have been fractured at one edge, with some displacement of the broken part.

BOULDERS FROM THE MIXTITE

GENERAL CHARACTERS

During the brief visit on which this paper is based, attention was directed almost exclusively to boulders having a greatest dimension in the approximate size range 5 to 50 cm. In addition to those *in situ* the slopes of the hill are abundantly scattered with boulders clearly derived from the nearby bedrock. Many of these have a circumferential flange of adherent matrix in the plane of the cleavage, so that in total shape they form discs with swollen centres, reminiscent of the ringed planet Saturn (Fig. 50A).

The boulders consist mainly of fine brown sandstone, a lesser proportion of acid volcanic rock, and rare examples of carbonate and quartz. Most of the sandstone boulders have flat tabular shapes, with the ratio of least to greatest diameters as much as 1:10; in a projection parallel to the least diameter the outlines of such flat boulders may be either equant or as elongate as 1:3. However, some sandstone boulders, and all boulders of acid volcanics, have generally equant shapes. With the exception of the faceting and striation described below, the boulders are well rounded, with smooth surfaces. The flat boulders are generally aligned in the plane of the cleavage, and at least some have their longest axes oriented near vertically.

FACETING AND STRIATION

Although most of the acid volcanic clasts are equant and well rounded some have smooth flat faces separated by comparatively abrupt, but nevertheless smoothly bevelled, edges (Fig. 48B): they have the faceted shapes commonly described as characteristic of till stones (Pettijohn, 1957, Pl. 14). Most of the tabular sandstone clasts naturally also have two similarly flat faces, although the term "flat" here includes convex surfaces with large radii of curvature.

Certain of the boulders of the mixtite, both of sandstone and of acid volcanic rock, have surface striations, or grooves. No systematic count was made of the proportion so marked, and this would be difficult, since judging striation is for practical purposes subjective, and there is also the problem in the case of the loose boulders of assessing the effect of weathering; however, it is likely that the proportion of striated clasts lies between 1 and 5 per cent.

Striae occur mainly on flat faces, but also extend onto some rounded surfaces (Fig. 47B). They range in depth from about 1 mm to the lower limit of confident identification at about 0.1 mm. The longest continuous groove noted is 10 cm long, while the shortest ones amount to little more than slightly elongate indentations (Fig. 47A). In relation to the size of the faces on which they lie most striae seem to persist for about half the available length. Most grooves terminate gradually at each end, but a few have one abrupt termination. The majority of grooves are insufficiently well developed to show a clear cross-sectional shape, but some, which clearly depart from the simple symmetrical U-shape or V-shape which may be expected, are variously flat-bottomed, clearly asymmetrical (Fig. 48A), or are themselves more finely striated internally (Fig. 49B).

The striae are mainly straight, but may be curved (Fig. 47A). The most sharply curved groove observed has a 30° difference in direction from end to end, with a radius of curvature of about 15 cm; the direction of curvature is consistent in any one groove. Striae may occur either singly, or in subparallel sets (Figs 47A, 48A, 49A); such sets may include a large number of comparatively shallow and closely spaced striae, or may be made up of only a few deep widely separated grooves. More than one set in different directions, and single grooves in several widely divergent directions, may be present on a single face (Figs. 48B, 49A). Wherever a set of parallel grooves is present on the face of a markedly elongate platy boulder the grooves invariably diverge little in direction from the longest diameter of the boulder (Figs. 47A, 49A).

PETROGRAPHY OF MATRIX AND BOULDERS

In thin section the siltstone matrix appears as poorly sorted on a small scale as does the mixtite as a whole on a larger scale. There is a fine-grained quartz-sericite-chlorite groundmass in which the smallest quartz grains that can be accepted as clastic with reasonable confidence are about 0.05 mm across; the slightly finer quartz mosaic, which is closely intergrown with subparallel chlorite and sericite flakes of about the same size, appears to have been substantially recrystallized in response to the stress which imposed the cleavage. Within this groundmass lie gradationally larger angular, subangular, and rounded grains of quartz, both polycrystalline and monocrystalline. These are as large as 1 mm across, and all have their longer axes arranged parallel to the cleavage (Fig. 50A). Some of the larger grains are recognizably of acid volcanic rocks like those of the boulders. All the siltstone samples collected have abundant disseminated rhombs of carbonate, mainly 0.01 to 0.05 mm across, which are mainly weathered to goethite; this accounts for the brown colouring of the rock.

The fine sandstone of the boulders differs from the matrix siltstone in grain size, in sorting, and in grain composition. The estimated modal grain diameter is between 0.1 and 0.2 mm, so that the rock is close to the lower limit of sandstone grain size. Closely packed sharply angular and subangular grains close to this size form the bulk of the rock, the interstices being filled by a fine-grained quartz-sericite-chlorite groundmass similar to that of the matrix siltstone. Unlike that matrix, there is no scattering of conspicuously larger grains, but there is a resemblance to the enclosing siltstone in that the sericite and chlorite flakes of the groundmass, and the longer axes of elongate grains, have a preferred subparallel orientation. This direction is less strongly developed than in the siltstone, and in platy boulders is parallel to both the elongation of the boulder and to the cleavage outside. Some thin sections of the sandstone boulders bear disseminated carbonate rhombs like that of the siltstone matrix, whilst others do not.

It is evident that the preferred orientation of the sericite and chlorite of the matrix has developed as an axial-plane structure in response to stress associated with folding. However, it is at present not clear whether the similar orientation within the sandstone clasts represents a related structure, or was present, possibly as a diagenetic bedding-plane structure, before disruption of the parent strata.

The original mineral composition of the boulders of acid volcanic rocks appears in thin section to have suffered substantial modification, but there is no sign that this has been effected by stress, and it seems more likely that this alteration took place within the body of the rock before its fragmentation. There is a general matrix of even-sized but irregularly sutured quartz mosaic, of average grain diameter about 0.1 m, the detailed texture of which is concealed by abundant random flakes of pale green sheet silicate less than 10 microns across. The rock was probably a rhyolite with snowflake texture (Snyder, 1962; Torske, 1975) in which the original alkali feldspar is now texturally represented by sheet silicate. Only the evenly scattered embayed and rounded phenocrysts of clear quartz (Fig. 50B) provide a clear indication of the real identity of this rock; they are mostly 1 to 2 mm in diameter but some are as large as 3 mm. Subrectangular and rounded areas of the same order of size, occupied by microcrystalline sericite, presumably represent degraded feldspar phenocrysts.

DISCUSSION

AGE OF THE MIXTITE

The total available isotopic evidence for the age of the Mount Bruce Supergroup has recently been reviewed by Trendall (1976). As far as the Wyloo Group as a whole is concerned a younger depositional limit of 1 720 m.y. is provided by the Boolaloo Granodiorite, which intrudes the group farther west (Leggo and others, 1965). A younger limit for the sediments adjacent to the Woongarra Volcanics, probably at least 500 m stratigraphically below the mixtite near Meteorite Bore, is given by their reported age of 2 000 m.y. (Arriens, 1975); this age is described as defining a younger limit because these acid volcanic rocks are now thought to be intrusive rather than extrusive (de Laeter and others, 1974, p. 91). Only wide limits can be placed on the oldest possible depositional age of the mixtite. If the Black Range dolerite (Lewis and others, 1975) represents a feeder for Fortescue Group lavas, then its deposition cannot be older than about 2 300 m.y.

A key point concerning the age of the mixtite is the provenance of the acid volcanic clasts. These resemble rocks of the Woongarra Volcanics, and no other local source of such rocks is known. If they were so derived, then a much smaller older limit, of 2 000 m.y is placed on mixtite deposition.

ORIGIN OF THE MIXTITE

Over the last decade a substantial body of literature concerned with the interpretation of pre-Pleistocene till-like sedimentary rocks has appeared, under the especial stimulation of a paper by Schermerhorn and Stanton (1963), in which a non-glacial, gravitational flow origin was advocated for Precambrian rocks from western Africa, possessing many of the features formerly widely accepted as characteristic of glacigene sediments. Harland and others (1966) have provided an objective review of the relevant work to that date, while Spencer (1971), in the most detailed published description of any single occurrence of Precambrian glacigene mixtite, in the Dalradian of Scotland, has also critically analyzed the interpretation by Schermerhorn and Stanton (1963) of their African sequence, which has strikingly close similarities to the Dalradian example.

Many of the criteria that can contribute to the judgement of whether any given deposit is glacigene involve an assessment of its regional stratigraphic extent and relationships. The restricted information given in this brief record of the mixtite at Meteorite Bore does not justify a full analysis of the evidence for its origin; this section of the discussion is therefore restricted to brief comment on the likely significance of the striated boulders.

There appear to be only three possible origins for the striations described: they may have been produced by some effect associated with glaciations, by some mechanism of non-glacial flow, or by tectonic means during folding.

The third possible origin is here rejected immediately, for two reasons. Firstly, if the striation is tectonic, it is hard to see why only a small proportion of the boulders are striated: many of the boulders have a similar lithology, shape, orientation, and matrix, but comparatively few bear striae. Secondly, it is even more difficult to conceive of any tectonic process, even if selective for no clear reason, which could produce widely divergent intersecting sets of striae.

Although striations are known to have been produced by non-glacial mass movement or by other forms of boulder transport (Kayser, 1923), Harland and others (1966, p. 247) nevertheless believed that "Striations are so definitive, under the proper conditions, that when present they can be one of the most important criteria for glaciation". Also, there is no published record so far of the occurrence of abundant striated clasts closely similar to those of a glacigene deposit in a non-glacigene one. Of all the criteria listed by Schermerhorn and Stanton (1963) the presence of striated (and faceted) stones was the one they found most difficult to explain in a supposedly non-glacial rock, and they were forced to suggest that the striated siltstone cobbles which they described were scratched in a slide or slump while they were soft. For the siltstone boulders from Meteorite Bore, as for those described from western Africa by Schermerhorn and Stanton (1963), it seems hard to imagine that a siltstone sufficiently lithified and brittle to break into quite large coherent flat slabs would at the same time be sufficiently soft to be exceptionally susceptible to striation. Certainly at Meteorite Bore the presence of striated volcanic clasts discounts this argument; in any case, for the softer rocks to be more commonly striated is consistent with known glacial deposits (Wentworth, 1936).

It is not yet certain whether the flat slabby siltstone boulders at Meteorite Bore are so shaped through tectonic deformation, although the preservation of surface markings in strongly deformed clasts would surely be remarkable (cf. Spencer, 1971, p. 63-5); it seems more likely either that the initially random slabs have been rotated to near parallelism during folding, or that the slabs lay close to the bedding plane, which may in turn at this locality be close to the axial plane cleavage.

Trendall and Blockley (1970, p. 296) have specifically suggested the local collapse of lately deposited parts of the Hamersley Group southwards into the developing depositional trough of the Wyloo Group to explain local stratigraphic discordance at its base, and the presence of conglomerates within the Wyloo Group. Meteorite Bore lies within the general area to which this suggestion would refer, and perhaps the origin of the described boulders should be sought in such a mechanism. But the possibility of a glacial origin for these clasts is sufficiently strong for a brief examination of some of its consequences.

POSSIBLE INTERCONTINENTAL CORRELATION

In an earlier review paper Trendall (1968) compared the banded iron-formations of the Hamersley Range area of Western Australia with those of the Lake Superior ranges and those of the northern Cape Province and Transvaal areas of South Africa, in terms of the total geological environment of each. For this purpose the iron formations were considered to have been deposited in three major basins of similar, but not necessarily the same, age: the Hamersley Basin, the "Animikie Basin", and the 'Transvaal System Basin". Both of these two latter terms were applied with stated reservations concerning their real validity. Partly to avoid confusing detail no reference was made to possible glacigene rocks as a feature requiring specific comparative comment, and this omission is here rectified.

For the "Animikie Basin" Trendall (1968, p. 1531) chose to simplify stratigraphic complications by suggesting that the deposition of the type Huronian rocks took place in a structurally separate basin from that in which the Animikie iron formations were laid down. Young (1973) has more recently summarized the occurrence of tillites in the Lower Proterozoic (Aphebian) of north America, and has re-emphasized his earlier contention (Young, 1966) that a correlation of the Fern Creek Formation (Pettijohn, 1943) of Michigan with the Huronian Gowganda Formation is consistent with both the stratigraphic and the isotopic age evidence. Roscoe (1969, p. 113), on other grounds, nevertheless agreed with Young that the iron formations of the Lake Superior ranges are likely to be younger than the type Huronian. If this view is accepted there exists, in the regional stratigraphy of the Lake Superior-Lake Huron area, a broad transition from glacigene and other clastic sedimentation to the chemical deposition of iron formation. The available isotopic evidence from this area (Van Schmus, 1965; Fairbairn and others, 1969) sets approximate limits of 2 100 to 2 500 m.y. for the time of this glaciation, with a most likely age about 2 300 m.y.

Young (1973) referred to glacial deposits of age comparable to the Huronian in the Witwatersrand System (= Supergroup of Wagener, 1972) of South Africa, and cited as authorities papers by Wiebols (1955) and Fuller (1958). These have mixed significance. The criteria used by Wiebols to argue an important glacial contribution to the deposition of all the major conglomerate horizons of the Witwatersrand Supergroup were largely general stratigraphic ones, and some of the specific criteria put forward to support his argument, for example the supposed presence of varves, were fairly certainly invalid (Truter, 1955). Other important criteria now regarded as critical, such as large penetrating dropped stones (Harland and others, 1966) were not described; in this respect it is surprising that Wiebols did not refer to the earlier description by Rogers (1922, p. 20) quoted in full by Fuller (1958), of a 25 ft (7.6 m) thick tillite within the Government Reef Series (= Hamberg Formation of Wagener, 1972) containing randomly scattered boulders, some of which are well striated and flattened on one or more sides. Du Toit (1954, p. 80) mentioned other, thicker, occurrences of similar material at the same stratigraphic level. However, no emphasis is currently placed on glaciation as a factor in the sedimentology of the Witwatersrand Supergroup (Pretorius, 1975), and it is not possible from published literature to determine whether, and if so, why, the evidence noted by Rogers (1922) has been reinterpreted. Hunter's (1974, p. 297) recent summary of the isotopic age evidence for Witwatersrand Supergroup deposition suggests limits of 2 340 to 2 720 m.y. so that Young's (1973) implied equivalence with the Huronian is possible within the approximate time span 2 300 to 2 500 m.y.

An alternative African equivalent, however, seems to be the tillite of the Transvaal Supergroup. This was first discovered, and very well described, by Rogers (1906, p. 162-4) from the northern Cape Province. Du Toit (1954, Pl.VII, 2) has illustrated two convincingly striated stones from it, and has summarized its occurrence at the same stratigraphic level, close below the Ongeluk Volcanics and above the main banded iron-formations, in both the northern Cape Province, where he refers to it as the Griquatown Tillite, and in the Transvaal, where it was called the Glacial Band at the base of the Ongeluk Quartzite of the Daspoort Group. In later stratigraphic reviews De Villiers (1967) and Truswell (1967) have amended the earlier nomenclature somewhat, but both these reviewers concur that the Transvaal Supergroup tillites have the stratigraphic status and extent as described by Du Toit. Hunter's (1974, p. 297) geochronological summary indicates that the Transvaal Supergroup has age limits of 1 950 to 2 340 m.y., which is consistent with a direct age of 2 220 m.y. for the Ongeluk Volcanics immediately overlying the tillite. This is once again within the Huronian limits.

A direct correlation of the Transvaal Supergroup tillites, overlying the main banded iron-formations, with the possible tillite at Meteorite Bore, above the banded iron-formation of the Hamersley Group, has obvious attraction. But if the acid volcanic clasts from Meteorite Bore are derived from the Woongarra Volcanics, and if these are 2 000 m.y. old, then apparently this correlation must be rejected. A close scrutiny of the isotopic data (not all published) may reveal a possibility that the Huronian and Transvaal Supergroup tillites were deposited coevally with the Meteorite Bore mixtite, perhaps at about 2 250 m.y., but from the total information now available it is impossible to verify such a hypothesis with acceptable confidence.

ACKNOWLEDGEMENTS

It is appropriate to emphasize my indebtedness to Mr. L. E. de la Hunty for introducing me to the Meteorite Bore exposures; to him must go the credit both for their discovery and for initial recognition of their probable glacial association.

REFERENCES.

Arriens, P. A., 1975, Geochronological studies of some Proterozoic rocks in Australia: Geol. Soc. Australia First Australian Geological Convention, Proterozoic Geology, Adelaide, May 1975, Abs., p. 63.

Daniels, J. L., 1968, Turee Creek, W.A.: West. Australia Geol. Survey 1 : 250 000 Geol. Series Explan. Notes, 18 p.

——— 1970, Wyloo, W.A.: West. Australia Geol. Survey 1 : 250 000 Geol. Series Explan. Notes, 20 p.

de Laeter, J. R., Peers, R., and Trendall, A. F., 1974, Petrography, chemical composition, and geochronology of two dolerite sills from the Precambrian Weeli Wolli Formation, Hamersley Group: West. Australia Geol. Survey Ann. Rept. 1973, p. 82-91.

de la Hunty, L. E., 1965, Mount Bruce, W.A.: West. Australia Geol. Survey 1 : 250 000 Geol. Series Explan. Notes, 28 p.

De Villiers, P. R., 1967, New stratigraphic correlation and interpretation of the geological structure of the Postmasburg-Sishen area: South Africa Geol. Survey Ann., v. 6, p. 39-42.

Du Toit, A. L., 1954, The geology of South Africa: Edinburgh and London, Oliver and Boyd, 611 p.

Fairbairn, H. W., Hurley, P. M., Card, K. D., and Knight, C. J., 1969, Correlation of radiometric ages of Nipissing diabase and Huronian metasediments with Proterozoic orogenic events in Ontario: Canadian Jour. of Earth Sciences, v. 6, p. 489-497.

Fuller, A. O., 1958, A contribution of the petrology of the Witwatersrand System: Geol. Soc. South Africa Trans., v. 61, p. 20-50.

Halligan, R., and Daniels, J. L., 1964, Precambrian geology of the Ashburton Valley region, North-West Division: West. Australia Geol. Survey Ann. Rept. 1963, p. 38-46.

Harland, W. B., Herod, K. N., and Krinsley, D. H., 1966, The definition and identification of tills and tillites: Earth Science Reviews, v. 2, p. 225-256.

Hunter, D. R., 1974, Crustal development in the Kaapvaal Craton, II. The Proterozoic: Precambrian Research, v. 1, p. 295-326.

Kayser, E., 1923, Lehrbuch der Allgemeinen Geologie: Stuttgart, Enke, v. 1, 466 p.

Leggo, P. J., Compston, W., and Trendall, A. F., 1965, Radiometric ages of some Precambrian rocks from the Northwest Division of Western Australia: Geol. Soc. Australia Jour., v. 12, pt. 1, p. 53-65.

Lewis, J. D., Rosman, K. J. R., and de Laeter, J. R., 1975, The age and metamorphic effects of the Black Range dolerite dyke: West. Australia Geol. Survey Ann. Rept. 1974, p. 80-88.

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

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

Pettijohn, F. J., 1943, Basal Huronian conglomerate of Menominee and Calumet districts, Michigan: Jour. Geology, v. 51, p. 387-397.

——— 1957, Sedimentary rocks: New York, Harper & Brothers, 718 p.

Pretorius, D. A., 1975, The depositional environment of the Witwatersrand goldfields: a chronological review of speculations and observations: Minerals Science Engineering, v. 7, pt. 1, p. 18-47.

Rogers, A. W., 1906, Geological survey of parts of Hay and Prieska with notes on Herbert and Barkly West: Cape of Good Hope Geological Commission 10th Ann. Rept. for 1905, p. 141-204.

——— 1922, The geology of the country around Heidelberg: South Africa Geol. Survey, Geol. Map Explan. Series.

Roscoe, S. M., 1969, Huronian rocks and uraniferous conglomerates in the Canadian Shield: Canada Geol. Survey Paper 68-40, 205 p.

Schermerhorn, L. J. G., 1966, Terminology of mixed coarse-fine sediments: Jour. Sed. Petrology, v. 36, p. 831-835.

Schermerhorn, L. J. G., and Stanton, W. I., 1963, Tilloids in the West Congo geosyncline: Geol. Soc. London Quart. Jour., v. 119, p. 201-41.

Snyder, J. L., 1962, Geologic investigations, central Davis Mountains, Texas: Texas Jour. Sci., v. 14, No. 2, p. 197-215.

Spencer, A. M., 1971, Late pre-Cambrian glaciation in Scotland: Geol. Soc. London Mem. No. 6, 100 p.

Torske, T., 1975, Snowflake texture in Ordovician rhyolite from Stord, Hordalan: Norges geol. Unders., Bull. 32, nr. 319, p. 17-27.

Trendall, A. F., 1968, Three great basins of Precambrian banded iron formation deposition: a systematic comparison: Geol. Soc. America Bull., v. 79, p. 1527-1544.

——— 1976, Guidebook for Excursion 43A (Hamersley Basin): Int. Geol. Congress XXV, Sydney.

Trendall, A. F., and Blockley, J. G., 1970, The iron formations of the Precambrian Hamersley Group, Western Australia: West. Australia Geol. Survey Bull. 119, 366 p.

Truter, A. A., 1955, Discussion of "A suggested glacial origin for the Witwatersrand conglomerates": Geol. Soc. South Africa Trans., v. 58, p. 383-385.

Truswell, J. F., 1967, A critical review of stratigraphic terminology as applied in South Africa: Geol. Soc. South Africa Trans., v. 70, p. 81-116.

Van Schmus, R., 1965, The geochronology of the Blind River—Bruce Mines area, Ontario, Canada: Jour. Geology, v. 73, No. 5, p. 755-780.

Wagener, G. F., 1972, Suggestions for the revision of the existing Witwatersrand stratigraphic classification and nomenclature: Geol. Soc. South Africa Trans., v. 75, No. 2, p. 77-84.

Wentworth, C. K., 1936, An analysis of the shapes of glacial cobbles: Jour. Sed. Petrology, v. 6, No. 2, p. 85-96.

Wiebols, J. H., 1955, A suggested glacial origin for the Witwatersrand conglomerates: Geol. Soc. South Africa Trans., v. 58, p. 367-382.

Young, G. M., 1966, Huronian stratigraphy of the McGregor Bay area, Ontario: relevance to the paleography of the Lake Superior region: Canadian Jour. of Earth Sciences, v. 3, p. 203-210.

——— 1973, Tillites and aluminous quartzites as possible time markers for Middle Precambrian (Aphebian) rocks of north America: Geol. Assoc. Canada Sp. Paper 12, p. 98-127.

THE SADDLEBACK GROUP – A NEWLY DISCOVERED ARCHAEAN GREENSTONE BELT IN THE SOUTHWESTERN YILGARN BLOCK

by S. A. Wilde

ABSTRACT

A previously unrecorded 5 to 12 km wide sequence of weakly metamorphosed sediments, felsic and mafic volcanic and pyroclastic rocks extends for 43 km north-northwest from Mount Saddleback, near Boddington, to Mount Wells. This sequence is herein formally named the Saddleback Group and is subdivided into the Hotham, Wells and Marradong Formations. The rocks are poorly exposed and extensively faulted. Contacts with adjacent Archaean granitic rocks are largely fault-controlled, although adamellite intrudes all three formations in the southwestern part of the belt, near the Hotham River. The Saddleback Group is more closely similar to the greenstone belts of the eastern Yilgarn Block than any other rock units so far described from the southwestern part. It may have developed on a basement composed of earlier, 3 000 m.y old layered Archaean rocks.

INTRODUCTION

During regional mapping of the Pinjarra 1:250 000 Geological Sheet by S. A. Wilde and K. J. B. Hirschberg, a previously unrecorded sequence of metasedimentary and metavolcanic rocks was discovered near Boddington, 110 km southeast of Perth. The rocks occur in a belt trending approximately 160° and are enclosed within Archaean granite, migmatite and gneiss. They constitute the only definite volcanogenic "greenstone" sequence known in the southwestern Yilgarn Block.

The rocks are very poorly exposed and almost entirely covered by Tertiary and Quaternary deposits. Occasional outcrops occur along the major river valleys and in minor drainage dissections of the extensive laterite surface. Even where best exposed, the rocks are largely obscured by soil and colluvium (Fig. 51). Strongly defined lineaments on the air-photographs appear to represent lines of faulting. These bound the greenstone belt in all but the southwestern corner, as well as causing displacement of the major units within the belt (Fig. 51). However, it is possible to trace the main lithologies throughout the extent of the belt and subdivision into formations has been possible.

DEFINITIONS AND FIELD RELATIONS

SADDLEBACK GROUP

The name is derived from Mount Saddleback, the 575 m high summit of a prominent range occurring 19 km south of Boddington. The Saddleback Group consists of a sequence of sedimentary, pyroclastic and volcanic rocks, metamorphosed to greenschist or lower amphibolite facies. The group trends approximately 160° north-northwest from the Murray River, 4 km south of Mount Saddleback, to about 5 km north of Mount Wells—a total distance of 43 km. The width of the sequence varies from 5 to 12km. The group has a steep regional dip to the east and consists of three main mappable units. These have been named, in ascending structural order, the Hotham, Wells and Marradong Formations; there is no direct evidence for true stratigraphic sequence.

East of George Hill, near the Hotham River, even-grained adamellite appears to intrude all three formations. However, the actual contact is only exposed at one locality, 6 km east-southeast of George Hill. The contact zone is about 10 m wide and consists of elongate xenoliths of felsic volcanic rock enclosed in an extremely variable granitic matrix. Irregular areas and veins of adamellite occur within felsic pyroclastic rocks of the Wells Formation for up to 200 m from the contact.

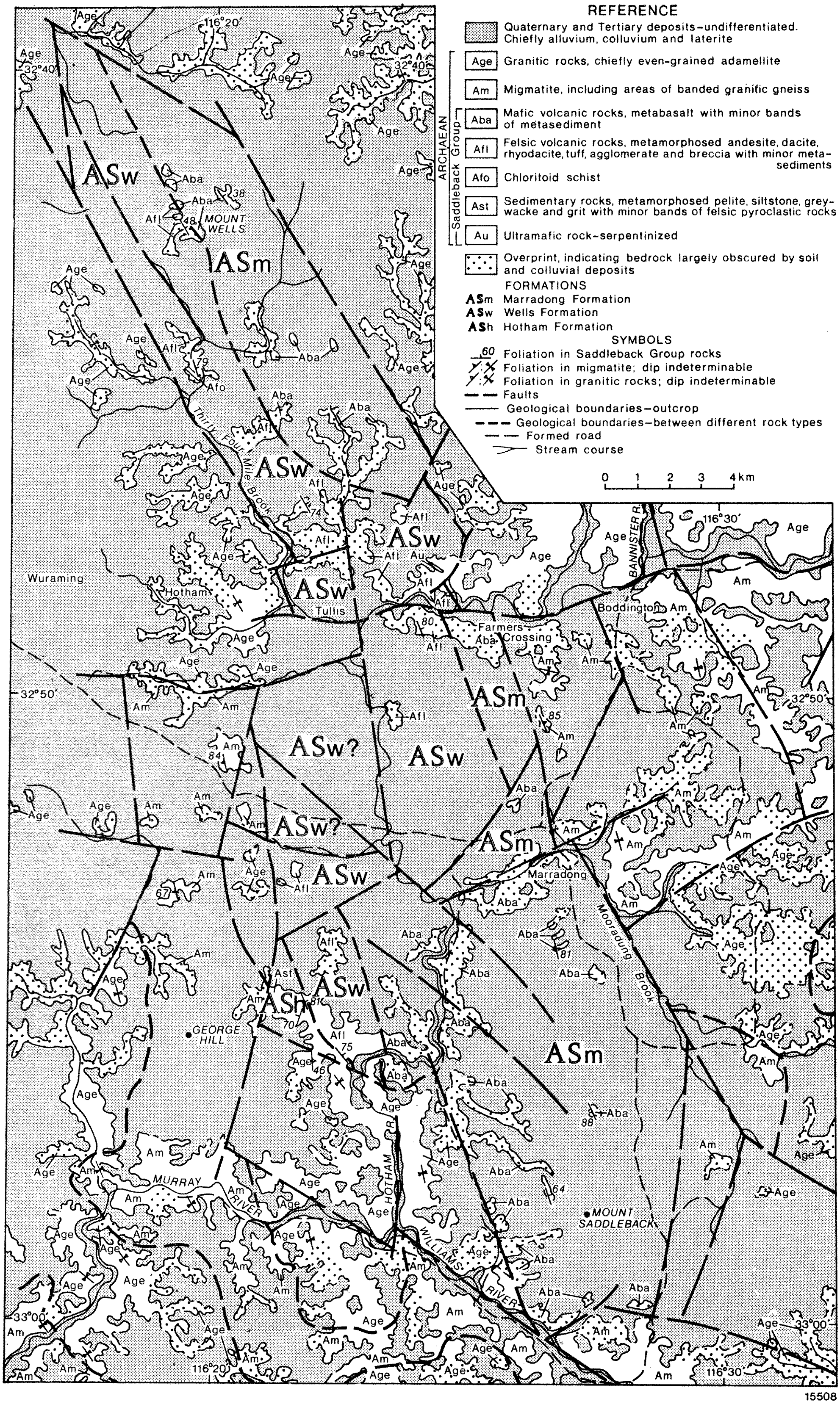


Figure 51. Geological map of the Mount Saddleback-Mount Wells area, showing formations.

Elsewhere, the group is strongly fault-bounded and chiefly margined by even-grained granite/adamellite. Migmatite occurs at places along the eastern, western and southern margins, whilst a strongly banded granitic gneiss adjoins the greenstone belt, 17 km south-southwest of Hotham. The major faults delineating the belt trend 160° and are subparallel to the general foliation trend of the rocks. The eastern boundary fault trending 150° and followed by the course of Mooradung Brook (Fig. 51) is marked by extensive shearing and alteration of the granitic rocks, whilst the major fault along the Williams River is paralleled by two zones of quartz veining. There is little evidence of faulting along the other contacts except for their strong linearity (often followed by stream courses) and the abrupt change in rock-type that occurs. Many later faults trending between 010° and 030° have displaced the boundary of the greenstone belt.

The northern limit of the greenstone belt is poorly defined. A fault trending 110° is postulated, parallel to a present creek (Fig. 51), although there is little evidence for this on the ground. Granitic rocks cropping out 8 km north-northwest of Mount Wells are characterized by a strong, braided, cataclastic foliation with linked quartz grains. Thin bands of mylonite and quartz are also present in these rocks and it appears that a later cataclastic foliation, trending 160°, has been superimposed on an earlier foliation, trending at about 140°. A similar braided foliation occurs in the greenstone belt rocks at Mount Wells and it is possible that the belt pinches out more gradually to the north. However, the total lack of exposure in the crucial area makes any interpretation speculative.

HOTHAM FORMATION

The formation is named after the Hotham River and is exposed on either side of a north-northwest-trending tributary, about 3 km east of George Hill. It consists of 1.6 km (maximum horizontal extent) of well-banded, silty metasediments with minor pyroclastic units. The foliation swings from 140° in the south to 005° in the north. A change in dip from moderate to steep westerly in the southwest to steep easterly in the northeast may be the result of folding. There is a local steep, north-plunging lineation, but no direct evidence of folding was observed. The total thickness of the unit is not exposed since it is fault-bounded to the west and intruded by adamellite to the south. The formation passes conformably into the overlying Wells Formation and the transition is marked by a rapid increase in felsic pyroclastic rocks.

The type area is on a ridge, 4.8 km east-southeast of George Hill. A 60 m wide sequence of grey and cream metasiltstone units ranges from a few millimetres to 20 cm in thickness and trends 141/75° E. A few thin bands containing ovoid lenses and felsic fragments are deformed agglomerate horizons.

An important feature is the presence of thin veins of fine, even-grained granite. These are generally parallel to the banding, but do locally transgress it. The metasiltstones can be traced to the northwest where they are underlain by a poorly exposed sequence of quartz-mica schist, metasiltstone, metatuff and fine-grained metagreywacke. It is often difficult to distinguish the tuffaceous rocks from metasediments.

WELLS FORMATION

The formation is named after Mount Wells, a prominent hill rising to 547 m, 17 km northwest of Boddington. Its maximum thickness is about 5.5 km, although it appears to thin to the south, being only about 2 km thick near the Hotham River. Rocks of the Wells Formation crop out for 32 km along the length of the greenstone belt. They consist of interdeveloped lavas (andesite, dacite and rhyodacite), tuffs, breccias, agglomerates and minor sediments, all variously deformed and metamorphosed. In general, lavas are more abundant in the north around Mount Wells, whilst pyroclastic rocks predominate south of the Bannister River. A further subdivision of the formation, based on the relative abundance of lavas and pyroclastic rocks, may be possible, but exposure is poor and there is insufficient data at present to justify a further breakdown.

Near the Hotham River, the Wells Formation conformably overlies the Hotham Formation and appears to be conformably overlain by the Marradong Formation. At Mount Wells, the junction with the overlying Marradong Formation appears sharp and conformable. There is a fairly abrupt change to metabasalt, although thin bands and lenses of metadacite occur within the basaltic rocks close to the contact. The western contact of the Wells Formation in this northern area appears to be fault-bounded.

The type area is on the western flank of Mount Wells. A 300 m section of metamorphosed dacites and rhyodacites (often porphyritic and schistose), with interbanded tuffs and minor sediments, is exposed in a west-trending gully. The porphyritic lavas contain oval quartz megacrysts up to 2 mm long, together with more diffuse megacrysts of feldspar. The rocks have a general trend of 148/64° E. It is often difficult to distinguish between fine-grained lavas, tuffs and sediments in the field.

Near Thirty Four Mile Brook, 4.6 km south of Mount Wells, schistose porphyritic dacite is underlain by chloritoid schist (trend 158/79° E). The schist is at least 10 m thick, but the base is obscured by laterite. It may represent a tuffaceous or pelitic horizon in the lava sequence.

Pyroclastic rocks of the Wells Formation are reasonably well exposed at Farmers Crossing and near the Hotham River. They consist chiefly of agglomerates, breccias and fine-grained tuffaceous rocks, with associated volcanogenic sediments, some of which are pyritic.

A serpentinized ultramafic rock occurs within the sequence, 4.2 km northwest of Farmers Crossing. It crops out for 50 m and lies subparallel to the volcanic rocks.

MARRADONG FORMATION

The formation is named after the townsite of Marradong, situated 7.5 km south-southwest of Boddington at the northern end of the Mount Saddleback range. It consists of 3 to 8 km of metabasalt, with apparently only minor intercalations of dark metasediment and rare metadacite. Exposure is very poor and the laterite cover is almost complete. The bauxite deposits of Mount Saddleback are developed over this formation.

The Marradong Formation conformably overlies the Wells Formation at Mount Wells. The junction is sharp, though a few bands and lenses of metadacite occur in the metabasalt close to the contact. The eastern boundary of the formation is everywhere faulted and its total thickness is unknown.

The type area is on Mount Saddleback, where the most continuous section is in a 400 m long "eye-shaped" incision into the laterite surface, 2 km south of Marradong. The rock is a fine-grained, schistose metabasalt with a general foliation trend of 166/81° E. Locally, thin, irregular, complexly folded veins of pink quartzo-feldspathic material traverse the rock. A 75 cm wide doleritic dyke cuts the sequence and is only distinguishable by its lack of foliation. Metabasalt devoid of quartzo-feldspathic veins is often more regularly schistose, with growth of amphibole along these surfaces.

An outcrop of metabasalt, 4 km northwest of Mount Saddleback summit, contains a 50 m wide intercalation of extremely fine-grained, pelitic metasediments associated with felsic volcanic/pyroclastic rocks. A smaller, 3 m wide, intercalation of felsic volcanic and pyroclastic rocks occurs 1.4 km northeast of Mount Wells.

INTERPRETATION

The main problem in interpreting the geology of the Saddleback Group is the paucity of exposure. Only four outcrops occur on the whole of the Mount Saddleback range, excluding a few fragmentary exposures (largely obscured by soil and colluvium) that are present along the flanks. Similarly poor exposure is typical of the whole greenstone belt. The natural diversity and rapidity of variation in such volcanogenic sequences also contributes to the uncertainty in correlation.

Correlation between such widely scattered outcrops is therefore hazardous and made even more so by the extensive block faulting that has affected the area (Fig. 51). Faulting on this scale of intensity is unusual in the Archaean of the southwestern Yilgarn Block. It appears to be related to the presence of the greenstone belt, although it does continue further eastward into the granitic terrain between Boddington and Wandering. In two fault-bounded blocks south of Tullis, no rock or colluvial fragments were found and grouping with the Wells Formation is thus open to question (Fig. 51).

A further complicating factor is the nature of the rocks themselves. With the exception of the agglomerates, it is extremely difficult to distinguish between the pyroclastic and sedimentary rocks in the field. This difficulty is enhanced by later deformation, so that sheared porphyritic dacite is virtually indistinguishable from certain deformed pyroclastic or gritty sedimentary rocks.

Examination of the rocks in thin section often throws little light on their origin. There has been extensive recrystallization associated with the deformation and metamorphism, so that few primary textures remain. The groundmass of original felsic lavas has been recrystallized and is now often similar, both in mineralogy and texture, to certain of the metasediments. The irregular distribution of constituents may help to differentiate tuffs from fine-grained lavas, but not from immature sediments, which also form part of the sequence.

The mafic volcanic rocks are generally distinct and consist of a fine-grained, ragged mosaic of amphibole and plagioclase, with minor quartz. Alteration to epidote and clinozoisite is often almost complete and primary textures are rare. However, the less altered rocks reveal an igneous rather than a metamorphic texture. The plagioclase laths have a fairly random orientation and are intergrown with the amphibole. This confirms the classification of the rocks as metabasalts rather than as amphibolites.

REGIONAL CONTEXT

The Saddleback Group appears to show a closer resemblance to the typical Archaean greenstone belts of the Eastern Goldfields Province of the Yilgarn Block, than any comparable rock sequence from the southwestern part of the block of which details have been published. It is a 5 to 12 km wide belt consisting predominantly of basalt and felsic volcanic and pyroclastic rocks, with minor sediments. The metamorphic grade is low and the original nature of the rocks is still discernible.

The group thus occupies an anomalous position, since all other known layered sequences within a distance of several hundred kilometres have a much higher metamorphic grade (amphibolite to granulite facies) and consist predominantly of metasediments and quartzo-feldspathic gneisses (of presumed sedimentary origin); no unequivocal mafic or felsic volcanic rocks have been recorded.

The presence of a weakly metamorphosed greenstone belt in a region characterized by vastly different layered sequences of higher metamorphic grade has important implications. The belt is intruded by even-grained granitic rocks, presumably formed during the 2 600 m.y. event common throughout the Yilgarn Block (Arriens, 1971). The rocks are thus older than this granite but probably younger than the more strongly metamorphosed layered rocks of the Jimperding Metamorphic Belt that date back to over 3 000 m.y. (Arriens, 1971). It is possible, therefore, that the Saddleback Group represents a younger Archaean greenstone belt assemblage that was deposited on a basement of pre-existing Archaean layered rocks, akin to the Jimperding Metamorphic Belt (Wilde, 1974). Granite gneiss and migmatite in the vicinity of Mount Saddleback may represent vestiges of this older layered sequence.

REFERENCES

Arriens, P. A., 1971, The Archaean geochronology of Australia: Geol. Soc. Australia, Special Pub. No. 3, p. 11-23.

Wilde, S. A., 1974, Explanatory notes on the Archaean rocks of the Perth 1 : 250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1974/15 (unpublished).

RECENT EXPLORATION FOR URANIUM IN THE KIMBERLEY REGION

by J. D. Carter

ABSTRACT

Uranium exploration in the Kimberley region during the period 1968-1975 as reported to the Mines Department involved 31 operations. There was core drilling during eight of these. Total exploration expenditure was probably of the order of several million dollars.

No economic deposit of uranium was proved though five occurrences of secondary uranium minerals were discovered.

It is suggested that conglomerates in the Kimberley Basin, apparently promising for uranium accumulation, are unmineralized because when these were deposited, likely source rocks of uranium had not been uncovered by erosion.

Most operations were preceded by airborne radiometric surveys. This cover of important parts of the geology is such that it is unlikely that there are, in these districts, unidentified uranium-based radioactive anomalies of any consequence detectable by the method.

The review illustrates examples of repetitious operations obtaining similar results and has a purpose of helping operators to avoid further duplication of exploration ventures.

INTRODUCTION

Since 1968, the Kimberley region of Western Australia has been a scene of moderately intense exploration for uranium with many companies participating, though none have discovered an economic uranium ore body. On this exploration there is little published information and for this reason the main results of ventures described in reports to the Mines Department are now brought together. It is hoped that the review will assist industry contemplating uranium exploration in the Kimberley region and in particular will help to avoid duplication of exploration ventures. There are cases of repetitous exploration obtaining similar results. For example, during separate operations begun in 1969 and 1973, each involving airborne radiometric surveys and ground follow-up, the venturers both detected the same small body of radioactive conglomerate within the Pentecost Sandstone. This was the subject of follow-up work, with the similar conclusion being reached that thorium probably was responsible for the radioactivity (operations G.S.W.A. M* 445 and 1408, and Tables 24 and 29 this report).

*Reports on mineral exploration other than for oil, gas and coal received from the industry by the Geological Survey are prefixed by M.

Exploration for uranium in the Kimberley region has passed through two periods of heightened activity, the first between 1955 and 1961 and the second taking place since 1968. The earlier activity was in response to the work of Traves (1955) who drew attention to the similarity of the geology of the country near Katherine and Darwin in Northern Territory, where there are ore bodies of uranium (Rum Jungle), to the geology of the Halls Creek district in the east Kimberley region. A result was a high-level airborne reconnaissance scintillometer survey carried out by the Bureau of Mineral Resources, Geology and Geophysics (BMR) when radioactive anomalies were recorded (Goodeve, 1955). Parts of the survey area were reflown by the BMR at low level using scintillometer (Gardener, 1960). No economic uranium deposits were discovered. Dow and Gemuts (1969) record exploration results of this period, the most interesting being the find of minor secondary uranium mineralization near Dunham Hill where autunite coats joints in a basic dyke and torbernite infills shears in granite.

During the years now under review, between 1968 and 1975, there was an upsurge in mineral exploration throughout Western Australia generally and renewed interest was shown in the uranium potential of the Kimberley region. The majority of ventures were mounted in response to a combination of apparently favourable geology and encouraging results of airborne radiometric surveys. Much attention was given to a radioactive conglomerate within the King Leopold Sandstone, cropping out along the western margin of the Halls Creek mobile zone (Fig. 52). Exploration results, however, once more were disappointing. Anomalous radioactivity was found to stem mainly from thorium minerals. No economic uranium deposit was disclosed although three uranium occurrences were thought to be sufficiently attractive to merit detailed evaluation (M395, 648/1 and 648/2).

In Table 24, the operations reported, 31 in number, are listed; Figure 52 shows that the greater part of the work took place over the southern portion of the Halls Creek mobile zone and along the margin of the Kimberley Basin adjoining this zone. It should be understood that the total exploration effort for uranium is not represented in this review. Only those operations reported to the Mines Department are described. Exploration over open ground does not carry reporting obligations and preceding many of the operations summarized in Table 24, examinations of very much larger tracts of country than those listed took place (usually employing radiometry). Since unfavourable results were eventually obtained from ground selected as the more promising, it follows that the uranium potential of ground rejected initially should be less favourable.

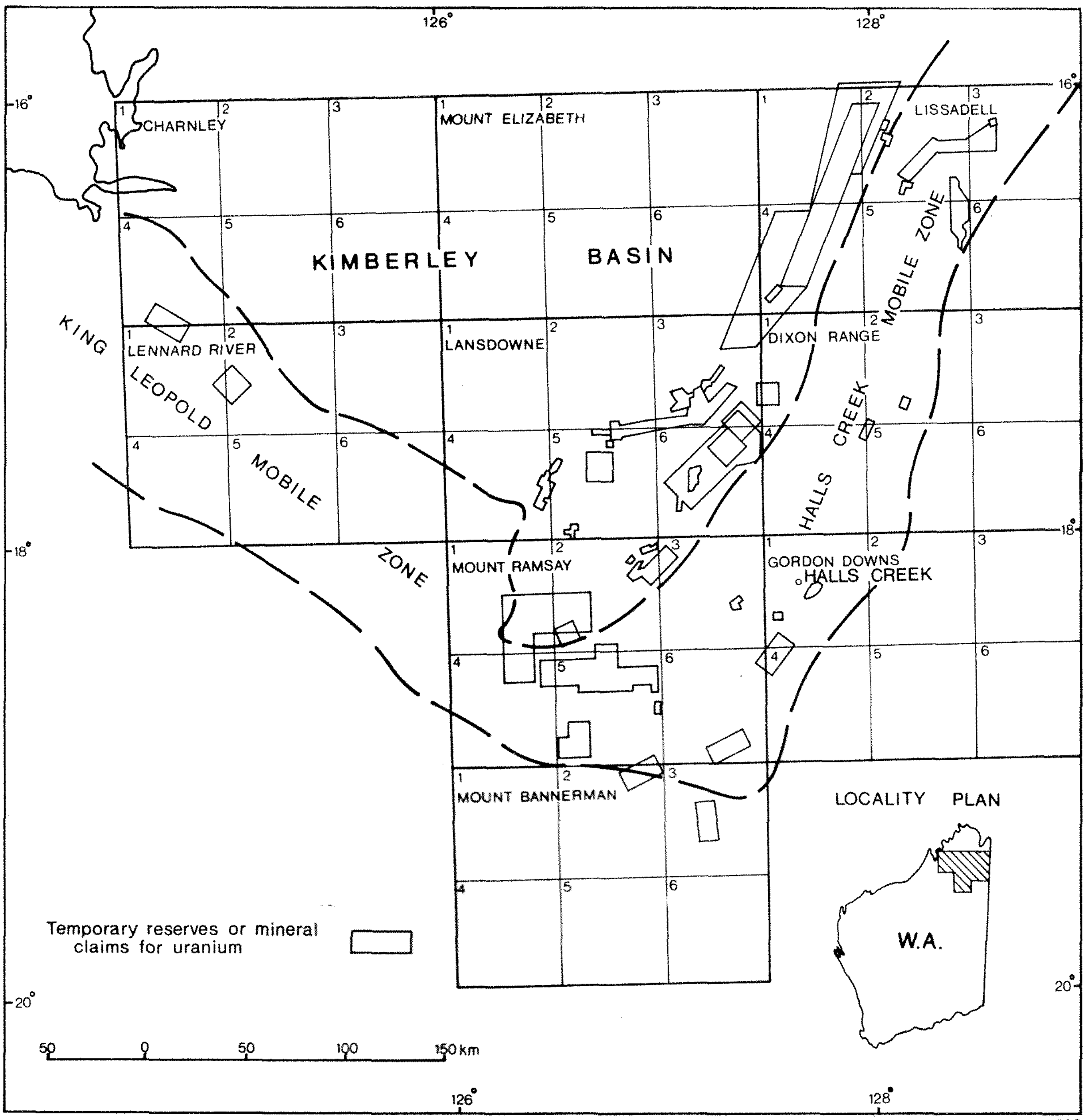


Figure 52. Kimberley region. Uranium exploration-principal locations.

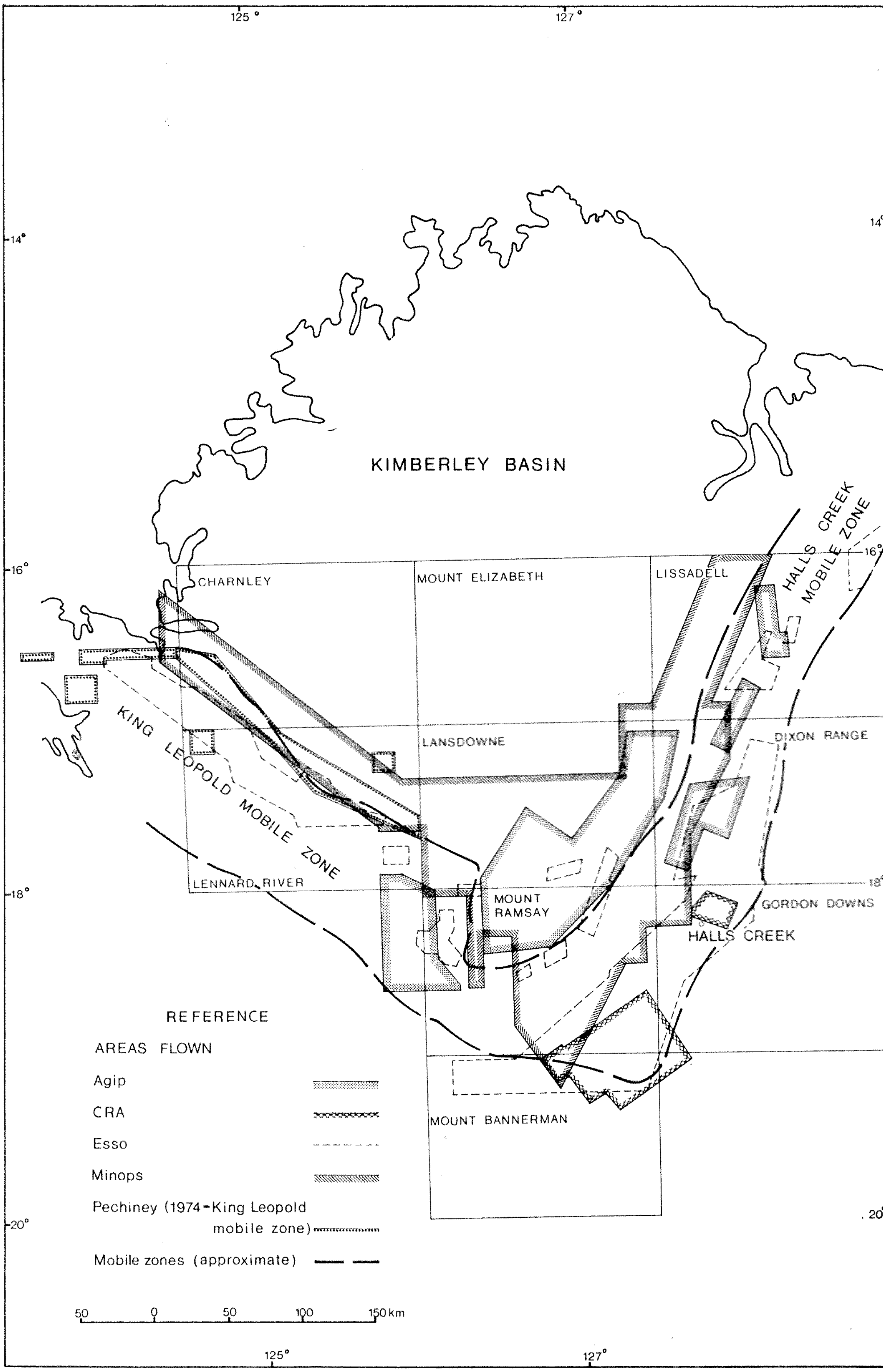


Figure 53. Selected regional airborne radiometric surveys.

The review is compiled from reports of operations chiefly made over mineral claims and Temporary Reserves* submitted to the Mines Department. The operating companies concerned are listed, together with abbreviations adopted to denote these companies:

- Agip Nucleare Australia Pty. Ltd.—Agip
- Australian Anglo American Ltd.—Aust Anglo American
- Carpentaria Exploration Company Pty. Ltd.—Carpentaria
- C.R.A. Exploration Pty. Ltd.—CRA
- Durack Mines Limited—Durack
- Esso Australia Ltd.—Esso
- Gunn Land and Exploration Partnership—Gunn Land
- Metals Miniere Ltd., M.M. Exploration Pty. Ltd. and Uranerzbergbau GmbH Co KG—MMEX-UEB
- Newmont Pty. Ltd.—Newmont
- Pickands Mather and Co. International—PMI
- South Pacific Miniere Pty. Ltd.—South Pacific Miniere
- The Broken Hill Pty. Co. Ltd.—BHP
- Trend Exploration Pty. Ltd.—Trend

*Temporary Reserve (T.R.), Crown Land reserved for mineral exploration.

GEOLOGY

For descriptions of the geology of the Kimberley region, publications listed in References should be consulted, particularly Thom (1975) who provides the most complete account. In Table 23 the rock units which have been principal targets for uranium exploration are listed and their more important outcrop areas are shown on Figure 54.

TABLE 23. STRATIGRAPHY AND OPERATIONS.

Unit	Formation	Lithology	Operations G.S.W.A. M
Upper Devonian	Ragged Range Conglomerate Member	Quartz conglomerate (300 m+)*	648/1
Proterozoic Louisa Downs Group		Sandstone, siltstone, shale, conglomerate, dolomite and tillite (up to 3 800 m)	298
Kuniandi Group		Sandstone, greywacke, siltstone, shale and tillite (up to 1 600 m)	298
Carr Boyd Group	Hensman Sandstone	Massive silicified quartz sandstone (150–250 m)	648/8
Kimberley Group	Pentecost Sandstone	Quartz sandstone with minor conglomerate (1 150 m)	445; 1408; 1409
	Elgee Siltstone	Siltstone and shale with sandstone (65–300 m)	
	Warton Sandstone	Sandstone with minor shale (210–900 m)	
	Carson Volcanics	Basalt with sandstone (300–900 m)	
	King Leopold Sandstone	Quartz sandstone, feldspathic sandstone and minor conglomerate (1 400 m)	290 and 328; 305, 330 and 340; 445; 695/1, 2 and 3; 985
Speewah Group	Luman Siltstone	Siltstone, shale and minor sandstone (900 m)	
	Lansdowne Arkose	Feldspathic sandstone, arkose, shale and siltstone (up to 500 m)	328; 1410; 1494; 1495/1
	Valentine Siltstone	Siltstone, sandstone, rhyolite and tuff (30–70 m)	
	Tunganary Formation	Quartz sandstone, arkose and siltstone (up to 1 100 m)	
	O'Donnell Formation	Subgreywacke, sandstone and shale (up to 300 m)	395; 1410; 1495/2
	Revolver Creek Formation	Basalt with arkose, sandstone and slate (up to 1 200 m)	338
	Moola Bulla Formation	Arkose, greywacke, siltstone, sandstone, conglomerate and shale (3 000 m+)	67/50
Lamboo Complex	Whitewater Volcanics	Rhyodacite tuff, tuffaceous siltstone, sandstone and conglomerate	648/7
	Undifferentiated igneous rocks	Granodiorite, tonalite, gabbro and ultrabasic	
	Acid igneous rocks	Granite, quartz feldspar porphyry and rhyolite	298; 338; 435; 648/2; 1184; 1498; 1499; 1660
	Tickalara Metamorphics	Schist, paragneiss, orthogneiss, migmatite, amphibolite and calc-silicate rocks	1551
(?) *Archaean*	Undifferentiated	Schist, quartzite, siltstone and greywacke	
	Olympio Formation	Subgreywacke, arkose, siltstone, minor dolomite and conglomerate (3 000 m+)	1288; 1412; 1673
Halls Creek Group	Biscay Formation	Basic lava, greywacke, siltstone and dolomite (1 500–3 000 m)	1288; 1497
	Saunders Creek Formation	Quartz conglomerate, sandstone and greywacke (to 195 m)	

* Thicknesses in brackets

The essential features are the Kimberley Basin containing flat-lying sedimentary and volcanic rocks of the Middle Proterozoic, and the Lower Proterozoic geosynclinal sediments, metamorphic and igneous rocks of the Halls Creek Province which flank the basin to the east and southwest (Fig. 52). The eastern arm of the province is termed the Halls Creek mobile zone and the western, the King Leopold mobile zone. The oldest rocks are geosynclinal sediments of the Halls Creek Group which could be Archaean or Lower Proterozoic in age, and crop out along the mobile zones. The Halls Creek Group is intruded by a wide range of Lower Proterozoic igneous rocks including granite, quartz feldspar porphyry and rhyolite named the Lamboo Complex. Metamorphic rocks formed from the Halls Creek Group are termed Tickalara Metamorphics. These units are unconformably overlain by the gently folded but extensively faulted and largely unmetamorphosed, Middle Proterozoic and younger, sedimentary and volcanic rocks which form the Kimberley Basin.

EXPLORATION

GENERAL

Operations are listed in Table 24.

The Table does not incorporate ventures mounted to search for other commodities in course of which there may have been incidental exploration for uranium. Under "Principal Geological Targets" the rock units shown were those selected for the main exploration effort. Targets of casual operations, such as those performed to check sporadic radioactive anomalies of low priority, are not included. The "Location" code refers to the six 1:100 000 sheets of the quarter-million sheets of the International Grid. These have a four-figure code number in the International System but are designated here Nos. 1, 2, 3, 4, 5 and 6 (Fig. 52). "Area" refers to approximate areas of ground secured for operations under mineral claims and Temporary Reserves and as explained in the Introduction, the figures often represent the least extent of country examined.

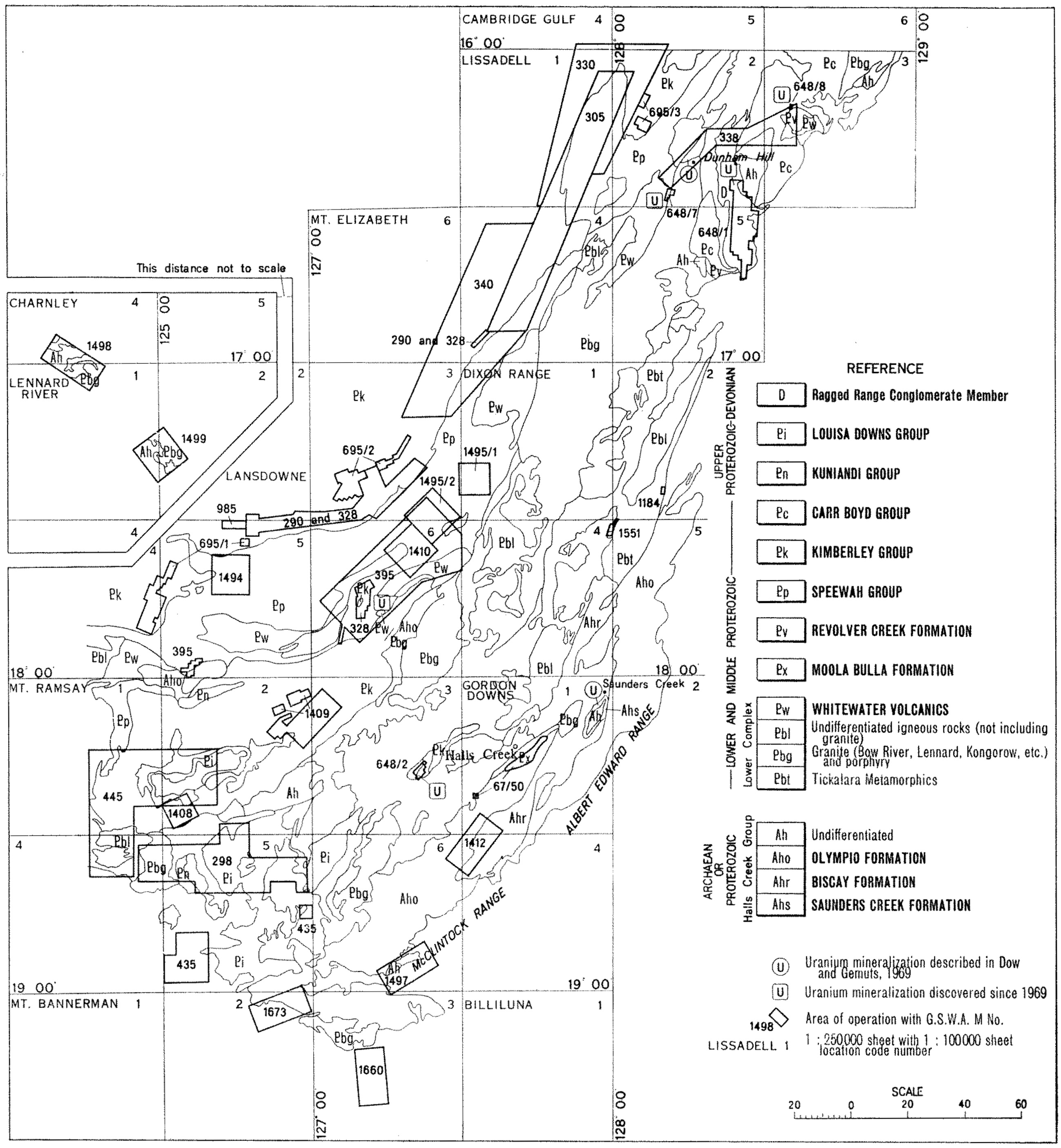


Figure 54. Geology and operations locations.

Types of uranium occurrences sought are usefully described following the method adopted by Bowie (1970) as either "peneconcordant", that is, deposits within conglomerates and sandstones, or, "discordant", referring to mineralization within features such as veins, shears and faults. For some operations the type of uranium occurrence sought is neither stated nor clear. In general however, during operations conducted over Halls Creek Group and Lamboo Complex units, uranium occurrences in discordant situations were considered ("Principal Geological Targets", Tables 24 and 25; Tables 26 and 27). Venturers over post-Lamboo Complex rocks such as the Speewah and Kimberley Groups generally searched for peneconcordant mineralization within sandstones and more particularly within conglomerates of the Lansdowne Arkose and King Leopold Sandstone ("Principal Geological Targets", Tables 24 and 25; Tables 28 and 29).

Exploration methods are summarized in Table 24. The general approach was to commission total radioactivity or gamma spectrometer airborne surveys to precede standard geological survey procedures, ground radiometric traverses and chemical assays. No other primary geophysical exploration method was reported though certain geophysical techniques including radon measurement were tested (M648/1). Drillholes were usually radiometrically logged. Geochemical methods of exploration were represented by a few drainage surveys, and soil surveys in two operations (M648/1, 2). Results of drainage surveys were apparently inconclusive, or negative. Soil surveys were considered useful in delimiting uranium anomalies. During some operations natural waters were analysed but no systematic hydrogeochemical survey appears to have been attempted. Of the sedimentary units examined, evidently only the King Leopold Sandstone was the subject of detailed sedimentological studies (M290 and 328).

TABLE 24.—OPERATIONS SUMMARY

G.S.W.A. M	Operating Company	Principal Geological Targets	Tenement	Location	Area km²	Duration	Principal Exploration Methods	Uranium Mineralization	Remarks
67/50	PMI	Moola Bulla Formation	....	Gordon Downs 1	130	1969–70	Airborne spectrometer survey, ground surveys, core drilling, assays	None	
290 and 328	BHP	Lansdowne Arkose King Leopold Sandstone	T.R.s 4742H and 5016H; mineral claims	Lansdowne 2, 3, 5, 6 Lissadell 4	500	1968–71	Airborne scintillometer survey, ground surveys, sedimentological studies, core drilling, assays	None	King Leopold Sandstone was explored in two localities (M290 and 328, Fig. 54); Lansdowne Arkose was explored in one locality (M328, Fig. 54)
298	BHP	Louisa Downs and Kuniandi Groups; Bow River Granite	T.R.4704H	Mount Ramsay 2, 4, 5	930	1968–72	Airborne spectrometer survey, ground surveys, assays	None	
305, 330 and 340	Durack	King Leopold Sandstone	T.R.s 4651H, 5001H and 5013H; mineral claims	Cambridge Gulf 4, 5 Lissadell 1, 2, 4 Mount Elizabeth 6 Lansdowne 3 Dixon Range 1	3 535	1968–72	Heli-borne, scintillometer surveys, ground surveys, core drilling, assays	None	Unified operation. Principal exploration was over the southern part of M340 (Lansdowne 3, Fig. 54)
338	BHP	Bow River Granite near Dunham Hill; Revolver Creek Formation	T.R.5051H	Lissadell 2, 3	438	1969–71	Airborne scintillometer survey, ground surveys assays	None	
395	South Pacific Miniere	Speewah Group, principally O'Donnell Formation	T.R.5112H	Lansdowne 3, 5, 6	1 183	1969–73	Heli-borne spectrometer survey, ground surveys, core drilling, assays	Phosphuranylite	Sporadic low-grade secondary uranium mineralization found in O'Donnell Formation was shown not to be economic
435	Gunn Land	(?) Bow River Granite	T.R.s 5082H and 5083H	Mount Ramsay 5	270	1969	Ground scintillometer traverses, assays	None	Very small-scale exploration in two localities
445	Newmont	Kimberley Group	T.R.4695H	Mount Ramsay 1, 2, 4	1 308	1969–71	Heli-borne scintillometer survey, ground surveys, shallow non-core drilling, assays	None	Radioactive anomalies were detected over Pentecost Sandstone only
648/1	MMEX–UEB	Ragged Range Conglomerate Member	Mineral claims	Lissadell 2, 5	200	1971	Heli-borne spectrometer survey, ground surveys including geochemical surveys, core drilling, assays	Carnotite	Trenching and drilling did not prove mineralization of economic potential

648/2	MMEX–UEB	Lamboo Complex gneisses	Mineral claims	Mount Ramsay 3	12	1971–73	Heli-borne spectrometer survey, ground surveys including geochemical surveys, core drilling, assays	Carnotite	Mineralization considered not to be economic. Ground is now covered by T.R.5959H
648/7	MMEX–UEB	Whitewater Volcanics	Mineral claims	Lissadell 2	6	1971	Heli-borne spectrometer survey, ground surveys, assays	Secondary uranium minerals	Mineral claims surrendered
648/8	MMEX–UEB	Hensman Sandstone	Mineral claims	Lissadell 3	<1	1971–73	Heli-borne spectrometer survey, ground surveys, assays	Phosphuranylite, torbernite	No further exploration recommended; mineral claim withdrawn
695/1	CRA	King Leopold Sandstone	Mineral claims	Landsdowne 4, 5	135	1968–71	Airborne including heli-borne scintillometer surveys, ground surveys, core drilling, assays	None	Minops Pty. Ltd. was the initial operating company of M695/1, 2 and 3
695/2	CRA	King Leopold Sandstone	Mineral claims	Lansdowne 3	100	1968–71	Airborne scintillometer survey, ground surveys, core drilling assays	None	
695/3	CRA	King Leopold Sandstone	Mineral Claims	Lansdowne 2	35	1968–71	Airborne scintillometer survey, ground surveys core drilling, assays	None	
985	Carpentaria	King Leopold Sandstone	Mineral claims	Lansdowne 5	29	1970–71	Fixed wing spectrometer survey	None	
1184	Aust Anglo American	Lamboo Complex Granite	Mineral claims	Dixon Range 2	4	1973	Ground scintillometer surveys, assays	None	
1288	Trend	Biscay and Olympio Formations	....	Gordon Downs 1	....	1973	Ground spectrometer surveys, assays	None	BMR 1959 airborne survey radioactive anomalies examined are not shown on Fig. 54
1408	Agip	Pentecost Sandstone	T.R.5767H	Mount Ramsay 1, 2	100	1973–74	Fixed wing spectrometer survey, ground surveys, assays	None	
1409	Agip	Pentecost Sandstone	T.R.5768H; mineral claims	Mount Ramsay 2, 3	285	1973–74	Fixed wing spectrometer survey, ground surveys, pitting, assays	None	
1410	Agip	Speewah Group, principally Lansdowne Arkose	T.R.5769H	Lansdowne 6	189	1972–74	Fixed wing and heli-borne spectrometer surveys, ground surveys, assays	None	

TABLE 24.—OPERATIONS SUMMARY—*Continued*

G.S.W.A. M	Operating Company	Principal Geological Targets	Tenement	Location	Area km²	Duration	Principal Exploration Methods	Uranium Mineralization	Remarks
1412	Esso	Olympio Formation	T.R.5793H	Gordon Downs 1, 4 Mount Ramsay 6	200	1973–74	Fixed wing spectrometer survey, ground surveys, percussion drilling, assays	None	
1494	Agip	Speewah Group, principally Lansdowne Arkose	T.R.5897H	Lansdowne 5	196	1972–74	Fixed wing spectrometer survey, ground surveys, assays	None	
1495/1	Agip	Lansdowne Arkose	T.R.5898H	Dixon Range 1 Lansdowne 3	184	1972–74	Fixed wing spectrometer survey, ground surveys, assays	None	
1495/2	Agip	O'Donnell Formation	T.R.5899H	Lansdowne 3, 6	184	1972–74	Fixed wing spectrometer survey, ground surveys, assays	None	
1497	CRA	Biscay Formation	T.R.5918H	Mount Ramsay 6 Mount Bannerman 3	200	1974	Fixed wing spectrometer survey, ground surveys, assays	None	
1498	Esso	Lamboo Complex granites	T.R.5892H	Lennard River 1, 2	200	1973–74	Fixed wing spectrometer survey, ground surveys, percussion drilling, assays	None	Initial target was Halls Creek Group in the King Leopold mobile zone
1499	Esso	Lamboo Complex granites	T.R.5891H	Charnley 4 Lennard River 1	200	1973–74	Fixed wing spectrometer survey, ground surveys, assays	None	Initial target was Halls Creek Group in the King Leopold mobile zone
1551	Agip	Tickalara Metamorphics	Mineral claims	Dixon Range 2, 4, 5	12	1972–73	Fixed wing spectrometer survey, ground surveys, assays	None	
1660	CRA	Lamboo Complex granite	T.R.5950H	Mount Bannerman 3	200	1974–75	Fixed wing spectrometer survey, ground surveys, percussion drilling, assays	None	
1673	CRA	Olympio Formation	T.R.5956H	Mount Ramsay 5 Mount Bannerman 2	200	1974–75	Fixed wing spectrometer survey, ground surveys, assays	None	

REGIONAL AIRBORNE RADIOMETRIC SURVEYS

Information on 14 regional airborne radiometric surveys is listed in Table 25 and ground examined during five surveys is shown on Figure 53. Line kilometres flown totalled approximately 135 000. The majority of surveys were made over the Halls Creek mobile zone and adjoining parts of the Kimberley Basin. A number are not shown on Figure 53 (including important surveys by BHP: M382 and 333; MMEX-UEB; Pechiney (i) 1971; and South Pacific Miniere). These were flown over country lying within the eastern limit of surveys of Esso and the western limit of Minops' cover, and in general were directed towards King Leopold Sandstone outcrops and stratigraphy close to principal unconformities, particularly to the unconformity below the Speewah Group. Along the Halls Creek mobile zone, the density of airborne radiometric cover over ground near the principal unconformities immediately below the Kimberley Basin and the King Leopold Sandstone outcrop on their west is such that it is unlikely that radioactive anomalies of any importance detectable by the techniques employed remain unidentified.

Surveys reported over the King Leopold mobile zone are shown on Figure 53. These were flown over stratigraphy associated with unconformities at the base of the Kimberley Basin sequence, and the Halls Creek Group (Esso).

HALLS CREEK GROUP

The Halls Creek Group forms the basement within the Halls Creek and King Leopold mobile zones and consists of folded, often slightly metamorphosed geosynclinal sediments (Table 23). Similarities between the geology of these rocks and the geology of the uranium province of Rum Jungle were largely responsible for initiating uranium exploration in the east Kimberley region in the 1950s. Near the base of the group, radioactive sandstone and conglomerate of the Saunders Creek Formation occur. These were unsuccessfully explored for uranium by diamond drilling, when the highest core assay was 0.16 per cent equivalent U_3O_8 over 10 cm and thorogummite was shown to be the principal radioactive mineral (Mercer, 1961).

Four small operations, listed in Table 26, were mounted over the Biscay and Olympio Formations but no uranium minerals were found. Although the ground examined during these ventures constitutes a very minor part of the group's outcrop, its units within the Halls Creek mobile zone have been the subject of several airborne radiometric surveys and it may be assumed that the majority, if not all, of radioactive anomalies within them, detectable by current methods, have been assessed for uranium content and rejected.

LAMBOO COMPLEX

Igneous and high-grade metamorphic rocks of the Lamboo Complex are found principally within the Halls Creek and King Leopold mobile zones. On Figure 54 the geology of the complex is simplified, the members being grouped in three categories. Rocks usually of immediate relevance to uranium exploration such as granite and quartz-feldspar porphyry are represented separately while other igneous rocks are grouped together. The third category shown is main outcrop areas of Tickalara Metamorphics. One unit, the Bow River Granite, is noteworthy by reason of its close association near Dunham Hill with minor occurrences of torbernite and autunite, the only uranium minerals recorded in the east Kimberley region by Dow and Gemuts (1969).

Ten operations were reported and their main features are shown in Table 27. During the single large-scale venture (M648/2), carnotite mineralization was found within a shear in gneissic rocks. The prospect was the subject of detailed exploration including core drilling; no conclusion was reached about its economic potential. This mineralization is now being explored under T.R.5959H. One other minor occurrence of secondary uranium minerals was identified. These were found in fractures within Whitewater Volcanics (M648/7). An attempt to find extensions of the Dunham Hill secondary mineralization was unsuccessful (M338).

Esso describe exploration of the uranium potential of the King Leopold mobile zone, this representing the only operation on the ground in the western part of the Kimberley region. The outcome of Esso's airborne radiometric surveys (shown on Fig. 53) consisted of disappointing results obtained from examinations of granites emplaced within envelopes of undifferentiated representatives of the Halls Creek Group (M1498 and 1499).

As in the case of the Halls Creek Group, while the extent of Lamboo Complex exposure reported as being examined is not great, these rocks, particularly in the Halls Creek mobile zone, have been surveyed by several operators using airborne radiometric techniques and it is possible that most, if not all radioactive anomalies detectable by available instrumentation have been located (Fig. 53).

SPEEWAH GROUP

Sandstone, arkose, greywacke and siltstone characterize the essentially arenaceous Speewah Group. It lies unconformably on rocks of the Lamboo Complex. The group consists of five formations (Table 23), exposures of two of which, the basal O'Donnell Formation and the Lansdowne Arkose near the top, have been examined closely for uranium mineralization.

Features of six investigations over these rocks are listed in Table 28. The largest operation (M 395) was directed towards the basal portion of the O'Donnell Formation around a small anticline near Mad Gap Yard exposing Whitewater Volcanics and Lamboo Complex granite (Lansdowne 6). Sporadic, low-grade secondary uranium mineralization represented by phosphuranylite was found but no commercial potential has been demonstrated as yet. Exploration was conducted principally in two separate large-scale programmes, each involving substantial core drilling, and conclusions from both were that there is no significant depth extension of the small surface mineralization. Some 30 km northeast of Mad Gap Yard, no uranium mineralization was detected during two operations over the O'Donnell Formation where the geological setting is similar (M1410 and 1495/2).

Radioactivity of the Lansdowne Arkose has been shown so far to stem mainly from thorium minerals. During the largest operation, radioactive conglomerates were explored by core drilling in the Carola Syncline. The conglomerates were found to be oxidized to at least depths of 300 m where their low radioactivity appeared to be thorium-based (M328).

Although the proportion of outcrop of the Speewah Formation explored on the ground for uranium is not great, a much larger part has been covered by airborne radiometric surveys (Fig. 53) and the lack of response to results of these, in terms of work on the ground, downgrades the uranium potential of this group in these areas.

KIMBERLEY GROUP

Formations of the Kimberley Group (Table 23) are essentially arenaceous, consisting mainly of quartz sandstone with siltstone and dolomite, and a basaltic formation, being altogether some 3 000 m thick. The group lies conformably on the Speewah Group although locally it is unconformable, transgressing the Speewah Group to rest on older rocks. It underlies the entire area of the Kimberley Basin. Of the five formations, the King Leopold Sandstone at the base of the group and the Pentecost Sandstone at the top have been principal targets for uranium exploration, but no uranium mineralization has been reported from any formation.

TABLE 25. REGIONAL AIRBORNE RADIOMETRIC SURVEYS 1968-74

Operating Company	G.S.W.A. M	Contractor	Aircraft	Instrument	Line km (Area km²)	Terrain Clearance/ Line Spacing metres	Principal Geological Targets	Remarks and Data Held
Agip*	1408, 1409, 1410, 1494, 1495 and 1551	Hunting Geology and Geophysics Ltd.	Fixed wing	Nuclear Enterprises NE 8424 Mark 15 spectrometer	18 140	90/800	Halls Creek Group, Lamboo Complex, Speewah and Kimberley Groups	
BHP	298	Geophysical Resources Development Co.	n.a.**	Spectrometer	6 100	90/800	Louisa Downs and Kuniandi Groups, Lamboo Complex	Survey data and plans showing total count and 1·6 to 2·0 Mev contours
BHP	328 and 338	n.a.	Fixed wing Helicopter	Spectrometer Scintillometer	40 250 16 100	n.a. n.a.	Principally sediments of the Kimberley Basin; Dunham Hill secondary uranium mineralization	
Carpentaria	985	Geophysical Resources Development Co.	Fixed wing	Exploranium DGRS 1000 spectrometer	790	90/200	King Leopold Sandstone	Plan showing thorium anomaly spots
CRA*	1497, 1660 and 1673	Geometrics International Corporation	Fixed wing	Exploranium DIGRS 3001 spectrometer	(i) 2 900 (ii) 120	n.a. / 1 500 n.a. / 5 000	McClintock Range geology Albert Edward Range geology	
Esso*	(i) 1412 (ii) 1498 and 1499	Geometrics International Corporation Aero Service (Australia) Pty. Ltd.	Fixed wing Fixed wing	Exploranium DIGRS 3001 spectrometer Hammer-Harshaw 10 crystal spectrometer	about 7 300 5 600	150 / 1 600 & 3 200 (infill 800 and 400) 120 / 800 and 1 600 (infill 400)	Halls Creek Group in Halls Creek mobile zone Halls Creek Group in King Leopold mobile zone	
Minops Pty. Ltd.*	695/1, 2, and 3	Hunting Geology and Geophysics Ltd.	n.a.	Harwell series 1531A scintillometer	about 18 000	120–150 / 1 600	Halls Creek and King Leopold mobile zones, and adjoining parts of the Kimberley Basin	Plans showing anomaly spots
MMEX-UEB	648/1, 2, 7 and 8	Terratest AB (Stockholm)	Helicopter	Spectrometer	11 362	n.a. / 200	Parts of Halls Creek Group and Lamboo Complex in Halls Creek mobile zone and principal unconformities above these. Ragged Range Conglomerate Member	Plans showing anomaly spots
Newmont	445	n.a.	Helicopter	Scintrex GIS-2 scintillometer	(260 km²)	30 / 400	Kimberley Group	Plan showing anomaly spots

Pechiney (Australia) Exploration Pty. Ltd. (No ground survey was carried out; this operation is **not** listed in Table 24)	1681	(i) 1971	Fixed wing	SPAT 3 scintillometer	1 620	(?75 / 800)	King Leopold Sandstone and adjacent formations cropping out between Lansdowne 3 and Lissadell 2	Anomalies were not checked on the ground which was examined largely during operations M 290 and 328; 305, 330 and 340, and 695/3
		(ii) 1974*	Fixed wing	DGRS 1002 spectrometer	2 620	75 / 800 and 1 600	Parts of Speewah Group and Kimberley Group, particularly basal sections; Devonian Van Emmerick Conglomerate (Lennard River 1)	No anomaly warranted checking on the ground
South Pacific Miniere	395	Terratest AB (Stockholm)	Helicopter	Spectrometer	5 488	20 / 200	O'Donnell Formation	Plans showing total count, K40 channel and U channel contours
Western Nuclear Australia Ltd.	290	n.a.	n.a.	n.a.	n.a.	n.a.	King Leopold Sandstone conglomerates on Lansdowne Sheet	Airborne scintillometer survey

* The approximate extent of ground flown is shown on Figure 53.

** n.a.—information not available.

TABLE 26. HALLS CREEK GROUP EXPLORATION SUMMARY

G.S.W.A. M	Initial Target	Drilling	Geophysical Response Max. X Background (*Spectrometric)	Max. Chemical Assay ppm U_3O_8	Conclusions	Remarks
1288 (Trend)	BMR 1959 airborne survey radioactive anomalies over Biscay Formation	....	....	37	No anomaly showed a significant uranium content when examined by spectrometer	A "Rum Jungle situation" was sought
1412 (Esso)	Airborne survey radioactive anomalies over Olympio Formation	73 non-core holes for 4 450 m	4–5X*	383	Ironstones within Olympio Formation and sheared dolerite carry low uranium values	Ironstones are assumed to be of intense ferruginization
1497 (CRA)	Biscay Formation	....	No radioactive anomalies of interest detected by airborne spectrometer survey	<10	No promising host lithologies are present. Environment is not similar to that of Rum Jungle	Ground selected on basis of possible favourable lithologies near McClintock Range Granite
1673 (CRA)	Airborne survey radioactive anomalies over (?) Olympio Formation	....	1·2X*	50	Anomalous uranium value in ferruginized quartzite due to scavenging by secondary iron minerals	

TABLE 27. LAMBOO COMPLEX EXPLORATION SUMMARY

G.S.W.A. M	Initial Target	Drilling	Geophysical Response Max. X Background	Max. Chemical Assay ppm U_3O_8	Conclusions	Remarks
298 (BHP)	Airborne survey radioactive anomalies over Bow River Granite	....	....	....	Low-order thorium mineralization causes radioactive anomalies	
338 (BHP)	Minor secondary uranium mineralization in Bow River Granite at Dunham Hill	....	....	....	Low-level airborne scintillometer traverses failed to detect extensions of known uranium mineralization	
435 (Gunn Land)	BMR 1954 airborne survey radioactive anomalies over (?) Bow River Granite	....	....	50	Operation terminated following negative results of scintillometer and geochemical traverses	Very small-scale exploration
648/2 (MMEX-UEB)	Airborne survey radioactive anomalies over gneissic rocks	8 core holes for 757 m; vacuum drilling	(Carnotite prospect)	(Carnotite prospect)	Carnotite mineralization in shear zone; mineralization considered not to be economic	Ground covered by T.R. 5959H
648/7 (MMEX-UEB)	Airborne survey radioactive anomalies over Whitewater Volcanics	....	(Secondary uranium minerals)	(Secondary uranium minerals)	....	Preliminary investigations were not followed up. The mineral claims were withdrawn
1184 (Aust Anglo American)	Ground survey radioactive anomalies over granite with cupriferous quartz veins	....	....	B.L.D.	Radioactive anomalies due either to potassium, or very minor thorium or uranium concentrations	
1498 (Esso)	Airborne survey radioactive anomalies over granites including Lennard Granite	13 non-core holes for about 670 m	2X (fixed-wing survey)	6 446	Uranium enrichment within shears in granite	No uranium minerals were reported. Drilling undertaken to determine lithologies
1499 (Esso)	Airborne survey radioactive anomalies over granites including Lennard and Kongorow Granites	....	2X (fixed-wing survey)	38	Minor uranium enrichment within shears in granite	
1551 (Agip)	Airborne survey radioactive anomalies over high-grade schists and gneisses of the Tickalara Metamorphics	....	5X	20	Operation terminated following discouraging results of ground follow-up	Very small-scale exploration
1660 (CRA)	Airborne survey radioactive anomally over Bow River Granite	37 non-core holes for about 962 m	....	13	Radioactivity caused by thorium minerals in pisolite veneer on granite	

Table 29 lists the main features of uranium exploration. Radioactive conglomerates up to about 10 m thick within the King Leopold Sandstone attracted attention by reason of similarities between their general geology and the geology of uranium-bearing conglomerates at Elliot Lake, Canada. Examinations of the conglomerates took place over a strike length of some 250 km (from Lissadell 2 to Lansdowne 4) and included percussion and diamond drilling. An unconformity situated within the King Leopold Sandstone below the conglomerates was demonstrated which is not shown on available geological maps (M290 and 328). A conclusion of the same sedimentological and structural study was that the conglomeratic horizons are of marine shoreline origin, representing coarse beach gravels with boulder deposits derived from headlands.

Drilling the conglomerates was performed primarily to determine whether there had been leaching, and redeposition of uranium at depth. A study of surface and drill-core samples showed a majority of samples were out of radioactive equilibrium (M695/1). However, the conclusions reached from each of the operations involving drilling was that uranium values were substantially the same both in outcrop and in depth. Near Mount Bedford (Lansdowne 3), the conglomerate was shown to be oxidised to a depth of at least 183 m (M290 and 328). Anomalous radioactivity of the conglomerates was attributed in all operations chiefly to the presence of thorium-bearing minerals, such as thorogummite.

TABLE 28. SPEEWAH GROUP EXPLORATION SUMMARY

Formation	G.S.W.A. M	Initial Target	Drilling	Geophysical Response Max. X Background (Spectrometric*)	Max. Chemical Assay ppm U_3O_8	Conclusions	Remarks
Lansdowne Arkose	328 (BHP)	Airborne survey radioactive anomalies	6 non-core holes for 937 m; one core hole for 210 m	Bore probes <2½ X	<50	Radioactivity is due to thorium	
	1410 (Agip)	Airborne survey radioactive anomalies	....	....	424 (red fine sandstone)	Radioactive anomalies are caused by thorium minerals	
	1494 (Agip)	Airborne survey radioactive anomalies	....	....	672 (heavy mineral sandstone)	Radioactive anomalies are caused by thorium minerals	
	1495/1 (Agip)	Airborne survey radioactive anomalies	....	....	731 (heavy mineral band)	Radioactive anomalies are caused by thin, discontinuous and only locally anomalous heavy mineral bands	
O'Donnell Formation	395 (South Pacific Miniere)	Geological setting of O'Donnell Formation	26 core and non-core holes for 1536 m	(phosphuranylite)	(phosphuranylite)	Low-grade secondary uranium mineralization occurs as sporadic surface enrichment with no significant extension in depth	
	1410 (Agip)	Airborne survey radioactive anomalies	....	....	<20	Radioactive anomalies located by fixed-wing survey were due to higher background values	No radioactive anomalies were detected during a heli-borne spectrometer survey
	1495/2	Airborne survey radioactive anomalies	....	....	47	Radioactive anomalies caused by lithological contrasts	

TABLE 29. KIMBERLEY GROUP EXPLORATION SUMMARY

Formation	G.S.W.A. M	Initial Target	Drilling	Geophysical Response Max. X Background	Max. Chemical Assay ppm U_3O_8	Conclusions	Remarks
Pentecost Sandstone	445 (Newmont)	Airborne survey radiometric anomalies	7 non-core holes for 14 m	5X	70	Thorium content of conglomerates is responsible for radioactive anomalies	Horizons examined were also prospected during M1408
	1408 (Agip)	Airborne survey radiometric anomalies	....	....	33	Radiation is due to a thorium mineral, probably thorogummite	
	1409 (Agip)	Airborne survey radioactive anomalies	....	10X	35	Radioactive anomalies due to thorium sources	
King Leopold Sandstone	290 and 328 (BHP)	Airborne survey radioactive anomalies over conglomerate	2 core holes for 339 m ; 6 non-core holes for 750 m	....	118	Main radioactive element down to 183 m is thorium	Two separate outcrop areas of conglomerate were examined (Fig. 54)
	305, 330 and 340 (Durack)	Airborne survey radioactive anomalies over conglomerate	3 core holes for 604 m	....	68	Radioactivity is due mainly to thorium minerals in matrix of conglomerate	Principal exploration and drilling took place near the southern boundary of M340 (Fig. 54)
	445 (Newmont)	....	....	....	....	No radioactive anomaly was detected during a heli-borne scintillometer survey	
	695/1 (CRA)	Airborne survey radioactive anomalies over conglomerate	17 core holes for 1 117 m	....	125	Radioactivity stems mainly from thorogummite	
	695/2 (CRA)	Depth extensions of radioactive conglomerate	....	....	....	....	No drilling
	695/3 (CRA)	Airborne survey radioactive anomalies over conglomerates	1 core hole for 246 m	60X	2	Radioactivity stems mainly from thorogummite	
	985 (Carpentaria)	....	....	....	....	No pronounced uranium anomalies were detected during an airborne spectrometer survey	

A similar conclusion, that thorium-bearing minerals are mainly responsible for anomalous radioactivity of the Pentecost Sandstone, was reached during the three operations reported over this formation (Table 29). There were minor examinations of other formations including sandstones of the Carson Volcanics, the Warton Sandstone and the Elgee Siltstone but again, thorium was considered to be the principal radioactive element.

OTHER UNITS

Other units explored for uranium were the Devonian Ragged Range Conglomerate Member and the Proterozoic Louisa Downs Group, Kuniandi Group, Carr Boyd Group, Revolver Creek Formation and Moola Bulla Formation. Only the Ragged Range Conglomerate Member and the Moola Bulla Formation were subjects of more than minor exploration.

Exploration of the Moola Bulla Formation took place a few kilometres east of Halls Creek, and some 25 km south of the town near Koongie Park over sediments which may be an outlier of Moola Bulla Formation (M67/50). East of Halls Creek, operations included drilling a core hole for 116 m through anomalously radioactive sandstone and conglomerate. It was concluded that much of the radioactivity was due to thorium. At Koongie Park, where anomalous radioactivity was discovered in the 1950s, a core hole for 198 m was sunk in fine-grained clastic sediments. No uranium mineralization was recorded. Selected parts of the core were assayed, the highest result being 26 ppm U_3O_8.

Over the Louisa Downs Group and Kuniandi Group in the Lubbock and Kuniandi Ranges, no radioactive anomalies were detected during an airborne radiometric survey (M298).

In the Hensman Sandstone of the Carr Boyd Group secondary uranium minerals including phosphuranylite and torbernite coat joints and fractures close to the Revolver Creek Fault (M648/8). This mineralization is spotty, extremely irregular and very limited in extent. It was formed apparently by near-surface uranium enrichment. There is no evidence to suggest this mineralization is connected with the Revolver Creek Fault. It was concluded that no uranium of commercial importance could be expected at depth at this prospect. Anomalous radioactivity of the Revolver Creek Formation was apparently thorium-based (M338).

During operations over the Ragged Range Conglomerate Member which included trenching, shaft sinking for 17 m and 23 core holes for 1 120 m, secondary uranium mineralization represented by carnotite was shown to have no commercial potential (M648/1). The secondary uranium mineralization is restricted to "a top layer of unconsolidated iron-rich conglomerates and sandstones".

CONCLUSIONS

No economic uranium mineralization has been identified in the Kimberley region despite histories of moderately intense exploration between 1955 and 1961, and since 1968.

Over large tracts of the King Leopold and Halls Creek mobile zones and immediately adjoining areas of the Kimberley Basin, the understanding of geology and radiometry is high. In these it is unlikely that there remain unidentified uranium-based radioactive anomalies of any consequence detectable by available airborne instrumentation. It must be concluded that the uranium potential of this country is low though there are important gaps in knowledge. The uranium geochemistry of granites and other possible source rocks and the uranium content of natural waters on a regional scale which may indicate areas of leaching and redeposition of the mineral apparently have not been studied. During further exploration it should be assumed that deposits are concealed and lack surface radiometric response and thus sub-surface exploration methods such as hydrogeochemistry and radon measurement will be required. Possible subjects for investigation are the numerous major faults which characterize the mobile zone. Near Dunham Hill and some 15 km to the south in the Whitewater Volcanics (M648/7) uranium mineralization is found near the Dunham Fault.

On the central and greater part of the Kimberley Basin there is no information on uranium exploration, an absence of exploration attention which is probably explained by the geology of the rocks. For most of the sediments within the basin a marine environment within "a steady ocean current (of the Gulf Stream type)" is suggested by Gellatly and others (1970) on the bases of facies changes and consistency of palaeocurrent directions. Such an environment is not favourable for uranium accumulation (p. 358, International Atomic Energy Agency, 1970). A possible explanation for the low uranium content of the conglomerates of the Kimberley Group and to some extent the Speewah Group is indicated also by the results of Gellatly and others. The conglomerates are considered to have accumulated during temporary reversals of current direction when previously deposited sediments of the basin, principally the Speewah Group, were eroded during uplifts of nearby parts of the mobile zones. A general absence of clasts of igneous rocks within the conglomerates suggests that possible uranium source rocks of the mobile zones were largely uncovered. It appears therefore the conglomerates were chiefly derived from sediments themselves deposited within an environment unfavourable for the accumulation of uranium. Exploration within the basin would need to aim at finding depositional environments of types which present eveidence suggests may not be widely developed.

Elsewhere within the Kimberley region, arenaceous rocks of the Phanerozic, such as the Devonian of the Hardman Basin, which are not known to have been the subject of exploration for uranium, offer possibilities for investigation.

REFERENCES

Bowie, S. H. U., 1970, World Uranium Deposits *in* Uranium Exploration Geology: International Atomic Energy Agency; Vienna, 1970, p. 23-33.

Derrick, G. M., and Playford, P. E., 1973, Explanatory notes on the Lennard River 1:250 000 Geological Sheet, W.A.: Australia Bur. Mineral Resources.

Dow, E. B., and Gemuts, I., 1969, Geology of the Kimberley Region, Western Australia: The East Kimberley: Australia Bur. Mineral Resources Bull. 106.

Gardener, J. E. F., 1960, Halls Creek Area Airborne Radiometric Survey, W.A. 1959: Australia Bur. Mineral Resources Rec. 1960/46 (unpublished).

Gellatly, D. C., Derrick, G. M. and Plumb, K. A., 1970, Proterozoic Palaeocurrent directions in the Kimberley Region, Northwestern Australia: Geol. Mag. v. 107, p. 249-257.

Gellatly, D. C., and Halligan, R., 1971, Explanatory notes on the Charnley 1:250 000 Geological Sheet, W.A.: Australia Bur. Mineral Resources.

Goodeve, P. E., 1955, Airborne Scintillometer Survey Halls Creek—Wyndham Region, W.A. June to September, 1954: Australia Bur. Mineral Resources Rec. 1955/108 (unpublished).

International Atomic Energy Agency, Vienna, 1970, Uranium Exploration Geology, 384p.

Mercer, R., 1961, Results of diamond drilling at Saunders Creek, near Halls Creek, Western Australia: Australia Bur. Mineral Resources Rec. 1961/39 (unpublished).

Thom, J. H. 1975, Kimberley region *in* Geology of Western Australia: West. Australia Geol. Survey, Mem. 2, p. 160-193.

Traves, D. M., 1955, The Geology of the Ord-Victoria Region, Northern Australia: Australia Bur. Mineral Resources Bull. 27.

THE ORD RANGE TIGER-EYE DEPOSITS

by J. G. Blockley

ABSTRACT

Attractive tiger-eye opal formed from crocidolite and set in red, brown and black jaspilite is mined from Archaean iron formation in the Ord Range near Mount Goldsworthy and sold under the trade name "tiger iron". The deposits appear to be the only recorded occurrences of crocidolite in Archaean iron formation.

The original asbestos was best developed in drag folds and later silicification to tiger-eye is related to a duricrusted peneplain surface, which also bears deposits of iron ore.

Of the four deposits of tiger-eye prospected, two are capable of yielding a total of about 150 to 300 t of the gemstone. It should be possible to mine the tiger-eye without interfering with later extraction of nearby iron ore deposits.

INTRODUCTION

Several years ago Perth gem shops began displaying an attractive rock made up of thin, closely spaced bands of golden tiger-eye opal (silicified asbestos) set in red and black jaspilite. It was obvious that the stone did not come from any of the known tiger-eye deposits in the Hamersley Range, but its exact place of origin for a time remained a mystery. Eventually, various sources of information placed its location in the Ord Range, between Port Hedland and Goldsworthy. The early reticence on the location of the deposits was apparently due to their being on a Temporary Reserve for iron ore, and to the consequent difficulties in obtaining mining titles.

The descriptive name "tiger iron" has been coined to refer to the tiger-eye-bearing jaspilite. Although it is now widely used in the gem trade, the term is in fact a trade name registered by the owners of M.C.7686 and should only be used for material from that claim.

The deposits were inspected by Dr. A. Hickman and the writer on May 24th, 1975 and again by the writer on September 15th, 1975. On neither occasion were the claims being worked, and there was no sign of activity in the period between the two inspections.

LOCATION AND ACCESS

The tiger-eye deposits are located at latitude 20° 17′ S, longitude 119° 09′ E, about 4 km on a bearing of 325° from the Survey Station on Mount Saint George (Fig. 55A). Access from the Port Hedland to Goldsworthy road is by way of a winding track branching off near the crossing of the Strelley River. The deposits are on either side of a steep gully which ends in a waterfall over a prominent line of cliffs. One branch of the access track leads to a rock hole at the foot of the waterfall and another climbs a spur and gives direct motor access to the deposits. The claims can also be reached by a former Goldsworthy Mining Ltd. exploration track which connects with the old Broome road west of the Ord Range.

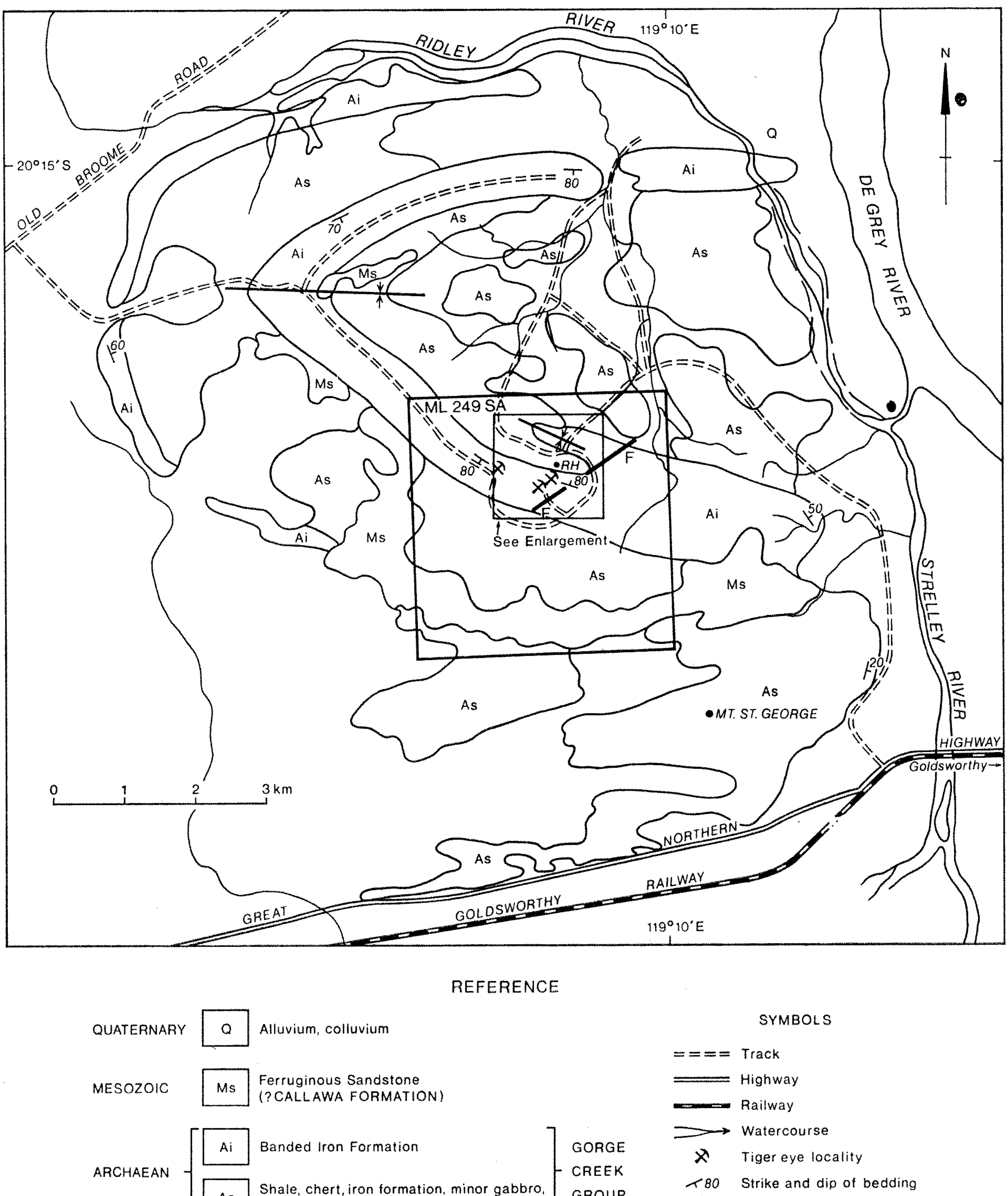
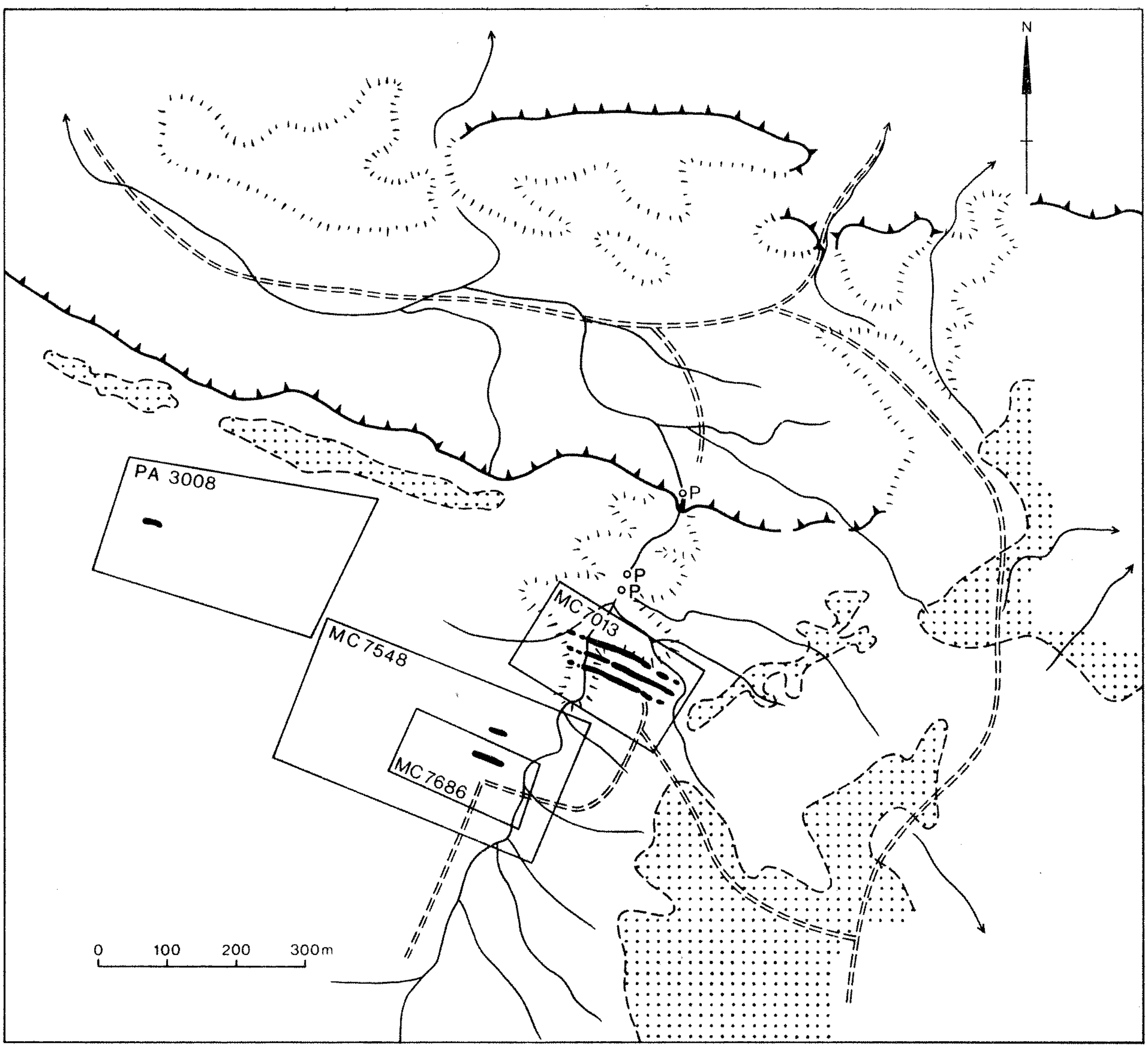


Figure 55. Plans showing locality and regional geology of the Ord Range Tiger-eye deposits.
A. Regional geological map showing access routes to the deposits.



REFERENCE

- Tiger eye seam
- Iron ore
- Mining tenement (position approximate)
- Track
- Scarp
- Steep slope
- Stream
- oP Pool

15512B

Figure 55B. Plan showing relationship of tiger-eye deposits to mining tenements and iron ore deposits. (Tenement boundaries are approximate only).

HISTORY AND TENURE

The first tenement registered for gemstones in this area, P.A. 2988 (now M.C. 7686), was taken up by J. Glass in November 1971. This was quickly followed by P.A. 2995 (now M.L. 7013) pegged by A. Williams and A. Davies, and a year or so later by P.A. 3008, applied for by R. Gray and subsequently refused. The current tenement situation is:—

MC 7013 Ord-Riddley Mining Pty. Ltd. (Approved)

MC 7548 Ord-Riddley Mining Pty. Ltd. (Approved)

MC 7686 Gelene Holdings Prop. Limited (Approved)

PA 3008 R. Gray (Refused)

All claims lie within Section 9 of M.L. 249 SA covering iron ore deposits of Goldsworthy Mining Ltd. The lease was formerly part of iron ore T.R. 2574^{H}. Locations of the various tiger-eye tenements are shown in Figure 55B.

No production of gemstones has been reported to the Mines Department from this locality, although the widespread distribution of the "tiger iron" in Perth gem shops and specimen cabinets indicates that a significant quantity has been mined.

GEOLOGICAL SETTING AND CONTROLS OF THE DEPOSITS

The tiger-eye deposits are situated within the thickest banded iron-formation (BIF) member of a sequence of chert, iron formation, ferruginous shale and volcanic rocks correlated with the Archaean Gorge Creek Group (Low, 1965; Hickman and Lipple, 1975). A prominent horseshoe-shaped ridge formed by the outcrop of the main BIF member reflects regional folding about a west-plunging syncline axis lying north of the deposits. South of the tiger-eye prospects, a regional antiform with an ill-defined axis passing through Mount Saint George is picked out by a sinuous ridge of chert. Drag folds on all scales from hundreds of metres to a few centimetres are common, and in places form local structurally complex areas.

Figure 56. Photographs of structures associated with the tiger-eye.

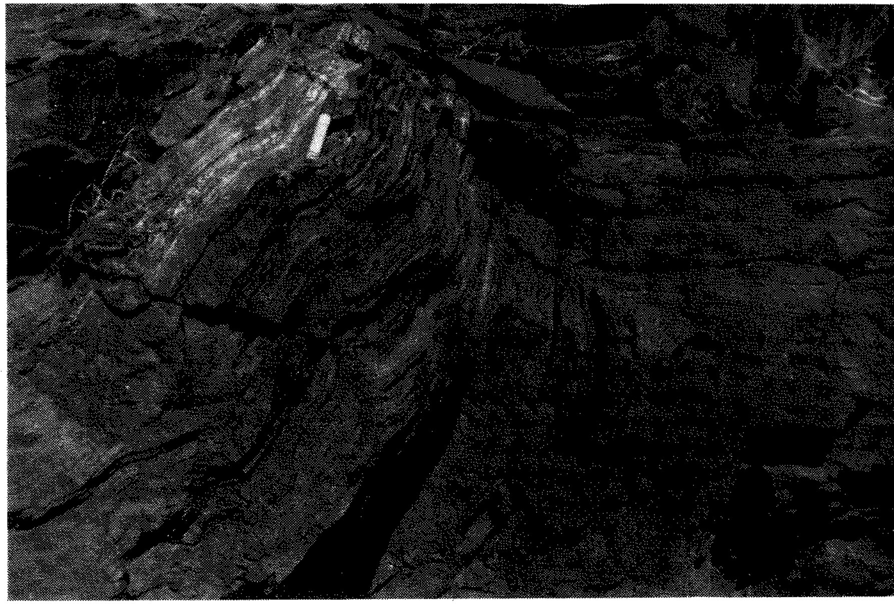
A. Several seams of tiger-eye developed in steeper limb of a small monocline, with greatest concentration near the hinge line of the fold.

B. Specimen of small drag fold with tiger-eye is of the type highly regarded by gemstone dealers. The cross fibre has formed only in the more open limbs of the fold.

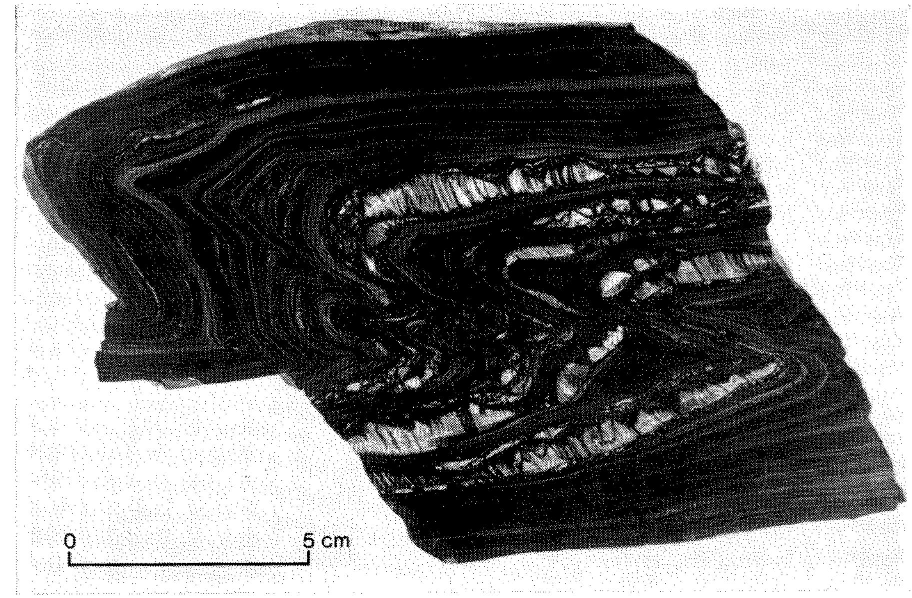
C. Typical seam of tiger-eye showing lenticular habit of individual bands, central parting of iron oxides, and cone structures.

D. Typical monoclinal step fold photographed looking easterly along axis. A seam of fibre is present in the steep southern limb.

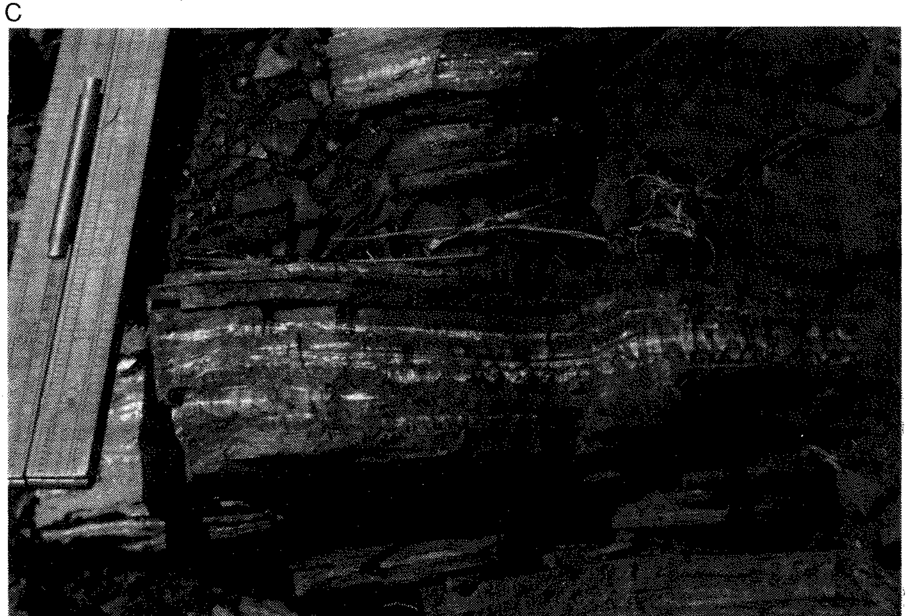
A



B



C



D

Overlying the Archaean rocks and flanking the main BIF ridge are several mesas of flat-lying ferruginous sandstone, regarded tentatively as outliers of the Upper Jurassic Callawa Formation.

Remnants of an old (?Tertiary) peneplain on the crests and upper slopes of the BIF and chert ridges are capped by duricrust and canga, which in a number of places can be considered as potential iron ores.

The main BIF member is about 600 m thick where least folded. It consists mainly of red, black and brown magnetite-rich jaspilite, but also contains banded grey, white and red chert, ferruginous shale, and nearly structureless jasper. Features resembling cross pods and small macules (Trendall, 1966) are common. Ripple-like structures on many bedding surfaces follow the expected drag-fold direction and are almost certainly of tectonic rather than sedimentary origin.

A section of the upper part of the main BIF member as exposed in the gully traversing the tiger-eye claims is, from top to bottom:

Approximate thickness (m)	Description
10 to 15	Brecciated, poorly banded jasper
120	Thinly mesobanded magnetite-rich BIF with red cherts
30 to 40	Black, pink and white BIF with thicker (3-5 cm) pink microbanded cherts spaced at intervals of 10 to 20 cm
70	Shaley iron formation weathering out to form a strike valley
+200	Thinly mesobanded red, black and brown magnetite-rich BIF with tiger-eye

The BIF with the thicker pink chert bands may constitute a usable marker horizon within the unit.

The cross-fibre asbestos parent of the tiger-eye appears to be confined to the lowermost of the units described above, but any more precise stratigraphic control could not be identified. It appears that the fibre may appear anywhere within the unit where geological conditions are favourable.

Structure has been an important agent in localizing the asbestos. All of the richer concentrations are situated in zones of crumpling and drag folding. Where a mineralized horizon can be traced away from a drag-folded zone into a relatively undisturbed area the fibre content decreases markedly. A small-scale example of structural control on a drag fold is shown in Figure 56A. On a broader scale the whole area of the deposits is situated at the margin of an extremely complexly folded zone and it is also close to a northeasterly-trending fault.

The tiger-eye opal was formed by replacement of the asbestos in parts of the BIF close to the duricrust capping. The best material is within 5 m or so of the duricrust; in the gorge which cuts the deposits, the tiger-eye is paler and more friable. Another feature which varies with depth is the colour of the associated chert, which is redder near the old surface.

MINERALOGY AND STRUCTURE OF THE TIGER-EYE

The tiger-eye opal was formed by oxidation and silicification of a pre-existing amphibole asbestos. Optical and X-ray studies carried out by the Government Chemical Laboratories in 1972 on fibres extracted from a sample of the opal indicate that the original fibre was crocidolite. Further samples of apparently less silicified fibre submitted to the Government Chemical Laboratories in 1975 failed to produce any positive indication of the identity of the parent asbestos.

The best of the silicified material is golden yellow with a strong chatoyancy. Its effect is enhanced where the tiger-eye bands are closely spaced and where the intervening chert bands are red. The most prized specimens are those in which the banding is folded (Fig. 56B).

Fibre bands are typically 0.5 to 1.0 cm wide, but each band varies considerably in width due to cone structures and pinch and swell effects. Kink bands in the fibre add a second dimension to the chatoyancy of the tiger-eye. Most bands have a central iron-oxide parting of irregular shape (Fig. 56C). Typical seams (i.e. groups of bands clustered closely enough to be extracted as a unit) range from 10 cm to 2 m in stratigraphic thickness.

True quartz fibre, as distinct from the tiger-eye, is also present in places.

COMMENT ON THE AGE OF THE DEPOSITS

Elsewhere in the world, crocidolite has been recorded from iron formations only in the Cape Province of South Africa, the Hamersley Range of Western Australia and the Lake Superior and Labrador regions of North America. All of these iron formations are of Proterozoic age.

Current geological mapping by this Survey has confirmed the Archaean age of the BIF in the Ord Range, and it appears that the occurrence of crocidolite here is the only one of this early age so far reported.

DESCRIPTION OF DEPOSITS

M.C. 7013

The most extensive deposits are on M.C. 7013 where the iron formation is folded into a series of monoclinal steps (Fig. 56D). Fibre occurs over a horizontal width of 30 to 40 m in which about three seams have been worked. The better tiger-eye is on the steeper limbs of the monoclines. Mining has been carried out by breaking the surface exposure with a bulldozer and ripper, followed by further hand breaking to extract the saleable material. It is not possible to estimate the amount of material removed as there are no well-defined openings whose volume can be measured. However, about 30 or 40 200 l drums on site probably give an idea of the scale of the claim holders' envisaged future operations.

M.C. 7686

In this claim tiger-eye has been mined from seams spread over a width of about 20 m and a length of 100 m. The host BIF is contorted, with the fibre particularly well developed in drag folds. The seams are less abundant than on M.C. 7013 but the average quality of the stone is better, probably because the claim is closer to the duricrust. Workings consist of a costean, probably 3 or 4 years old, and surface bulldozing. Again no estimate of production can be made on the ground, but the lease holders state that they have about 100 t stockpiled in Perth.

M.C. 7548

This claim surrounds M.C. 7686 and covers tiger-eye in an horizon 30 or 40 m above that worked in M.C. 7686. No development has been done and in general the fibre bands are too widely spaced to give good quality commercial stone.

P.A. 3008

This area is on strike with and about 500 m west of the deposit on M.C. 7548. A few pits have been excavated on comparatively sparse seams of tiger-eye in zones of minor drag folding. Between P.A. 3008 and the other deposits the BIF dips steeply and uniformly north and contains very little fibre.

CONFLICT WITH IRON ORE INTERESTS

Because the tiger-eye deposits are within a mineral lease (formerly a Temporary Reserve) for iron ore there has been a predictable conflict of interests. From a geological point of view, mining the tiger-eye can have no detrimental effect on the reserves of enriched ore in the lease and only an insignificant effect on the reserves of taconite ore. The conflict arose mainly because the area of any tenement granted for gemstones is automatically excised from the iron ore tenement, and the holders of the iron ore rights would have been denied access to certain of their deposits had all gemstone areas been granted. However, the best deposits are now within approved mineral claims and ample supplies of tiger-eye are available for the gem market.

ESTIMATED RESERVES

Given conservative assumptions that only about 1 per cent of material in the ore zones is suitable for polishing, and for reasons of fall-off in quality or difficulties of mining, the material can only be quarried to a depth of 1 m, then estimated reserves amount to about 100 to 200 t in M.C. 7013 and 50 to 100 t in M.C. 7685. These reserves are sufficient to maintain the sale of gemstones but could not long support any more ambitious programme to produce facing stones from the material.

REFERENCES

Hickman, A. H., and Lipple, S. L., 1975, Explanatory notes on the Marble Bar 1:250 000 Geological Sheet, Western Australia: West. Australia Geol. Survey Rec. 1974/20 (unpublished).

Low, G. H., 1965, Port Hedland, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Trendall, A. F., 1966, Second progress report on the Brockman Iron Formation in the Wittenoom-Yampire area: West. Australia Geol. Survey Ann. Rept. 1965, p. 75-87.

GEOLOGY AND GEOCHRONOLOGY OF ALTERED RHYOLITE FROM THE LOWER PART OF THE BANGEMALL GROUP NEAR TANGADEE, WESTERN AUSTRALIA

by R. D. Gee, J. R. de Laeter*, and J. R. Drake

ABSTRACT

The Bangemall Basin is the youngest major Proterozoic sedimentary basin in the Western Australian Shield. Approximately 60 m above the basal unconformity in the central part of the basin, there occurs a line of six small rhyolite bodies within Bangemall Group conglomerates. The attitude of contorted flow banding indicates these bodies erupted as viscous lava domes or plugs. Initially the rocks were glassy rhyolites with quartz and sanidine phenocrysts, but subsequent alteration has resulted in extreme enrichment of K_2O, and depletion of Na_2O. Rb-Sr isotopic data give an isochron of 1 098 ± 42 m.y. which probably dates the alteration event. This age accords well with previous scant isotopic dates elsewhere in the Bangemall Group. The rhyolite probably formed by local melting on a movement plane in the basement granitoid during early development of the Bangemall Basin.

INTRODUCTION

A small but well-exposed occurrence of altered, flow-banded rhyolite was recently encountered at lat. 23° 37′ 00″ S, long. 118° 47′ 00″ E near Tangadee by J. C. Barnett of this Geological Survey during regional mapping in the central part of the Bangemall Basin. This occurrence, which appears to be one of the few unequivocal examples of felsic volcanic rocks in the Bangemall Group occurs at a stratigraphically low level, only about 60 m above the basal unconformity, at a point where a relatively large basement high of probable Lower Proterozoic granitoid is exposed in the axial part of the basin.

The Bangemall Group is composed of a sequence of conglomerate, carbonates, sandstone, chert, and shale that forms the youngest major Precambrian sedimentary basin in the Western Australian Shield. Both unpublished company exploration reports and published literature, including the review by Gee, 1976, refer to volcanic or volcanogenic material, especially at the stratigraphic level just below the Discovery Chert. Unusual siliceous and potassium-rich shales appear to be widespread at this general level, although their precise volcanic content is uncertain.

Daniels (1969) refers to a felsic volcanic occurrence near Mount Palgrave in the western part of the Bangemall Basin, found by Westfield Minerals (W.A.) N.L. This occurrence is believed to be a dyke and related flow (J. L. Daniels, pers. comm.) in siliceous shale immediately beneath the Discovery Chert. Daniels (1969) also refers to tuffaceous sandstones in the Kiangi Creek Formation, which is low in the sequence.

The discovery of rhyolite near Tangadee, although of small extent and at an unexpected stratigraphic level, is therefore important, as it establishes felsic volcanic activity in this part of the Bangemall Group, and also provides material that may date the beginning of the Bangemall Group. Compston and Arriens (1968) have previously obtained a poor Rb-Sr isochron of about 1 080 m.y. from the Mount Palgrave felsic rocks, and also a Rb-Sr age of 1 080 ± 80 m.y. from shale in the Curran Formation which lies about 700 m stratigraphically above the Discovery Chert. These represent the only previous geochronological controls of the Bangemall Group.

The purpose of this paper is to document the Tangadee occurrence, to discuss its origin and significance, and to report on its age.

FIELD OCCURRENCE

ENVIRONMENT OF ERUPTION

The rhyolite occurs within a basal conglomeratic unit. The underlying rocks are predominantly cobble and granule conglomerate composed of quartz clasts in a gritty matrix of single-crystal quartz and feldspar grains derived from the basement granitoid. Beds of fairly well-sorted and cross-bedded sandstone occur within the underlying conglomerate. The overlying conglomerates are much coarser, consisting of well-rounded boulders and cobbles of quartz, jaspilite (presumably of distant origin), and sandstone. Festoon cross-stratified beds about 1 m in thickness are present. Granite and rhyolite clasts are generally absent, and except for one important occurrence discussed below, the conglomerate is devoid of volcanic clasts.

The rhyolite was erupted onto sheets of well-washed clastics that were deposited in shallow water, and then covered by coarse fluvial rubble that was deposited from fast, pebble-laden braided streams.

THE RHYOLITE BODIES

Six plugs (designated as shown in Figure 57) occur over a strike length of 2.5 km, along a line trending east-northeast. Only bodies A and B have been examined in detail; however, they are all characterized by broadly concordant tops and bases, steep discordant walls, and complex flow layering. On the northwestern end of body F a cleft is present in the top of the rhyolite as it dips under the overlying conglomerate. In this cleft is a bed of conglomerate about 1 m in thickness which sits on the rhyolite and contains angular fragments of rhyolite. The rhyolite fragments are about 5 cm in diameter. This important feature establishes clearly that at least one rhyolite plug broke through to the surface.

There is a surprising lack of any thermal metamorphic effects, even at the bases. Consequently the steep discordant walls are difficult to interpret. They may either be walls of intrusives, or the walls of steep-sided domes that stood up above the sediments.

*Department of Physics, Western Australian Institute of Technology.

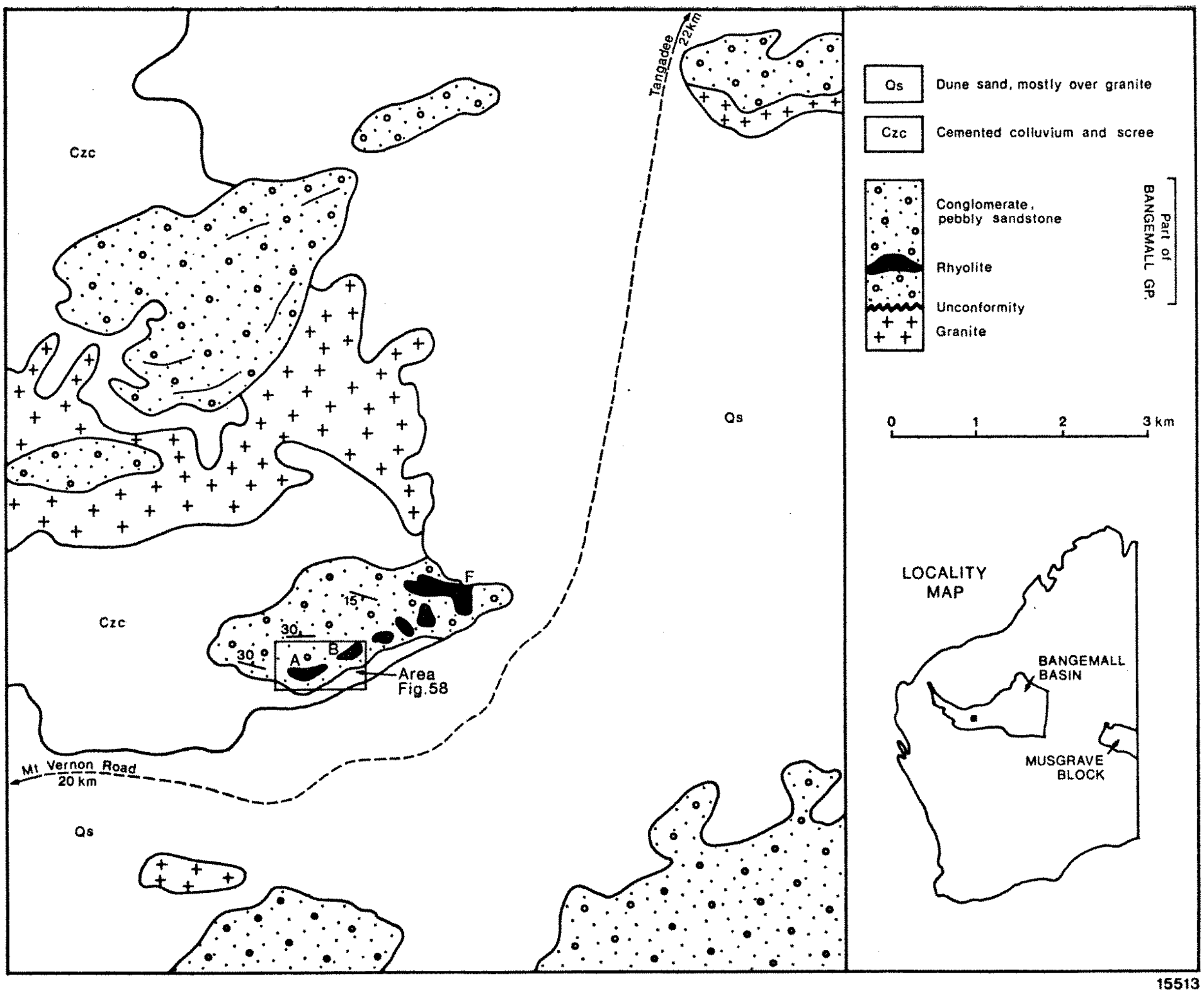


Figure 57. Locality diagram showing geological setting of rhyolite bodies near Tangadee.

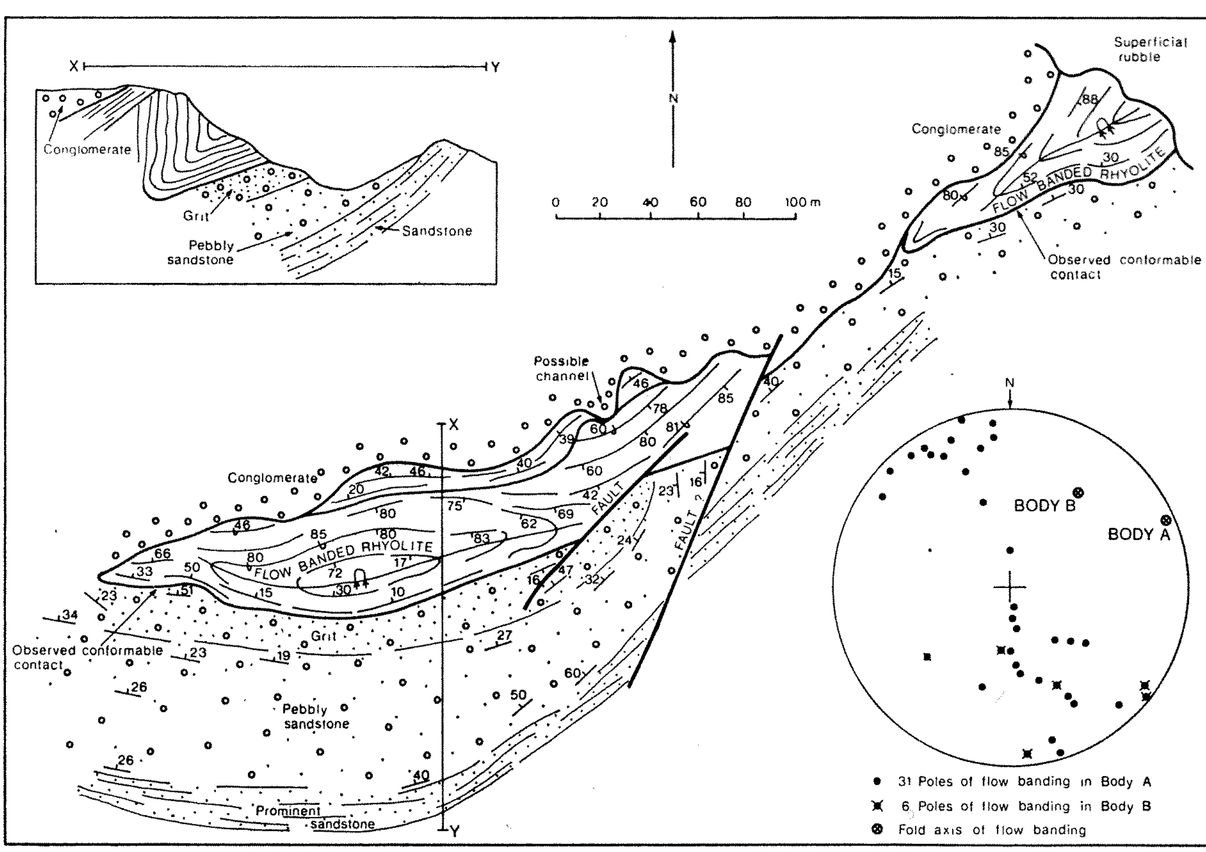


Figure 58. Detailed geological map of bodies A and B, showing orientation data of flow banding.

54809—(8)

MORPHOLOGY OF BODIES A AND B

Figure 58 is a detailed map of body A and the exposed part of body B. A most interesting feature is the flow layering which forms an overturned synformal fold whose upper limb is, in places, truncated and capped by a thin planar layer of rhyolite. The enclosing conglomerates dip about 20 to 30° north, and if this dip is flattened, the synform would be recumbent. Except where complicated by later faulting the bottom contacts are invariably conformable, and the actual contacts are observable at the points shown on Figure 58. Orientation data for the banding are shown stereographically in Figure 58.

The fold axis in body A is almost horizontal, and the apparent canoe-shaped outline of the traces of the flow banding is an apparent effect due to topography. In body B, the axis plunges moderately northeast, but would rotate to subhorizontal if the dip of the enclosing sediments was turned back to horizontal about the east-northeast strike. Bodies A and B therefore appear to comprise the same synform. The overturning indicated on the traces of flow banding is relative to the lower contact which is concordant and therefore upward facing.

The planar capping on body A is present only on the central and thickest portion. At the extremities, gently dipping conglomerate directly overlies the vertically banded rhyolite. The overlying conglomerate appears to transgress the different parts of the body, although the true relationship is difficult to establish conclusively because the exposure of conglomerate is expressed only as a thin veneer of bouldery rubble on a flat hill top. In a few places small areas of conglomerate have been stripped off by recent erosion, exposing a smooth flat top to the vertically banded rhyolite.

A depression occurs in the top of the body at the position shown in Figure 58. This depression cuts down through the planar capping to intersect the vertically banded part. Although no fragments of rhyolite occur in this depression, it has the form of an erosional channel.

These features of the upper contact of body A, together with the cleft in the top of body F, are taken to indicate an erosional top that was washed clean and smooth prior to covering by the conglomerate.

GENERALIZED RECONSTRUCTION OF THE PLUGS

The alignment of the bodies, the concordant bases but disconformable walls, the recumbent folding of the banding which is discordantly capped by planar-banded rhyolite, and the eroded tops are depicted diagrammatically in Figure 59. The rhyolite appears to have erupted along a fissure, forming a line of viscous domes that grew upward and outward as the earlier extruded rhyolite was shouldered aside by later extrusions and slumped laterally. The plugs were then subject to active scouring that removed most of any associated debris. Based upon this model, the total volume of rhyolite extruded would not exceed $0.02\ km^3$. The amount removed by erosion is unknown, but could be of the same order of magnitude.

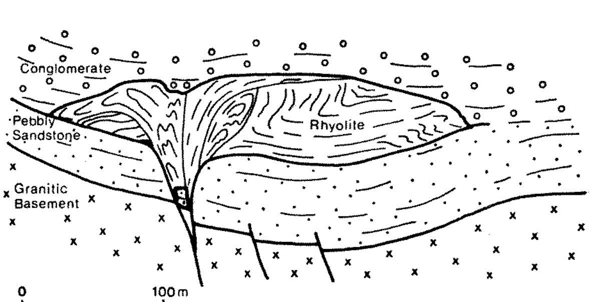


Figure 59. Generalized reconstruction of a rhyolite plug.

FLOW BANDING IN THE RHYOLITE

The flow banding is a varicoloured delicate lamination invariably showing fine crumpling and in places also fragmentation. The rhyolite is aphanitic with a pearly lustre, and mostly colour banded in tones of pale cream and buff. The more oxidized varieties are pallid but the banding is accentuated by very thin pale green and pink laminae, whereas those fresh specimens still retaining unoxidized pyrite are streaked with black and dark grey.

Individual laminae, which vary in thickness from paper-thin to a few centimetres, are laterally continuous over distances of several centimetres to several metres. Termination of laminae is mostly due to intricate folding which produces attenuation of limbs, microscopic detachment planes parallel to the banding, and minute detached fold cores (Fig. 60, A and B). The laminae also show regular pinching and swelling that predates the folding. All these features impart to the rock a streaky eutaxitic banding.

Phenocrysts of quartz and feldspar, up to 3 mm in diameter are wrapped by the flow banding, and commonly have coronas and tails of rolled-up laminae.

The folds vary in style from angular crumpling to truly isoclinal, and even crumpled isoclinal cores. There is a general tendency for the axes of microfolds to align with the main overfold, and in places this is strong enough to give the rock a conspicuous lineation. However, this is not a stretching or flow lineation along the direction of flowage, which is deduced to be perpendicular to the axis of the overfold.

Fragmentation is clearly the result of *in situ* disruption of once continuous laminae by folding. Where this fragmentation is strong the texture is dominated by small sinuous vermiform pale-coloured fragments completely encircled by darker material (Fig. 60D). There is no evidence whatsoever of primary fragmental texture in the form of shards and streaked pumiceous fragments and so the rock is not considered to be a welded ash-flow.

PETROGRAPHY

In thin section the rhyolite consists of euhedral quartz and feldspar phenocrysts, in a cryptocrystalline groundmass of mainly quartz and microcline, with accessory biotite, chlorite, zircon, and opaques. The overwhelming predominance of quartz and microcline in the mode is confirmed by X-ray diffraction.

The quartz phenocrysts are hexagonal (Fig. 61A) or rhomboidal in section (Fig. 61B), preserving the bipyramidal shape of β-quartz. Most phenocrysts are embayed by the groundmass, and many have become well rounded. Fragmentation of phenocrysts is rare, although many show healed cracks.

The feldspar phenocrysts now consist of granular intergrowths of quartz and microcline with small rosettes of chlorite and are euhedral with a monoclinic pseudohexagonal outline (Fig. 61C). These are considered to have been sanidine phenocrysts. Quartz and former sanidine phenocrysts amount to about 5 per cent of the rock, and commonly form glomeroporphyritic aggregates.

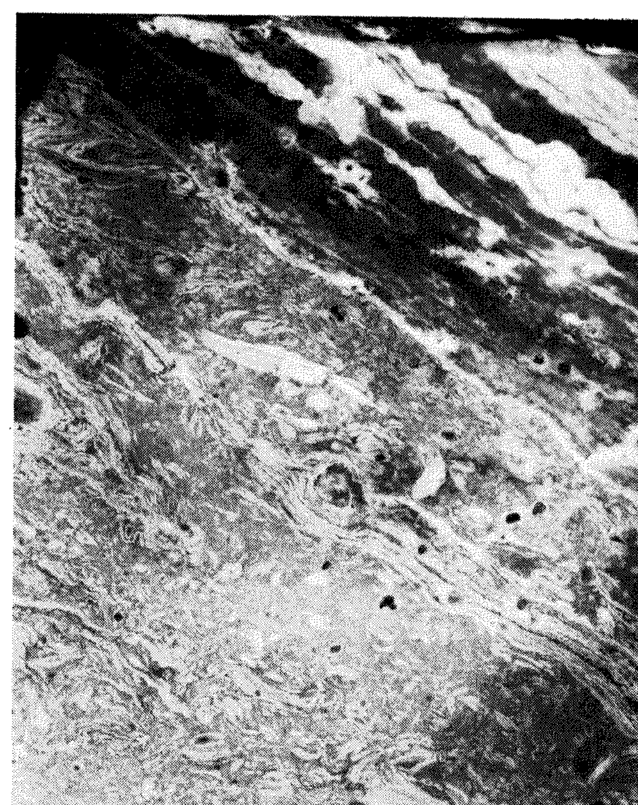
Irregular or distinctly spherical-shaped lithophysae, generally less than 2 mm in diameter, are sparsely distributed. These bodies generally contain quartz and microcline with a diffuse concentric structure, but also contain chlorite, carbonate, ilmenorutile, and sulphide. The dark square spots in Figure 60A consist of poikilitic pyrite (now oxidized) intergrown with quartz, and this structure is encircled by concentric rings of a quartz and microcline mosaic. Fresh skeletal pyrite with intergrowths of quartz especially in the cores, is shown in Figure 60C (the clear white phenocrysts in this photograph are altered microcline).

Figure 60. Flow banding on polished slabs of rhyolite near Tangadee.
A. Specimen 47025. Eutaxitic flow banding. Note detached microfold in centre, intricate crumpling of fine microlamination lower centre, and small lithophysae (primary sphenulites) with opaque cores.
B. Specimen 47021. Strongly folded, irregular lamination; however, note paper-thin internal laminae in isoclinally folded pale coloured band in centre of photograph.
C. Specimen 4 030. Dark grey and black irregularly streaked rhyolite. Larger white subhedral phenocrysts are altered sanidine, the smaller darker spots are intergrowths of quartz in skeletal pyrite.
D. Specimen 47024. Disrupted and fragmental laminae. Note wrapping of small lithophysae by laminae. Fragmented layer is capped by planar banded rhyolite with continuous microlaminae.

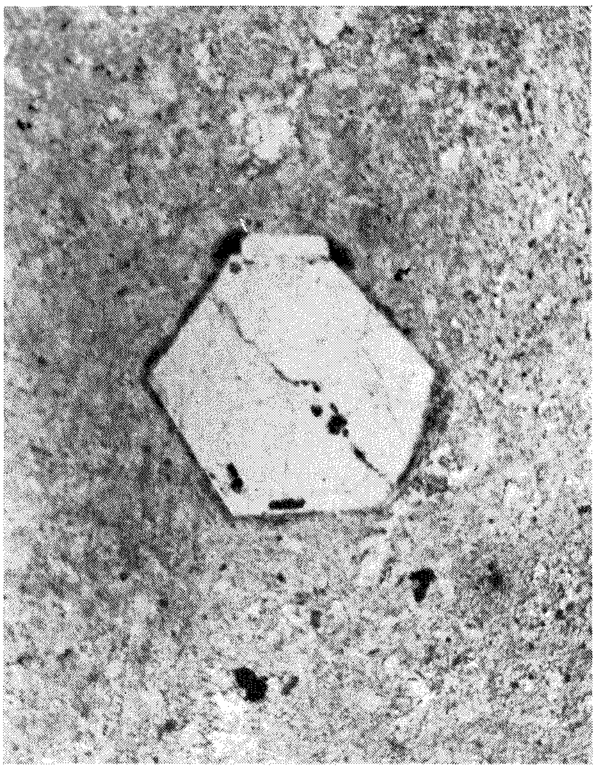
A 0 2 cm

B 0 1 2 cm

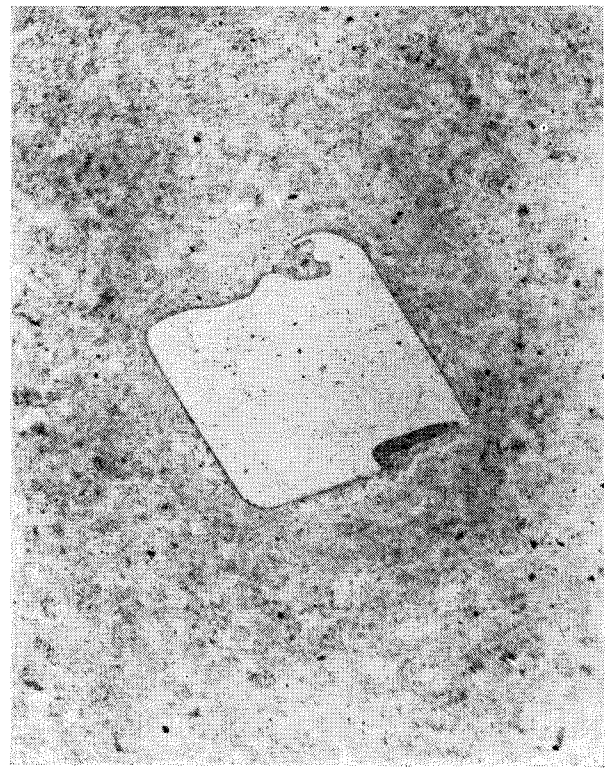
C 0 1 2 cm



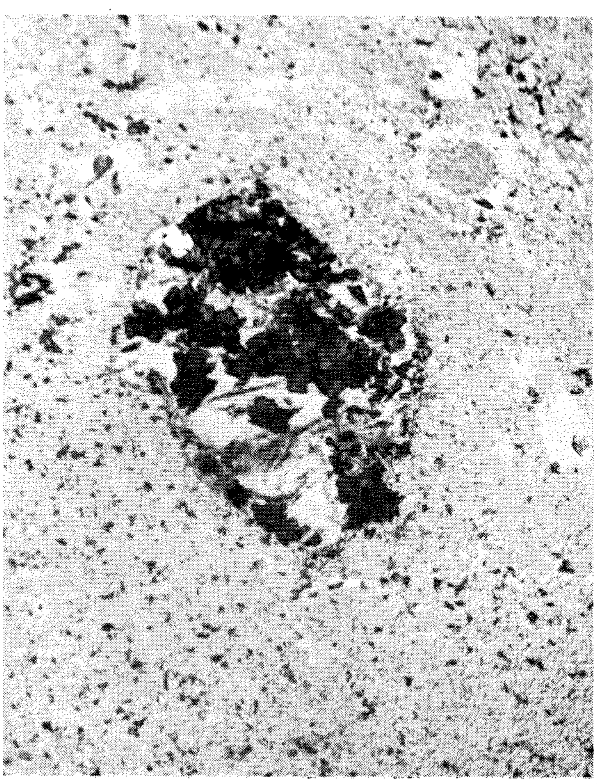
D 0 1 2 cm



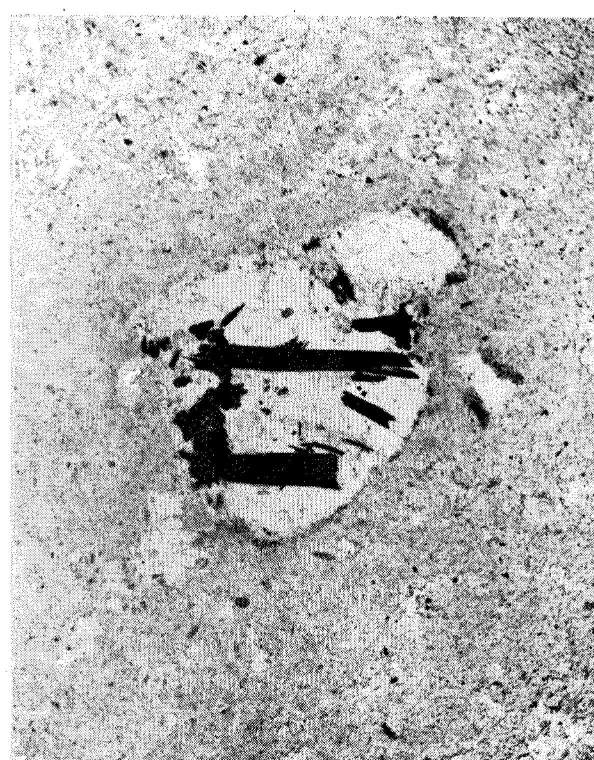
A 0.5 mm



B 0.5 mm



C 0.5 mm



D 0.5 mm

Figure 61. Photomicrographs of rhyolite near Tangadee.

A. Hexagonal cross section of original B-quartz phenocryst in fine-grained groundmass. A healed fracture crosses the phenocryst. Plane polarized light.
B. Partially resorbed bipyramidal phenocryst of original B-quartz. Curved trails of fluid inclusions in phenocryst may be healed fractures. Plane polarized light.
C. Euhedral phenocrysts, formerly of sanidine in fine-grained groundmass. The phenocrysts is now microcline, with abundant inclusions of chlorite. Plane polarized light.
D. Irregular-shaped body infilled with fine-grained quartz and microcline, and containing needles of black ilmenorutile. Plane polarized light.

Figure 61D illustrates another type of lithophysae, in this case black needles of ilmenorutile are encased in a globular aggregate of quartz and microcline. A partial analysis of the ilmenorutile gave the following ratios by weight; TiO_2:FeO: Ta_2O_5 : Nb_2O_5 = 84 : 7 : 0.6 : 8.

These lithophysae are wrapped by the flow banding, and therefore were in existence as solid objects while the lava was still flowing.

Despite the perfect preservation of the thin laminae that is conspicuous on polished faces, in thin section the groundmass is a featureless cryptocrystalline mosaic probably resulting from the devitrification of glass. These is no evidence of shards or perlitic cracking. Although patches of "snowflake" texture are visible under a hand lens, a texture considered by Anderson (1970) to be indicative of an ash-flow tuff, but refuted by Green (1970), the balance of evidence is that these rocks were lavas and not welded tuffs.

In summary these rocks were initially extruded viscous glassy lava that contained phenocrysts of β-quartz and sanidine. The origin of the flow banding is uncertain, as the original geochemical and textural contrasts, if any, between laminae are not known.

GEOCHEMISTRY

Chemical analyses of three samples from body A are given in Table 30. They show a chemistry most unusual for rhyolite, but compatible with the modal predominance of microcline and quartz. Normatively they average 36 per cent *q*, 56 per cent *or*, and 1.5 per cent *an*. Also included in this table for comparison, is the average calc-alkali rhyolite of Nockolds (1954), and also an analysis of the Hilda Rhyolite of the Cassidy Group from the Warburton Range (Daniels, 1974). This latter analysis is included because it is the most potassic and siliceous rhyolite in that area, and it is of similar age to the rhyolite at Tangadee. Clearly the rhyolite near Tangadee is highly altered, as emphasized by extremely high K_2O and extremely low Na_2O.

TABLE 30. CHEMICAL ANALYSES OF RHYOLITE NEAR TANGADEE

Oxides (%)	1	2	3	4	5
SiO_2	78·0	76·1	74·9	73·66	71·34
Al_2O_3	11·1	12·3	12·3	13·45	12·64
Fe_2O_3	0·12	0·21	0·13	1·25	2·73
FeO	0·49	0·37	0·84	0·75	1·72
MgO	0·02	0·02	0·23	0·32	0·79
CaO	0·10	0·06	0·04	1·13	0·60
Na_2O	0·15	0·15	0·20	2·99	2·87
K_2O	9·06	9·21	10·45	5·35	6·13
H_2O+	0·51	0·80	0·29	0·78	0·34
CO_2	0·02	0·02	0·02	....	<0·01
TiO_2	<0·01	<0·01	<0·01	0·22	0·31
P_2O_5	<0·01	<0·01	<0·01	0·07	0·30
SO_3	0·04	0·03	0·03	....	....
Cr_2O_3	0·32	0·26	0·04	....	<0·01
V_2O_5	<0·01	<0·01	<0·01	....	0·01
MnO_2	<0·01	<0·01	<0·01	0·03	0·10
Total	99·97	99·57	99·87	....	....
Elements (ppm)					
Cu	45	190	110		
Li	<5	<5	<5		
Mo	<10	<10	<10		
Pb	110	110	65		
Rb	150	160	180		
Sn	<20	20	<20		
Sr	20	20	20		
W	5	<5	<5		
Zn	17	16	15		

1, 2, 3: G.S.W.A. Samples 41839A–C, rhyolite near Tangadee, body A. *Analyst:* Government Chemical Laboratories. Major oxides by classical methods, trace elements by atomic absorbtion and colorimetric methods.
4: Average calc-alkali rhyolite from Nockolds (1954)
5: Hilda Rhyolite quoted by Daniels (1974)

TABLE 31. ALKALI AND RELATED TRACE ELEMENT GEOCHEMISTRY FOR RHYOLITE NEAR TANGADEE

G.S.W.A. sample no.	Rhyolite body	* Na_2O (%)	* K_2O (%)	Rb (ppm) *	Rb (ppm) †	†Sr (ppm)	K/Rb	†Rb/Sr
47019	A	0·12	9·42	150	....	....	521	....
47020	A	0·15	10·2	150	155	10·6	545	14·4
47021	A	0·13	8·02	130	130	9·1	512	14·3
47022	A	0·14	9·84	150	....	....	545	....
47023	B	0·15	7·79	170	167	10·9	387	15·5
47024	A	0·16	7·92	140	156	10·7	420	14·4
47025	A	0·12	5·74	110	118	8·2	403	14·5
47026	A	0·14	7·69	140	145	11·1	440	13·1
47027	B	0·20	9·97	170	189	12·6	438	15·2
47028	F	0·16	7·15	140	237	7·7	250	31·2
47029	F	0·17	7·35	145	166	8·2	369	20·1
47030	F	0·19	8·37	115	168	8·0	413	21·0

**Analyst:* E. Tovey, Government Chemical Laboratories—atomic absorption.
†*Analyst:* J. R. de Laeter. The Rb and Sr concentrations, and the Rb/Sr ratios have been measured by X-ray fluorescence spectrometry. The Rb and Sr concentrations have been determined by comparison with a number of standard rocks from an assessment of the mass absorption coefficient of each sample, and are accurate to ± 7 per cent. The Rb/Sr ratios are accurate measurements and do not correspond exactly with the ratio derived from the separate Rb and Sr determinations. K/Rb ratios derived from de Laeter data where available.
Rb determinations by different analysts are made from different crushings of the same sample.

In order to examine this unusual geochemistry of the alkalis, an additional 12 samples from scattered locations in bodies A, B, and F were analyzed for K_2O, Na_2O, and Rb (Table 31). These samples formed the pool of samples for isotopic mass spectrometry, and independent Rb and additional Sr values are also included in Table 31.

These figures confirm remarkably constant levels of potassium enrichment and sodium depletion. There is no correlation between Na_2O and K_2O, there being a variation of 5.7 to 10.2 per cent K_2O with virtually fixed values of negligible Na_2O. There is no correlation between K_2O and Rb, thus similar values of K_2O (specimen 47023 and 47030 in Table 31) produce the widest range of Rb. The rubidium values are not excessively high, comparing favourably with the value of 115 ppm Rb for the average Andean calc-alkaline rhyolite of Solomon and Griffiths (1975). However, the strontium is severely depleted in comparison with the value of 123 ppm Sr for the same average rhyolite. Unreasonably high values of K/Rb, in comparison with that for a calc-alkaline rhyolite of about 350 ppm also points to a strong enrichment of potassium relative to rubidium.

Geochemically these rocks bear no comparison to any known volcanic rock series, however, they do bear comparison to some altered rhyolite in alteration zones and fumarolic mounds within otherwise normal rhyolite. For example Ratté and Stevens (1967) quote a range of 7 to 11 per cent K_2O and 1.3 to 0.40 per cent Na_2O in the Batchelor Mountain rhyolite in the Creede Caldera. Similar, but not quite so extreme values were obtained from fumarolic mounds in a Pleistocene rhyolite ash-flow tuff by Sheridan (1970).

The presumed alteration processes include a slight increase in SiO_2, dramatic increase in K_2O together perhaps with an increase in Rb, almost total loss of Na_2O, and loss of CaO and related Sr. These trends are consistent with weathering; however, the very low values of H_2O^+, the presence of fresh sulphides, the geochemical homogeneity, the general clarity of the microcline, together with the hard flinty appearance of the rock suggests that the alteration considerably predated any recent weathering.

Geochemically the rhyolite is comparable to an analysis of the Woongarra Volcanics published by Trendall (1972, p. 72). Additional unpublished analyses of the Woongarra Volcanics (A. F. Trendall, pers. comm.) show an inverse variation between Na_2O and K_2O to extremes that match the rhyolite at Tangadee.

The geochemistry is also directly comparable to unusually high-potash shales with volcanogenic content in a transition zone between dolomite and banded iron-formation in the Lower Proterozoic Hamersley Group, noted by Davy (1975, p. 94). Davy (1975, p. 97) discusses mechanisms for potassium enrichment, involving fixation of potassium ions from sea water on to montmorillonite clays that may form in the early stages in the devitrification of volcanic glass shards. The net result is the formation of nearly pure authigenic potash feldspar.

Another possible mechanism involves initially the conversion of both the feldspar phenocrysts and glassy groundmass, both of which should have contained a considerable molecular proportion of albite, to analcime and other zeolites, during incipient burial metamorphism. Shephard and Gude (1973) have shown petrographically that zeolites can then be completely replaced by pure potash feldspar. They envisage this to be a low-temperature ion-exchange reaction of Na^+ in the zeolite for K^+ in circulating bore water, in an alkaline and slightly saline environment.

Because of the complete textural and chemical reconstitution of the rhyolite near Tangadee, there are no clues to the mechanism and timing of the alteration. The cryptocrystalline nature of the groundmass points to complete devitrification of the groundmass, to which was probably related the alteration of the sanidine. There is no indication that zeolite was, or was not present, so that either mechanism outlined above is possible.

From the geochronological point of view, it seems that the last isotopic homogenization would date the alteration event, and not the primary crystallization of the lava.

GEOCHRONOLOGY

The experimental procedures of Rb-Sr isotopic analysis are essentially the same as those described by Lewis and others (1975). However, an additional step was introduced in the ion-exchange chemistry to remove alkali and alkali earth impurities. The eluate from cation exchange column was redissolved in 11M HCl and loaded on a small cation column. After washing with several column volumes of 11M HCl, the Sr was eluted with 2.5M HCl and then loaded in the mass spectrometer. The value of $^{87}Sr/^{86}Sr$ for the NBS 987 standard measured in this laboratory is 0.7102 ± 0.0001, normalized to 8.375 2 for $^{88}Sr/^{86}Sr$. The value of $1.39 \times 10^{-11} yr^{-1}$ was used for the decay constant of ^{87}Rb. The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ for 10 samples are given in Table 32.

TABLE 32. ANALYTICAL DATA FOR THE RHYOLITE NEAR TANGADEE

G.S.W.A. sample no.	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Samples Included In Isochron			
47026	13·1	39·5 ± 0·4	1·3023 ± 0·0002
47020	14·4	43·9 ± 0·4	1·3552 ± 0·0001
47024	14·4	44·0 ± 0·5	1·3582 ± 0·0002
47027	15·2	47·2 ± 0·5	1·4290 ± 0·0002
47030	21·0	66·6 ± 0·7	1·7092 ± 0·0002
47028	31·1	104·6 ± 1·0	2·3011 ± 0·0003
Samples Not Included in Isochron			
47023	15·5	48·0 ± 0·5	1·4702 ± 0·0002
47025	14·5	45·1 ± 0·5	1·5024 ± 0·0001
47021	14·3	43·7 ± 0·5	1·3166 ± 0·0001
47029	20·1	62·7 ± 0·7	1·5304 ± 0·0002

The data are plotted in Figure 62. The errors are at the 95 per cent confidence level. Six points form an isochron, which, using the regression analysis of McIntyre and others (1966) give a Model 3 isochron of $1\,098 \pm 42$ m.y., with an initial $^{87}Sr/^{86}Sr$ ratio of 0.6881 ± 0.0334. The other four samples scatter both above and below the isochron, presumably the result of removal of ^{87}Rb or loss of total Sr respectively. There is no petrographic or geochemical basis for the exclusion of the four samples from the isochron; the basis of selection is that the other six samples lie on the isochron within experimental error.

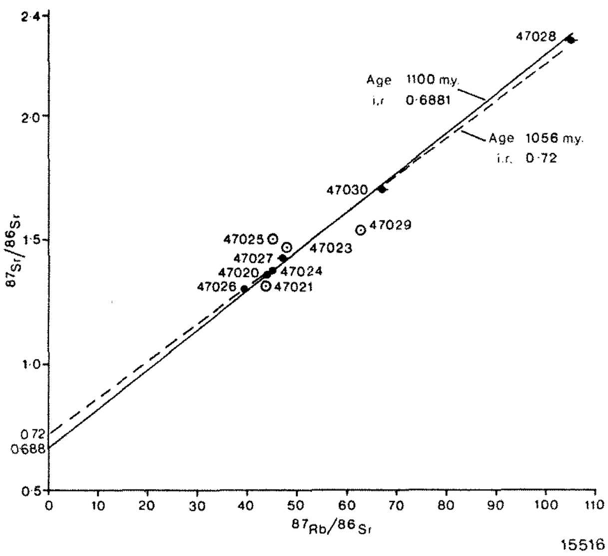


Figure 62. Isochron plot of samples from rhyolite near Tangadee. Open circles are analyses not used on isochron. Broken line is Model 2 isochron generated by assuming initial ratios of 0·72.

An initial ratio of 0.6881 ± 0.0334 is geologically and theoretically untenable. A mantle-derived mafic rock of this age should have an initial ratio of about 0.702, and crustal-derived silicic rocks should have an initial ratio as high as 0.720, according to the strontium evolution curve of Faure and Powell (1972, p. 45). As an exercise to determine the effect of an assumed initial ratio, by successively including initial ratios at 0.005 increments up to a realistic maximum of 0.720 in a Model 2 regression, five additional isochrons are generated, as shown in Table 33. It can be seen that this progressively reduces the slope of the isochron, to a minimum age of $1\,056 \pm 20$ for an initial ratio of 0.720. This isochron is plotted for reference also on Figure 62. Furthermore, all the isochrons generated in this way fall within the ± 42 m.y. error of the uncontrolled Model 3 isochron.

This means that the isotopic age of $1\,098 \pm 42$ m.y. is realistic and meaningful, although the experimental data yield no indication of the true initial ratio, and hence no isotopic evidence of the origin of the rhyolite.

TABLE 33. VARIATIONS OF ISOCHRON AGE WITH INITIAL $^{87}Sr/^{86}Sr$ RATIO

Initial ratio	Isochron (m.y.)
Model 3 derived i.r. 0·6881 ± 0·0334	1098 ± 42
Model 2 assumed i.r. 0·700	1083 ± 15
0·705	1076 ± 16
0·710	1070 ± 17
0·715	1063 ± 19
0·720	1056 ± 20

CONCLUSIONS

Evidence of the origin of the rhyolite includes the restriction of small plug-like bodies along an east-northeast trend, and its occurrence about 60 m above the granite basement. The most likely origin is localized melting along a plane of movement in the basement granitoid. Sedimentological and stratigraphic evidence (Brakel and Muhling, 1976) indeed shows that the early stages of Bangemall Group sedimentation in this central part of the Bangemall Basin were influenced by basement faults of this trend.

The isotopic evidence is not inconsistent with this origin, and the range of possible ages accords well with the approximate age of 1 080 m.y. obtained by Compston and Arriens (1968) for both acid igneous rocks at Mount Palgrave, and shale of the Curran Formation. The isotopic age of the rhyolite near Tangadee is taken to register either early devitrification of the volcanic glass, or early burial metamorphism.

The significance of these rather dramatic chemical changes is uncertain, but it may be related to the general problem of the high-potash and highly siliceous rocks that occur at stratigraphically higher levels in the Bangemall Group.

Finally, the similarity of isotopic ages of Bangemall Group rocks with the 1 060 m.y. ages (Compston and Nesbitt, 1967) from acid volcanics of the Bentley Supergroup in the Musgrave Block, should be noted. This supergroup is largely composed of thick sequences of potassic rhyolite lavas, ignimbrites, pyroclastics, and related cauldron subsidence areas (Daniels, 1974). This area represented a major centre of explosive felsic volcanic activity, evidently contemporaneous with Bangemall Group sedimentation, and whose influence must have been felt for considerable distances.

ACKNOWLEDGMENTS

The authors would like to thank Mr. D. J. Hosie of the Department of Physics, Western Australian Institute of Technology, for technical assistance during the project.

REFERENCES

Anderson, J. E., 1970, Recognition and time distribution of texturally altered welded tuff: Geol. Soc. America Bull., v. 81, p. 287-292.

Brakel, A. T., and Muhling, P. C., 1976, Stratigraphy, sedimentation, and structure in the western and central part of the Bangemall Basin: West. Australia Geol. Survey Ann. Rept. 1975, p. 70.

Compston, W., and Arriens, P. A., 1968, The Precambrian geochronology of Australia: Canadian Jour. of Earth Sciences, v. 5, p. 561-583.

Compston, W., and Nesbitt, R. W., 1967, Isotopic age of the Tollu Volcanics, W.A.: Geol. Soc. Australia Jour., v. 14, p. 235-238.

Daniels, J. L., 1969, Edmund, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

———— 1974, the geology of the Blackstone Region Western Australia: West. Australia Geol. Survey Bull. 123.

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

Faure, G., and Powell, J. L., 1972, Strontium isotope geology: Berlin, Springer-Verlag.

Gee, R. D., 1976, The Bangemall Basin, *in* Knight, C. L. (ed.), Economic geology of Australasia and Papua-New Guinea: Australasian Inst. Mining Metall., Melbourne.

Green, J. E., 1970, Snowflake texture not diagnostic of devitrified ash-flow tuffs: Discussion: Geol. Soc. America Bull., v.81, p.2527-2528.

Lewis, J. D., Rosman, K. J. R., and de Laeter, J. R., 1975, The age and metamorphic effects of the Black Range dolerite dyke: West. Australia Geol. Survey Ann. Rept. 1974, p.80-88.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research, v.71, p. 5459-5468.

Nockolds, S. R., 1954, Average chemical compositions of some igneous rocks: Geol. Soc. America Bull., v.65, p.1007-1032.

Ratté, J. C., and Stevens, T. A., 1967, Ash-flows and related volcanic rocks associated with the Creede Caldera, San Juan Mountains, Colorado: U.S. Geol. Survey Prof. Paper 524-4.

Shephard, R. A., and Gude, A. J., 1973, Zeolites and associated authigenic silicate minerals in tuffaceous rocks of the Big Sandy Formation, Mohane County, Arizona: U.S. Geol. Survey Prof. Paper 830.

Sheridan, M. F., 1970, Fumarolic mounds and ridges of the Bishop Tuff, California: Geol. Soc. America Bull., v.81, p.851-868.

Solomon, M., and Griffiths, J. R., 1975, Aspects of the early history of the southern part of the Tasman Orogenic Zone, *in* The Tasman Geosyncline—a symposium in honour of D. H. Hill: Geol. Soc. Aust. Queensland Div. p.19-44.

Trendall, A. F., 1972, Apparent age, and origin, of black porcelanite of the Joffre Member: West. Australia Geol. Survey Ann. Rept. 1971, p.68-74.

TECTONIC SUBDIVISIONS AND GEOCHRONOLOGY OF THE NORTHEASTERN PART OF THE ALBANY-FRASER PROVINCE, WESTERN AUSTRALIA

by J. A. Bunting, J. R. de Laeter,* and W. G. Libby

ABSTRACT

The northeastern part of the Proterozoic Albany-Fraser Province can be divided into four main subdivisions: 1) Transition Zone, in which the Archaean rocks of the adjacent Yilgarn Block are reworked, and intruded by Proterozoic granites; 2) Western Gneiss and Granite Zone, of predominantly amphibolite facies, grading to granulite facies, Proterozoic rocks with no Archaean remnants; 3) Fraser Complex, consisting of mafic rocks predominantly of granulite facies; and 4) Eastern Gneiss and Granite Zone which is largely unexposed. New Rb-Sr age determinations give isochrons of 2 592 ± 25 m.y. for Archaean gneissic granite, 1 725 ± 149 m.y. for adamellite and mafic rock within the Transition Zone, 1 592 ± 36 m.y. for a rapakivi granite-mafic hybrid complex within the Western Zone, and 1 289 ± 21 m.y. for muscovite-bearing rocks within granulite facies gneisses at Salt Creek, near the Western Gneiss and Granite Zone—Fraser Complex boundary. The Salt Creek granulites do not form a good isochron, but must be at least 1 730 m.y. old. This represents a period of granulite facies metamorphism older than that which affected the Fraser Complex (about 1 330 to 1 300 m.y.), and one which probably preceded the emplacement of the Fraser Complex source rocks.

*Department of Physics, Western Australian Institute of Technology.

INTRODUCTION

The Archaean greenstone belts and granitic rocks of the Yilgarn Block are flanked to the south and east by a Proterozoic mobile belt, the Albany-Fraser Province. The boundary between these two major tectonic units is marked by a sharp increase in metamorphic grade from greenschist and amphibolite facies in the Archaean rocks to a high-grade terrain in the mobile belt, and by the truncation of the north-northwest trends of the Yilgarn Block by northeast-trending structures in the Albany-Fraser Province (Fig. 63). These features prompted Wilson (1969a) to compare the boundary, which he believed coincided with the Fraser Fault, with the Grenville Front in Canada which also separates a stable Archaean craton (the Superior Province) from a high-grade Proterozoic orogenic zone (the Grenville Province). This comparison may still be valid, although the Albany-Fraser Province boundary is now placed 10 to 25 km west of the Fraser Fault. The exact placing of the boundary in the area of this study (Fig. 64) depends largely on the parameters chosen to define it. For present purposes it is taken as the western limit of Proterozoic igneous and metamorphic activity, that is, the western margin of the Transition Zone (Fig. 63). Along most of its length it is affected by strong shearing. The transitional nature of the boundary is indicated by the presence in the Transition Zone of much reworked and remnant Archaean material, and by brittle fracture and cataclastic effects in typical Archaean rocks up to 20 km from the boundary.

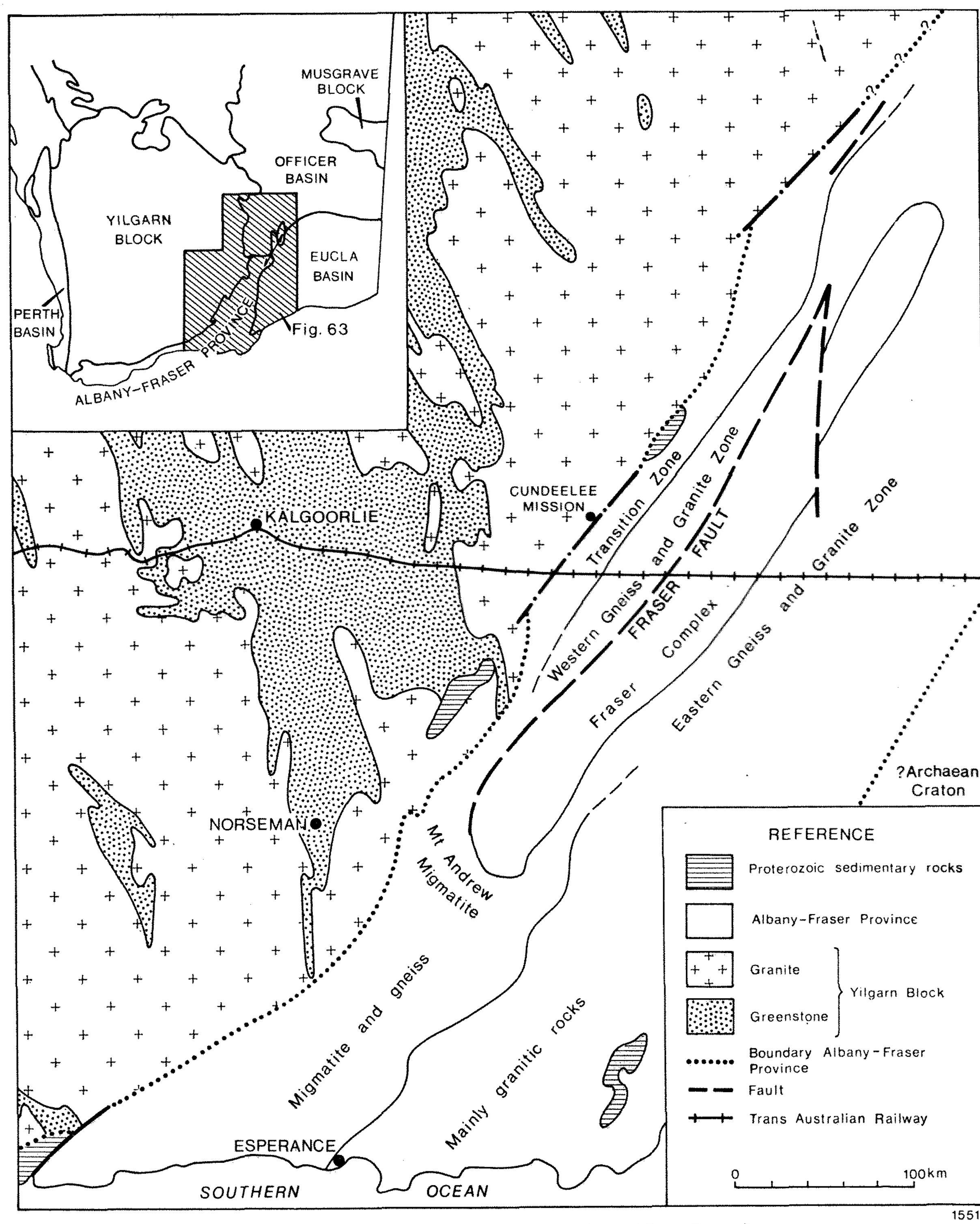


Figure 63. Precambrian tectonic subdivisions, northeast Albany-Fraser Province.

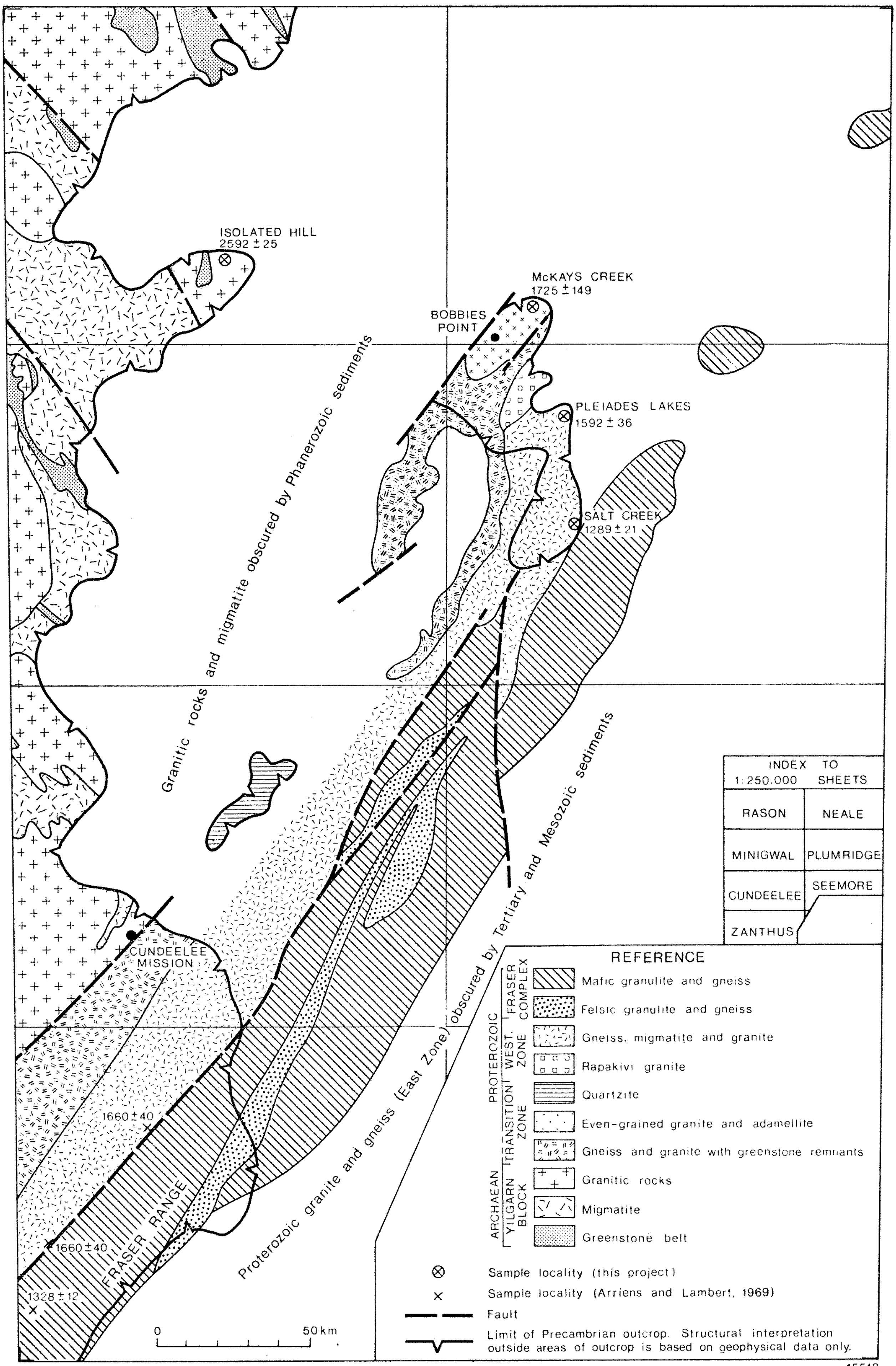


Figure 64. Geology and sample localities, northeast Albany-Fraser Province and adjacent Yilgarn Block.

The regional significance of the high-grade rocks in the Fraser Range area was first appreciated by A. F. Wilson in 1952. His numerous publications describing the granulites and gneisses of the Fraser Range, along with a history of geological investigations of the area, are summarized in Wilson (1969a). Doepel (1969 and 1973) and Doepel and Lowry (1970) describe the regional geology of the area south of, and including, the Fraser Range. The most comprehensive review of the Albany-Fraser Province is by Doepel (1975).

Wilson and others (1960) report a Rb-Sr age of 1 280 m.y. and K-Ar age of 1 210 m.y. for muscovite in a pegmatite from the Fraser Range. Arriens and Lambert (1969), in a more comprehensive study of the Fraser Range area, report Rb-Sr ages of 1 328 ± 12 m.y. for granulite facies rocks, and 1 660 ± 40 m.y. for gneiss and granite immediately west of the granulite belt.

Systematic regional mapping of the area north of the Fraser Range (Fig. 64) was carried out during 1972, and the results have been published as preliminary editions of explanatory notes (Van de Graaff, 1973, Gower and Boegli, 1973; Van de Graaff and Bunting, 1974a and b; Bunting and Van de Graaff, 1974; Bunting and Boegli, 1974). During the mapping difficulties were encountered in trying to delineate the extent of the tectonic units, mainly because the Precambrian rocks are largely obscured by more recent sediments of the Officer and Eucla Basins, but also because of the ambiguous nature of much of the evidence from the rocks. As an aid to the tectonic interpretation an isotopic age determination programme was organized in conjunction with the Western Australian Institute of Technology.

The aim of this paper is to present a tectonic synthesis of the northeastern part of the Albany-Fraser Province incorporating the 1972 mapping, the new geochronological and petrological data, and earlier work by various authors in the Fraser Range area to the south.

TECTONIC SUBDIVISIONS

The area of this study (Fig. 64) can be divided into five main subdivisions. From northwest to southeast these are:—

- Yilgarn Block.
- Transition Zone.
- Western Gneiss and Granite Zone.
- Fraser Complex.
- Eastern Gneiss and Granite Zone.

All except the Yilgarn Block form the northeast part of the Albany-Fraser Province, and all of these four form linear belts trending northeast. This dominant northeast direction is also marked by major faults and mylonite zones, and is the predominant trend of fold axes in each subdivision.

YILGARN BLOCK

The eastern margin of the Yilgarn Block is characterized by a predominantly granitic terrain enclosing small north-northwest-trending greenstone belts. These belts consist of mafic volcanic, ultramafic, sedimentary, and felsic volcanic rocks metamorphosed in the upper part of the greenschist or lower part of the amphibolite facies.

The granitic rocks are equally divided between migmatite and homophanous granitoid. Typically the migmatite is well banded, with a foliated melanocratic granodiorite or tonalite paleosome and a leucocratic adamellite or granite neosome. The homophanous granitoids range from granite to granodiorite. In patches the rock is porphyritic, and a strong penetrative foliation is commonly developed near the margins of the greenstone belts.

TRANSITION ZONE

The Transition Zone forms a belt up to 50 km wide in which Archaean remnants are affected by Proterozoic metamorphism and igneous intrusion. The Archaean remnants contain rocks typical of the greenstone belts of the eastern Yilgarn Block.

Proterozoic intrusive rocks include the adamellite from McKays Creek, dated at 1725 m.y. (see below), and small intrusions penetrating the Archaean rocks. The adamellite from McKays Creek shows peralkine affinities (Van de Graaff and Bunting, 1974a), and is intruded by riebeckite-bearing rhyolite porphyry. Cataclastic deformation is common, and a strong fracture cleavage strikes consistently northeast.

An unusual metamorphosed layered gabbro 35 km southwest of McKays Creek varies from mafic to ultramafic. The predominant rock type is a faintly banded metagabbro containing green amphibole (after pyroxene), epidotized plagioclase, and abundant garnet. Quartz, yellow epidote (Cr-bearing pistacite), green clinopyroxene, and brown hornblende are minor constituents in some samples. The clinopyroxene is a high-alumina (4.74 per cent) salite, while the garnet contains almandine (55 per cent), grossular (7), andradite (22), spessartine (2), and pyrope (11). Microprobe analyses (analyst: R. B. W. Vigers, CSIRO) of the yellow epidote, garnet, and clinopyroxene are discussed in unpublished petrology reports of the Geological Survey of Western Australia (Nos. 633 and 635).

At least two metamorphic events are recorded in the metagabbro: a high-grade event producing the garnet and possibly pyroxene and brown hornblende, and a later intermediate-grade metamorphism giving green hornblende and epidote. The ages of these events and the original igneous crystallization are not known.

Tightly folded quartzite crops out as northwest-trending strike ridges near McKays Creek (Neale Sheet area), in the northwest of the Plumridge Sheet area, and northeast of Cundeelee Mission. At the latter locality it contains pale-green muscovite, kyanite, garnet, and tourmaline. Bunting and Van de Graaff (1974) suggest a possible correlation with the Woodline Beds, 100 km southwest of Cundeelee, which were dated by Turek (1966) at 1 620 ± 100 m.y.

In the Zanthus Sheet area (Fig. 64) a belt of mixed granitic rocks mapped by Doepel and Lowry (1970) falls within the Transition Zone. In this belt Proterozoic leucocratic granite intrudes Archaean porphyritic, even-grained and gneissic granitic rocks.

WESTERN GNEISS AND GRANITE ZONE

This zone contains Proterozoic igneous and metamorphic rocks with no recognizable Archaean remnants and with predominantly amphibolite facies metamorphism. It includes the rocks dated by Arriens and Lambert (1969) at 1 660 ± 40 m.y., and also the Pleiades Lakes and Salt Creek localities of this paper. The zone is equivalent to the Mount Andrew Migmatite east of Norseman (Doepel, 1973).

The area is characterized by a variety of felsic gneisses, including migmatite, which have been intruded by mafic and ultramafic rocks, rapakivi granite, and leucocratic granite. The predominant gneiss is a banded microgneiss (a medium-grained rock with gneissic structure) which commonly contains alkali feldspar, quartz, and minor biotite. Garnet is common in the Salt Creek area. Textures are granoblastic with a poorly developed foliation. The pre-metamorphic rock was probably a quartzofeldspathic sediment.

At several places within the zone there is a distinctive assemblage which includes microgneiss, metadolerite, metagabbro, and rapakivi granite. The mafic rock is even grained and contains orthopyroxene, amphibole, lath-like plagioclase (labradorite), and minor biotite, indicating metamorphism in the granulite or pyroxene hornfels facies with later retrogressive uralitization. In the rapakivi granite, phenocrysts of perthitic microcline, plagioclase, and a pale-blue milky quartz are set in a coarse adamellite matrix. A few microcline phenocrysts are mantled by plagioclase.

At Pleiades Lakes a group of hybrid rocks is associated with the metadolerite and rapakivi granite. Inset grains of pale-blue milky quartz, plagioclase-mantled microcline, and plagioclase aggregates with orientated grains, all occur in a matrix ranging from a biotite-rich felsic to mafic composition. The percentage of insets decreases as the matrix becomes more mafic. The aggregates of plagioclase have probably partly replaced alkali feldspar phenocrysts.

The presence of mantled feldspars in rocks ranging from mafic (hybrid rock) to felsic (rapakivi granite) requires explanation. Typical rapakivi granites from Scandinavia and elsewhere have long been accepted as products of magmatic crystallization (Sederholm, 1932; Marmo, 1962), and such an origin is reasonable for the porphyritic rapakivi granite in the Albany-Fraser Province. For the hybrid rocks a likely origin is the invasion of a partly crystallized granite magma by a mafic magma. Quartz phenocrysts were resorbed on contact with the mafic magma, and plagioclase replaced alkali feldspar in microcline phenocrysts, thus releasing silica which generated a plagioclase-quartz rim around the phenocrysts. The potassium released may have then combined with magnesium and iron to form biotite in the matrix. Intrusive relationships in outcrop are ambiguous; in places the more felsic hybrids intrude mafic hybrids while elsewhere the reverse is the case.

Intermittent exposure is present for about 20 km along the north-south line of Salt Creek. The northern end is predominantly migmatite in which a paleosome of banded biotite-garnet-quartz-feldspar gneiss with amphibolite lenses is intruded by a leucocratic granite or pegmatite neosome. Unlike the microgneiss elsewhere in the zone, the feldspar is predominantly plagioclase.

Near the southern end of Salt Creek the regional garnet-biotite-orthoclase microgneiss is cut by sheared crystalloblastic granitic or pegmatitic rocks containing garnet, muscovite, and microcline. In places the garnet is being replaced by muscovite. The muscovite-bearing rocks probably were derived from the regional microgneiss by recrystallization accompanied by metasomatic introduction of potassium along shear or joint planes.

FRASER COMPLEX

The Fraser Complex (Doepel and Lowry, 1970) forms a linear belt of mafic granulite, with minor felsic granulite, gneiss, granite, and metagabbro. These rocks are well exposed in the Fraser Range, but to the northeast are largely obscured by Phanerozoic sediments. However, their subsurface extent is easily defined by an intense gravity ridge and strong magnetic relief. At the southern end of Salt Creek mafic and ultramafic granulites occur as bands within microgneiss which is itself compatible with, although not diagnostic of, granulite facies metamorphism. Arguments put forward later in this report show that the Salt Creek granulites are older than the Fraser Complex, and that the mafic rocks indicated by geophysical anomalies to the south of Salt Creek belong to the Fraser Complex but may not have reached granulite facies.

In the Fraser Range area the contact between the Fraser Complex and the Western Gneiss and Granite Zone is a major fault (the Fraser Fault) which is marked by a sharp change in facies and rock type across a zone of intense shearing. Wilson (1969b) interprets the movement on the fault to be reverse and sinistral, whereby the main granulite block moved up and northwards.

Wilson (1969a) suggests that the mafic granulites were derived from a sequence of extrusive basalts and minor gabbro, with some of the felsic bands representing originally quartzo-feldspathic sediments. Doepel and Lowry (1970) found no evidence for supracrustal material and believe that the mafic granulites were derived from a uniform rock mass of basaltic composition. However, the weight of evidence, for example the presence of thin quartzite layers, rounded zircons in felsic granulite bands, and possible amygdales and pillows in mafic granulites, supports Wilson's hypothesis.

EASTERN GNEISS AND GRANITE ZONE

This zone is almost totally unexposed in the study area (Fig. 64), but a flat magnetic relief suggests a granitic or gneissic terrain. Between the Fraser Range and the south coast Doepel (1969) describes a variety of porphyritic, leucocratic, and mixed granitic rocks. To the east of this zone, gravity patterns indicate a possible concealed Archaean block underlying the Eucla Basin (Fraser, 1973).

METAMORPHISM

It is probable that Archaean rocks in the Transition Zone have been affected by Archaean and Proterozoic regional metamorphism, although none of the episodes have been positively identified. At least two periods of metamorphism, the earlier one reaching at least upper amphibolite facies, are present in the garnetiferous mafic and ultramafic rocks 35 km southeast of McKays Creek.

Metamorphic grade within the Western Gneiss and Granite Zone increased from north to south, that is, towards the granulite facies rocks of the Fraser Complex. This is best illustrated by the Salt Creek section. In the migmatite of the northern part, plagioclase, apparently in equilibrium with epidote, varies southward from sodic oligoclase to calcic oligoclase and finally labradorite. Associated with this increase of calcium in plagioclase is a progressive bleaching of garnet, a decrease in the amount of epidote, and an increase in grain size.

Towards the southern end of Salt Creek garnet appears and untwinned alkali feldspar (?orthoclase) replaces microcline in regional microgneiss. Heier (1961) has suggested that a change from triclinic to monoclinic feldspar closely defines the transition from amphibolite to granulite facies, but evidence from Broken Hill, New South Wales (Binns, 1964) and elsewhere throws doubt on the accuracy of the transition as a grade indicator. It may be significant that at Salt Creek the alkali feldspar change in the microgneiss corresponds to the first appearance of metamorphic orthopyroxene (indicating granulite facies) in mafic bands. Polymetamorphism is suggested by some samples of microgneiss in which biotite replaces garnet along cracks.

In the mafic granulites at the southern end of Salt Creek, the presence of hornblende and orthopyroxene in equilibrium indicates a position low in the granulite facies. Upper granulite facies rocks, predominantly augite-hypersthene-plagioclase granulite, with no hornblende, occur in the Fraser Range.

GEOCHRONOLOGY SAMPLING AND PETROLOGY

Samples were collected from four main localities (Fig. 64), plus some from intervening areas, in order to give a series of determinations across the predominant strike in the study area. Isolated Hill was included as it represented the nearest undoubted Archaean to the presumed Proterozoic rocks in the Plumridge and Neale Sheet areas. Brief descriptions of the four areas follow. Petrographic descriptions of individual samples are given in the Appendix. Sample numbers of the Geological Survey of Western Australia are used throughout the article.

ISOLATED HILL

Porphyritic gneissic hornblende-biotite adamellite is intruded by leucocratic gneissic granite and shallow-dipping pegmatite dykes. The foliation and a strong subhorizontal lineation (mineral elongation) trend 353°.

McKAYS CREEK

This area is dominated by medium-grained granite and adamellite of alkaline affinities. Apart from a few thin veins of aplite minor intrusions are lacking. Samples of these rocks were collected together with hybrid rocks at the margins of large mafic xenoliths, and also riebeckite porphyry which intrudes the granite at Bobbies Point, 15 km southwest of McKays Creek.

PLEIADES LAKES

A variety of metamorphosed mafic and rapakivi-textured granitic and associated hybrid rocks intrude augen gneiss and microgneiss. These are in turn intruded by leucocratic granite, aplite, and pegmatite.

SALT CREEK

Samples were collected from the regional microgneiss and also from cross-cutting foliated muscovite pegmatite and granite. The gneisses in the vicinity of the muscovite-bearing rocks also contain minor muscovite.

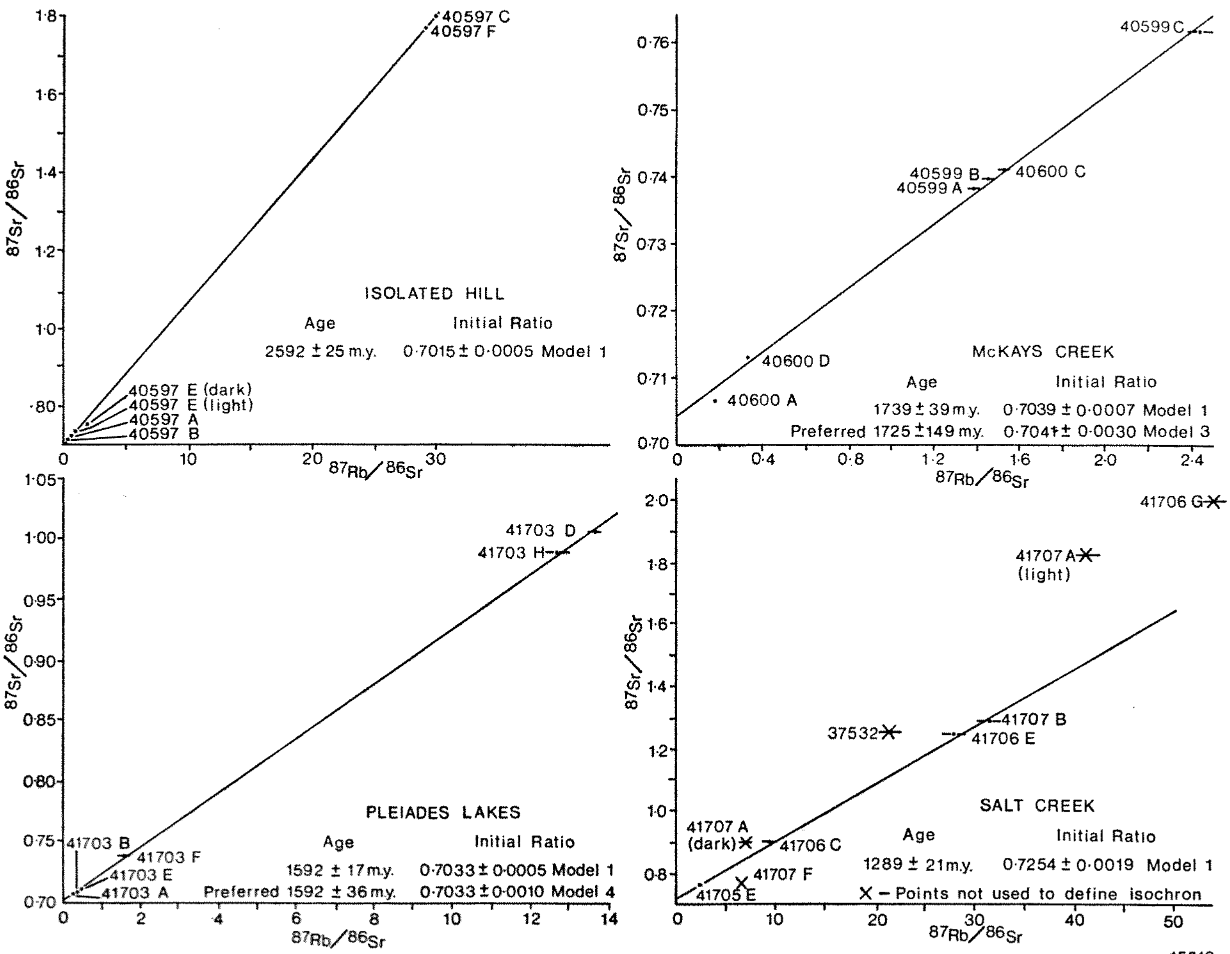
All samples were analyzed for Na, K, and Sr in order to give some guidance to the final choice of geochronology samples. Twenty-six samples were finally chosen from the four main localities. Two more were added later from the Salt Creek area in an attempt to clarify the isochrons from that locality. Full chemical analysis has not been attempted, but analyses of examples of most rock types were reported by Van de Graaff and Bunting (1974, a and b).

EXPERIMENTAL PROCEDURES

All instruments and methods used in this study are the same as those described by Lewis and others (1975), page 84.

RESULTS OF ISOTOPIC ANALYSIS

The measured Rb/Sr and $^{87}Sr/^{86}Sr$ ratios, as well as the calculated $^{87}Rb/^{86}Sr$ ratios are given in Table 34. Errors accompanying the data are at the 95 per cent confidence level. The data are plotted as isochrons in Figure 65. A value of 1.39×10^{-11}/yr was used for the decay constant of ^{87}Rb.



15519

Figure 65. Isochron plots for samples from Isolated Hill, McKays Creek, Pleiades Lakes, and Salt Creek.

TABLE 34.—ANALYTICAL DATA FOR SAMPLES FROM ISOLATED HILL, McKAYS CREEK, PLEIADES LAKES, AND SALT CREEK.

Sample no.	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Isolated Hill					
40597B	67	586	0·115 ± 0·001	0·332 ± 0·003	0·71383 ± 0·00010
40597A	67	578	0·116 ± 0·001	0·335 ± 0·003	0·71402 ± 0·00012
40597E (dark)	128	522	0·247 ± 0·003	0·715 ± 0·008	0·72738 ± 0·00009
40597E (light)	164	290	0·566 ± 0·007	1·64 ± 0·02	0·76155 ± 0·00011
40597F	323	36	9·085 ± 0·1	28·9 ± 0·4	1·7637 ± 0·00018
40597C	245	26	9·36 ± 0·1	29·9 ± 0·4	1·7985 ± 0·00019
McKays Creek					
40600A	32	507	0·061 ± 0·001	0·176 ± 0·003	0·70644 ± 0·00008
40600D	53	490	0·113 ± 0·002	0·33 ± 0·004	0·71329 ± 0·00008
40599A	93	196	0·480 ± 0·005	1·39 ± 0·02	0·73876 ± 0·00009
40599B	95	190	0·505 ± 0·005	1·46 ± 0·02	0·74032 ± 0·00009
40600C	95	178	0·533 ± 0·006	1·54 ± 0·02	0·74151 ± 0·00009
40599C	106	125	0·846 ± 0·01	2·45 ± 0·03	0·76242 ± 0·00010
40598A*	110	5	22·75 ± 0·3	73·6 ± 1·0	1·93236 ± 0·00016
Pleiades Lakes					
41703A	31	340	0·0904 ± 0·001	0·261 ± 0·003	0·70882 ± 0·00009
41703B	33	332	0·0998 ± 0·001	0·288 ± 0·003	0·70902 ± 0·00008
41703E	39	352	0·112 ± 0·001	0·32 ± 0·003	0·71069 ± 0·00008
41703F	136	250	0·542 ± 0·006	1·57 ± 0·02	0·73932 ± 0·00011
41703H	360	85	4·27 ± 0·05	12·7 ± 0·15	0·98881 ± 0·00012
41703D	536	115	4·63 ± 0·06	13·7 ± 0·02	1·0064 ± 0·00015
Salt Creek					
41705B	100	122	0·828 ± 0·008	2·40 ± 0·02	0·76827 ± 0·00009
41707F*	200	88	2·28 ± 0·02	6·61 ± 0·07	0·76662 ± 0·00009
41707A (dark)*	195	82	2·37 ± 0·02	6·97 ± 0·07	0·89401 ± 0·00013
41706C	245	75	3·24 ± 0·03	9·53 ± 0·1	0·90183 ± 0·00010
37532*	358	51	7·06 ± 0·07	21·5 ± 0·3	1·2522 ± 0·0002
41706E	234	26	9·16 ± 0·1	27·8 ± 0·3	1·21890 ± 0·00011
41707B	285	28	10·25 ± 0·1	31·3 ± 0·3	1·29091 ± 0·0002
41707A (light)*	257	20	12·85 ± 0·1	41·2 ± 0·4	1·8280 ± 0·00028
41706G	200	12	16·56 ± 0·2	53·9 ± 0·6	2·01001 ± 0·00021

* Indicates samples not used in final isochron calculations.

NOTE: The Rb and Sr concentrations have been determined by comparison with a number of standard rocks. Although no assessment of the mass absorption coefficient of individual samples was made we believe the values are accurate to about ±7 per cent. The Rb/Sr ratios do not correspond exactly with the ratios that would be derived from the separate Rb and Sr values shown.

Regression analyses of the data were carried out using the programme of McIntyre and others (1966). The ages derived from the data are 2 592 ± 25 m.y. (Model 1) for the Archaean gneiss at Isolated Hill, Rason 1:250 000 Sheet area, 1 725 ± 149 m.y. (Model 3) for the granitic and mafic plutonic rocks from McKays Creek, and 1 592 ± 36 m.y. (Model 4) for the metamorphosed mixed plutonic rocks at Pleiades Lakes. Four muscovite-bearing late granitic rocks at Salt Creek provided an age of 1 289 ± 21 m.y. (Model 1). Other rocks in the Salt Creek area gave a scatter of values to which a reliable isochron could not be fitted.

For the McKays Creek and Pleiades Lakes isochrons the mean square of the weighted deviates is greater than unity implying a scatter in the data points greater than can be expected from experimental uncertainties alone. Either or both of the assumptions that the initial $^{87}Sr/^{86}Sr$ ratios were homogeneous, and that all samples were closed to Rb and Sr, therefore, do not hold for these suites of samples. The programme has examined each set of data for geological variation and indicated that the rocks comprising the McKays Creek isochron had the same initial $^{87}Sr/^{86}Sr$ ratios but slightly different ages (Model 3), whereas the rocks within the Pleiades Lakes isochron had slightly different initial ratios and ages (Model 4). The scatter of points from the Isolated Hill and Salt Creek localities is within experimental error, and therefore a Model 1 isochron is preferred.

DISCUSSION OF RESULTS

ISOLATED HILL

The age of 2 592 ± 25 m.y. from the adamellite gneiss and related minor intrusive granitic rocks at Isolated Hill is within the error limits of many granitic rocks of the Eastern Goldfields Province of the Yilgarn Block and is towards the end of the middle period (2 700 to 2 550 m.y.) of acid magmatism and metamorphism delimited by Arriens (1971). The strong gneissic foliation and lineation developed in the rocks at Isolated Hill suggests the age is that of metamorphic rather than igneous crystallization, and probably represents one of the last phases of Archaean tectonism. The initial $^{87}Sr/^{86}Sr$ ratio of 0.7015± 0.0005 is consistent with an immediate mantle derivation for the granitic rocks.

McKAYS CREEK

The biotite adamellite to hornblende granodiorite plutonic and hypabyssal rocks at McKays Creek provide an age of 1 725 ± 149 m.y. The large uncertainty factor is due to the preference for a Model 3 isochron and probably reflects genuine age differences in the samples. A magmatic event may be recorded here. Alteration of the rocks is limited to dusting of plagioclase and, in some samples, saussuritization. The initial $^{87}Sr/^{86}Sr$ ratio of 0.7041 ± 0.0030 does not distinguish between immediate derivation from the mantle and derivation from older crustal rock with a low Rb/Sr ratio, that is, mafic rocks.

No other rocks in the Albany-Fraser Province have yielded comparable ages.

A single sample of porphyritic riebeckite rhyolite (40598A) from Bobbies Point shows a high Rb/Sr value, and the point does not lie near any of the isochrons.

PLEIADES LAKES

The metamorphosed igenous complex at Pleiades Lakes provides an isochron at 1 592 ± 36 m.y. The date probably reflects the age of metamorphism rather than the age of the complex igneous processes which resulted in the rapakivi textures and hybridization of magmas in this area. Metamorphyic recrystallization has affected most of the rocks which have been studied. Minor igneous activity, represented by aplite (sample 41703H) and pegmatite (sample 41703D) may have accompanied metamorphism. These rocks are not notably metamorphosed.

The initial $^{87}Sr/^{86}Sr$ ratio of 0.7033 ± 0.0010 is not significantly different to that from McKays Creek, but when the younger age at Pleiades Lakes is considered, the ratio indicates that the material which formed the igneous rocks at Pleiades Lakes must have been derived from the mantle only a short time before the event recorded in the 1 592 m.y. isochron.

The preference for a Model 4 isochron may reflect incomplete homogenization during metamorphism of originally complex igneous rocks which had slightly different initial $^{87}Sr/^{86}Sr$ ratios.

The rocks at Pleiades Lakes are of the same types and occur in the same tectonic zone as samples described by Arriens and Lambert (1969) 300 km to the southwest which gave an age of 1 660 ± 40 m.y. The 1 660 m.y. isochron includes samples of gneiss, porphyritic granite, and rapakivi granite, and probably represents a metamorphic event which affected the gneiss and which also deformed the rapakivi granite to produce an augen gneiss.

SALT CREEK

The isochron at 1 289 ± 21 m.y. from the Salt Creek locality is formed by four muscovite-bearing rocks (41705B, 41706C, 41706E, and 41707B). This date may be the age of potassic metasomatism which formed replacement dykes in shear zones in garnet-bearing microgneiss, and affected the gneiss in the vicinity of the dykes. The 1 289 m.y. age is similar to an age of 1 280 m.y. for muscovite from pegmatite in the Fraser Range (Wilson and others, 1960), but it is slightly younger than the 1 328 ± 12 m.y. of mafic granulites in the Fraser Complex (Arriens and Lambert, 1969).

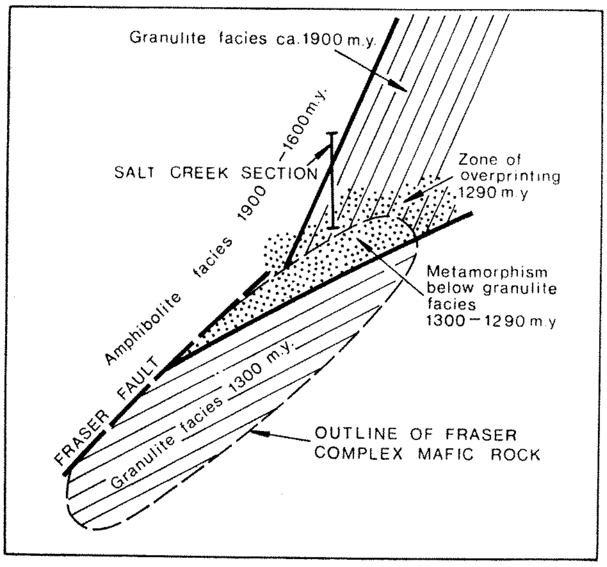
The initial $^{87}Sr/^{86}Sr$ ratio for data from the muscovite-bearing samples from Salt Creek is 0.7254 ± 0.0019, significantly greater than 0.7049 ± 0.012 reported by Arriens and Lambert (1969) for the Fraser Complex. The high initial $^{87}Sr/^{86}Sr$ ratio of the Salt Creek rocks seems to indicate that these rocks have been extant in the crust longer than the mafic granulites of the Fraser Range which have the same isotopic age. They are not derived directly from the mantle or derived by differentiation from the Fraser Complex.

The isotopic data are consistent with petrographic suggestions that the muscovite-bearing rocks of Salt Creek may be derived from the regional microgneiss (which they cut) by recrystallization accompanying shearing and metasomatic introduction of potassium along joints or minor shears. These processes would have occurred late in the Fraser Range metamorphism and would have been contemporaneous with the emplacement of pegmatite in the Fraser Range area.

While the muscovite-bearing rocks at Salt Creek can be correlated with events in the Fraser Range, the regional microgneiss which they cut seems clearly older. There is no reliable isotopic age for the microgneiss but points on the isochron diagram plot well above the isochron at 1 289 m.y. generated by the muscovite-bearing rocks. The slope of the line formed by the light and dark phases of sample 41707A gives an age of about 1 900 m.y. and this may represent a minimum age of granulite facies metamorphism in the Salt Creek area. Sample 41706G falls below this line, but it has been affected by two periods of deformation, the second of which can be related to the shearing associated with the muscovite-bearing rocks of the 1289 m.y. isochron. The shearing may have caused loss of radiogenic strontium, giving a lower age than that of the unaffected gneisses.

Two further samples were analyzed in an effort to improve the older isochron. Sample 37532 falls slightly below the line formed by the two phases of sample 41707A. Sample 41707F, for unknown reasons, has suffered almost total loss of radiogenic strontium.

Small pods of mafic rock enclosed in the regional microgneiss at Salt Creek carry metamorphic orthopyroxene indicating metamorphism in the granulite facies and implying that the enclosing microgneiss has also been subjected to granulite metamorphism. Arriens and Lambert (1969) and Wilson (1969b) have suggested that emplacement of the Fraser Range basalts preceded metamorphism (at 1 329 ± 12 m.y.) by no more than 300 m.y. Thus if the argument for metamorphism of the microgneiss at about 1 900 m.y. or earlier is acceptable, the Salt Creek rocks would have experienced metamorphism in the granulite facies before emplacement of the (now granulite facies) basalts of the Fraser Complex. On the assumption that granulite facies metamorphism at 1 330 m.y. at Salt Creek would have reset the isotopic ratios, two periods of granulite facies metamorphism are required. Granulite facies metamorphism of the later (Fraser Range) period did not reach the Salt Creek area (Fig. 66), but lower grade effects are evident in the metasomatic and retrogressive features of the rocks. This hypothesis implies that some of the mafic rocks towards the northeast end of the Fraser Complex (now completely obscured by sand) did not reach granulite facies. Thus the Fraser Complex may have to be redefined to include not only the mafic granulites, but all of the predominantly mafic rocks that were emplaced in the same episode as the basalts which were later metamorphosed to give the Fraser Range granulites.



15520

Figure 66. Schematic map of possible metamorphic facies relationships, northeast Albany-Fraser Province.

EVOLUTION OF THE NORTHEAST ALBANY-FRASER PROVINCE

In early Proterozoic times a thick sequence of quartzo-feldspathic sediments accumulated in a subsiding basin flanking the southeast edge of the Yilgarn Block. This was followed by metamorphism, igneous intrusion, and tectonism, at various times from about 1 900 to 1 590 m.y., which affected both the sediments and the adjacent Yilgarn Block. The intrusion of granitic rocks at McKays Creek, metamorphism to amphibolite and granulite facies at Salt Creek, and tight folding along northeast axes occurred during this period. The emplacement of mafic rock, rapakivi granite, and leucogranite at Pleiades Lakes and west of the Fraser Range probably represents an intrusive event towards the end of this period of orogeny.

Further development of the basin, accompanied by northeast-trending fractures, resulted in accumulation of thick piles of mafic rock with associated minor sediments—the source rocks for the Fraser Complex. A second orogenic period at 1 330 to 1 280 m.y. metamorphosed the rocks in the Fraser Range area to granulite facies, and in the Salt Creek area produced metasomatic and retrograde effects in the earlier granulite rocks.

ACKNOWLEDGEMENTS

The authors would like to thank Mr. R. Dring and Mr. D. Hosie of the Department of Physics, Western Australian Institute of Technology, for technical assistance during this project.

REFERENCES

Arriens, P. A., 1971, The Archaean geochronology of Australia: Geol. Soc. Australia Special Publication No. 3, p. 11-23.

Arriens, P.A., and Lambert, I. B., 1969, On the age and strontium isotopic geochemistry of granulite-facies rocks from the Fraser Range, Western Australia, and the Musgrave Ranges, Central Australia: Geol. Soc. Australia Special Publication No. 2, p. 377-388.

Binns, R. A., 1964, Zones of progressive regional metamorphism in the Willyama Complex, Broken Hill District, New South Wales: Geol. Soc. Australia Jour., v. 11, p. 283-330.

Bunting, J. A., and Boegli, J.-C., 1974, Explanatory notes on the Minigwal 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1974/17 (unpublished).

Bunting, J. A., and van de Graaff, W. J. E., 1974, Explanatory notes on the Cundeelee 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1974/12 (unpublished).

Doepel, J. J. G., 1969, The Precambrian geology between Zanthus and Israelite Bay, Western Australia: West. Australia Geol. Survey Ann. Rept. 1968, p. 41-42.

———1973, Norseman, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

———1975, Albany-Fraser Province, *in* Geology of Western Australia: West. Australia Geol. Survey, Mem. 2, p. 94-102.

Doepel, J. J. G., and Lowry, D. C., 1970, Zanthus, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

Fraser, A. R., 1973, A discussion of the gravity anomalies of the Precambrian shield of Western Australia: Australia Bur. Mineral Resources Rec. 1973/105 (unpublished).

Gower, C. F., and Boegli, J.-C., 1973, Explanatory notes on the Rason 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey. Rec. 1973/14 (unpublished).

Heier, K. S., 1961, The amphibolite-granulite facies transition reflected in the mineralogy of potassium feldspars: Cursillos of Conferencias, Fasc. 8, p. 131-137.

Lewis, J. D., Rosman, K. J. R., and de Laeter, J. R., 1975, The age and metamorphic effects of the Black Range dolerite dyke: West. Australia Geol. Survey Ann. Rept. 1974, p. 80-88.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research, 71, p. 5459-5468.

Marmo, V., 1962, On granites: Finland Geol. Commission Bull. No. 201.

Sederholm, J. J., 1932, On the geology of Finland with special reference to the Precambrian: Finland Geol. Commission Bull. No. 98.

Turek, A., 1966, Rubidium-strontium isotopic studies in the Kalgoorlie-Norseman area, Western Australia: Australian Nat. Univ. Ph.D. thesis (unpublished).

van de Graaff, W. J. E., 1973, Seemore, W.A.: West. Australia Geol. Survey 1:250 000 Geol. Series Explan. Notes.

van de Graaff, W. J. E., and Bunting, J. A., 1974a, Explanatory notes on the Neale 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1974/9 (unpublished).

——— 1974b, Explanatory notes on the Plumridge 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1974/11 (unpublished).

Wilson, A. F., 1969a, The pyroxene granulites and associated gabbros of the Fraser Range, Western Australia, and their economic significance: Australasian Inst. Mining Metall. Proc., 231, p. 47-57.

——— 1969b, Granulite terrains and their tectonic setting and relationship to associated metamorphic rocks in Australia: Geol. Soc. Australia Special Publication No. 2, p. 243-258.

Wilson, A. F., Compston, W., Jeffrey, P. M., and Riley, G. H., 1960, Radioactive ages from the Precambrian rocks in Australia: Geol. Soc. Australia Jour., v. 6, p. 179-195.

APPENDIX—PETROGRAPHIC DESCRIPTIONS OF GEOCHRONOLOGY SAMPLES

ISOLATED HILL

40597A Adamellite

This gneissic, myrmekitic, epidote-bearing hornblende-biotite adamellite has plagioclase megacrysts of moderate size and large euhedral microcline megacrysts. Sphene is brown-orange. Quartz has been severely strained.

40597B Adamellite

Similar to 40597A. Oscillatory zoning in plagioclase megacrysts suggests an igneous origin.

40597C Micro-adamellite

This inequigranular micro-adamellite consists of abundant irregular to rounded coarse megacrysts of microcline and less plagioclase in a medium-grained quartzo-feldspathic groundmass with minor small grains of biotite. Strained quartz and irregular grain shape suggest recrystallization after cataclasis. Plagioclase is sodic oligoclase.

40597E (light and dark) Biotite adamellite gneiss

Feldspar megacrysts are set in a matrix of coarse, strained quartz and fine or medium-grained feldspar. Accessory sphene ranges from colourless to orange-brown, in part metamict.

Plagioclase has been altered but biotite is fresh.

40579F Adamellite

A grossly inequigranular, seriate, leucocratic adamellite. Biotite is rare, dark brown. The rock is cataclastic.

McKAYS CREEK

40598A Riebeckite rhyolite

Phenocrysts of irregular to euhedral coarse perthitic microcline, and rounded, irregular to rarely subhedral strained quartz are set in a fine-grained matrix of perthitic poikilitic K-feldspar, anhedral quartz, biotite, riebeckitic amphibole, and opaques.

Secondary carbonate is common. The groundmass and probably the marginal part of phenocrysts have been metamorphically recrystallized. Quartz is strained.

40599A Biotite adamellite

This is a plagioclase-dominant medium to coarse-grained biotite adamellite cut by fine-grained porphyritic dykelets. Oligoclase is euhedral with oscillatory zoning. Subhedral to vermicular fine-grained plagioclase is poikilitically enclosed by quartz to form a very unusual texture. The texture is developed generally throughout the rock but cores of some quartz grains are free of inclusions.

40599B Biotite adamellite

Similar to 40599A, but poikilitic quartz is less general.

40599C Porphyritic rhyodacite

Phenocrysts of K-feldspar, plagioclase, and quartz as well as lithic aggregates of coarse quartz, feldspar, and granophyre are set in a fine, probably recrystallized quartzo-feldspathic groundmass.

Some insets have the irregular intergrowth between coarse quartz and fine plagioclase which is characteristic of 40599A and B. The rock probably is hypabyssal.

40600A Hornblende granodiorite

Euhedral elongate grains of plagioclase are set in coarse masses of quartz and untwinned K-feldspar. Apatite, magnetite, and sphene are common, as are secondary chlorite and epidote. Saussuritization has been intense. More mafic than the 40599 series, but possibly texturally related.

40600C Biotite adamellite

Very coarse elongate plagioclase grains are set in a coarse, even-grained, hypidiomorphic granular groundmass of quartz, subhedral microcline, and zoned plagioclase with less biotite.

40600D Biotite granodiorite

Even-grained, coarse-grained; saussuritization has been intense.

PLEIADES LAKES

41703A Metadolerite

Heavily saussuritized coarse to medium-grained blotchy to lath-like plagioclase, now with irregular margins, is felted among lath-like or elongate mafic grains now altered to a complex of very fine stubby elongate grains of green amphibole and medium-size grains of biotite. The apparent colour index is about 50. The present plagioclase composition is about An_{40} (optical).

41703B Metadolerite

Similar to 41703A but the plagioclase has much less epidote; instead, many grains are filled with green amphibole which surrounds abundant opaque inclusions.

41703D Microcline

This sample is microcline with quartz inclusions from a quartz-microcline pegmatite dyke. The quartz has been cataclastically granulated.

41703E Metamorphosed quartz gabbro

Similar to 41703A and B. The lath-like plagioclase suggests an igneous origin. The mafics have been altered to pseudomorphous masses of green amphibole similar to uralite. Biotite is common. A few quartz grains, interstitial to plagioclase, are scattered through the rock.

41703F Hybrid rapakivi rock

Very coarse euhedral microcline, coarse grains of rounded quartz, and coarse euhedral plagioclase are set in a crystalloblastic matrix of quartz, epidote-filled plagioclase, and very abundant biotite (about 20 per cent of rock?). The margins of the very coarse microcline grains are an aggregate of fine to coarse-grained plagioclase in microcline, giving a mantling effect similar to rapakivi texture. In part, the internal portions of microcline grains consist of subhedral grains of plagioclase and of microcline set in interstitial, almost poikilitic, quartz. The coarse microcline phenocrysts seem incongruous in the rock which is dominated by biotite and epidote. This together with evidence of reaction suggests a hybrid origin.

41703H Microgranite

Medium-grained, subhedral, commonly elongate microcline, and mosaic to sutured aggregates of quartz with less biotite are the dominant minerals. Quartz appears to be recrystallized. Dusky-blue tourmaline is an accessory.

SALT CREEK

37532 Garnet-quartz-feldspar microgneiss

This is a garnet gneiss, but medium rather than coarse grained, hence the name microgneiss. Fine to medium-grained felsic minerals are sutured and weakly elongated. K-feldspar is untwinned. Garnet is abundant but biotite is an accessory.

This is part of the regional microgneiss suite in the Salt Creek area.

41705B Biotite microgneiss

Thin layers of strongly oriented biotite with epidote are interleaved with thicker layers of equidimensional felsic minerals dominated by quartz and microcline but including plagioclase. Colourless mica, carbonate, and green biotite (?ferrostilpnomelane) are minor.

The rock is distinguished from the regional microgneiss of sample 41707 by M-twinning of microcline, the association of epidote and plagioclase, the presence of colourless mica, and the absence of garnet.

41706C Muscovite granite gneiss

This is a cataclastic gneiss consisting mainly of quartz and microcline with less plagioclase, muscovite, and biotite. Garnet and opaques are accessories. Quartz is strongly oriented; biotite and muscovite are less strongly oriented.

41706E Garnet and muscovite-bearing granite pegmatite

Quartz and microcline are dominant, with less albite or oligoclase, biotite, and garnet. Trains or patches of felsic minerals, including muscovite, suggest healed cataclasis. Garnet is associated with muscovite and partly altered to biotite.

41706G Garnet-biotite gneiss

Principal minerals are quartz and mesoperthitic K-feldspar with less plagioclase, brown to green biotite, and scattered garnet. Elongate, anhedral quartz, and included wisps of feldspar are oriented obliquely to the compositional layering, defined by concentration of biotite and garnet. Some biotite is oriented parallel to the compositional layering, some parallel to quartz elongation. Neither muscovite nor epidote is present.

41707A (light) Garnet-biotite-feldspar-quartz microgneiss

Untwinned K-feldspar, quartz and less plagioclase are the dominant minerals, accompanied by minor garnet and less biotite. The felsic minerals are of medium grain size and are interlocked with sutured boundaries. There is no pronounced foliation. This is the leucocratic phase of the regional microgneiss of the Salt Creek area.

41707A (dark) Garnet-biotite-feldspar-quartz microgneiss

This sample and 41707A (light) are dark and light phases of the same specimen. The two phases are similar, though in the dark phase biotite and garnet are abundant. With the presence of dark minerals foliation can be recognized; biotite is strongly oriented and sharply concentrated in layers 0.25 mm thick. Garnet is distributed evenly through the rock. There is minor alteration of garnet to biotite. Muscovite is rare. This is a member of the regional microgneiss suite.

41707B Garnet-bearing muscovite granite

The sample is from a dyke 0.5 m wide which cuts the regional microgneiss of sample 41707A. Quartz and strongly twinned microcline are dominant; muscovite and sodic oligoclase are less abundant. Garnet is common. Muscovite is poikiloblastic, quartz forms mosaic to sutured masses as well as blebs and vermicular intergrowths in plagioclase. Plagioclase tends to be globular with sutured margins and microcline normally is irregular but forms a few small subhedral insets. Fragments of garnet seem to be partly replaced by muscovite. The overall aspect is granoblastic.

41707F Garnet-biotite-feldspar-quartz microgneiss

This sample is almost identical to 41707A (dark), with somewhat stronger orientation of elongate quartz. Felsic minerals are intricately sutured; garnet is weakly elongate. Biotite is strongly oriented and concentrated in thin layers. K-feldspar is untwinned. This is a part of the regional microgneiss suite.

Rb-Sr WHOLE-ROCK AND MINERAL AGES FROM THE GASCOYNE PROVINCE

by J. R. de Laeter*

ABSTRACT

A Rb-Sr geochronological study of 14 whole-rock samples and 11 mineral separates from the southern portion of the Gascoyne Province has provided additional isotopic data for this geologically complex region. Three suites of whole-rock samples gave ages of 1 672, 1 776 and 2 208 m.y. The associated initial $^{87}Sr/^{86}Sr$ ratios support the geological evidence, namely that the granitic and migmatic rocks have been derived from older Archaean rocks admixed with younger magmatic or supercrustally reworked material. Seven mineral isochrons give ages ranging from 739 to 809 m.y. with an average value of 780 m.y. The uniformity in mineral ages throughout the area indicates a widespread time of relatively fast cooling, possibly related to folding and uplift of the Bangemall Basin.

INTRODUCTION

In 1969, the Regional Geology and Mineral Resources Divisions of the Geological Survey carried out joint photogeological and reconnaissance traverses in the Glenburgh and Mount Phillips 1:250 000 Sheet areas, in support of the preparation of a summary of the geology of the Gascoyne Province, to be incorporated in a publication dealing comprehensively with the geology of the State; that publication (Geological Survey of Western Australia, 1975) has now been completed and issued, and it includes the resultant account of the Gascoyne Province (Daniels, 1975). The results of isotopic analyses of samples collected during those traverses carried out in 1970-71 have not been published. It was planned to combine their publication with sufficient further geological detail to fully illustrate their significance; but this has not proved practicable, and the purpose of this paper is to publish these results within a more limited geological context, so that the conclusions which may nevertheless be drawn from them are made generally available.

THE GASCOYNE PROVINCE

Daniels and Horwitz (1969) used the term Gascoyne Block to denote a triangular area of igneous and metamorphic rocks, about 65 000 km^2 in extent, bounded on the west by the eastern margin of the Phanerozoic Carnarvon and Perth Basins, on the northeast by Middle Proterozoic sedimentary rocks of the Bangemall Basin, and on the southeast by Archaean igneous and metamorphic rocks of the Yilgarn Block. Daniels (1975) applied the term Gascoyne Province to a more restricted area, of about 41 000 km^2, the decrease being due to a northward adjustment of the southeastern margin.

According to Daniels (1975, Fig. 6) the rocks of the Gascoyne Province are the final product of a complex sequence of interrelated tectonic, magmatic, and metamorphic events. An initial Archaean association of folded greenstone belts and dominantly granitic intrusions was subjected to migmatization in late Archaean or early Proterozoic times. Deposition of the Lower Proterozoic rocks of the Mount Bruce Supergroup was accompanied by faulting and followed by further magmatization, granite emplacement, and further movement along established fault zones. After deposition of the Middle Proterozoic Bangemall Group further folding and renewed faulting took place. As a result it might be expected that the granitic and migmatitic rocks of the province may be variously derived from older Archaean granitic rocks and greenstones, admixed with younger magmatic or supercrustally reworked material and variously affected by metamorphic events of different kinds.

Limited geochronological information was available in the Gascoyne Province prior to this study. Aldrich and others (1959) reported Rb-Sr ages of 980 and 940 m.y. for two pegmatitic muscovites from Yinnietharra together with associated K-Ar ages of 905 and 890 m.y. respectively. These large pegmatites are emplaced in east-west-trending metamorphic rocks which yield an age of 1 730 ± 240 m.y. from seven whole-rock samples of gneisses collected some 60 km northwest of Yinnietharra (Compston and Arriens, 1968). Compston and Arriens (1968) also report an age of 1 690 m.y. from granite at Minnie Creek homestead which is of comparable age to the Boolaloo granite dated by Leggo and others (1965) at 1 720 m.y. in the Wyloo Group. Black shales from the

*Department of Physics, Western Australian Institute of Technoolgy.

Curran Formation in the Bangemall Group give an isochron of 1 080 ± 80 m.y. (Compston and Arriens, 1968) and a similar age is obtained from acid lavas in the same region.

The Poona-Dalgaranga area in the northwest corner of the Yilgarn Block, adjacent to the southeast portion of the Gascoyne Block contains a batholith of granitic rocks which has been dated by Muhling and de Laeter (1971) by the Rb-Sr whole-rock technique. Indicated ages are 2 590 ± 23 m.y. for the granitic batholith and 2 605 ± 51 m.y. for several disconnected granitic masses on the eastern edge of the complex. The ages and initial ratios of these granites are typical of the younger period of granitic emplacement in the Archaean of Western Australia distinguished by Compston and Arriens (1968) from 2 750 to 2 600 m.y. These authors also defined an older episode from 3 050 to 2 900 m.y.

MATERIAL ANALYSED

Fourteen whole-rock samples were analysed for Rb and Sr, and for Sr isotopic composition. Biotite separated from seven of the samples was similarly analysed, and from three of these seven, muscovite was also obtained and analysed; microcline was additionally analysed from one of the samples used for whole-rock, biotite and muscovite analysis.

All the samples consisted either of migmatite thought to have altered Wyloo Group as paleosome, or of granitic rock. All were medium-grained rocks of granitoid mineralogy (mainly quartz and feldspars, with subordinate micas) and appearance, with some degree of foliation or banding normally developed. The nominal identity of each is included in Table 35, and localities appear on Figure 67. The selection of samples was made so that the influence of dolerite dykes was not encountered.

TABLE 35. ANALYTICAL DATA FOR 14 WHOLE-ROCK SAMPLES AND 11 SEPARATED MINERALS FROM THE GASCOYNE PROVINCE.

Sample number	Rock type	Material analysed	Rb (ppm)	Sr (ppm)	Rb/Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
20804E	G	WR	175	200	0·90 ± 0·01	2·62 ± 0·02	0·780 8 ± 0·000 8
		BT	....	....	4·8 ± 0·1	14·1 ± 0·3	0·907 9 ± 0·001 5
20807A	G	WR	115	115	1·0 ± 0·02	2·91 ± 0·05	0·787 9 ± 0·000 8
20813B	M	WR	45	255	0·18 ± 0·002	0·52 ± 0·01	0·728 2 ± 0·000 7
		BT	....	....	7·1 ± 0·1	20·9 ± 0·4	0·936 3 ± 0·001 2
20814B	M	WR	103	150	0·69 ± 0·007	1·96 ± 0·02	0·764 1 ± 0·000 7
20817B	G	WR	6·5	310	0·021 ± 0·001	0·06 ± 0·003	0·715 5 ± 0·001 0
20828	G	WR	83	380	0·22 ± 0·004	0·64 ± 0·01	0·725 3 ± 0·003 1
		BT	....	....	10·8 ± 0·21	32·3 ± 0·6	1·083 6 ± 0·001 3
20836B	G	WR	48	245	0·20 ± 0·004	0·58 ± 0·01	0·731 5 ± 0·001 0
20836D	G	WR	32	272	0·124 ± 0·002	0·36 ± 0·007	0·725 0 ± 0·001 2
		BT	....	....	3·39 ± 0·07	9·91 ± 0·2	0·833 1 ± 0·001 4
20846	M	WR	40	420	0·1 ± 0·001	0·28 ± 0·01	0·719 6 ± 0·000 6
		BT	....	....	1·20 ± 0·02	3·5 ± 0·06	0·753 0 ± 0·001 3
		MT	....	....	0·29 ± 0·005	0·84 ± 0·02	0·725 3 ± 0·001 2
20852	M	WR	56	83	0·681 ± 0·009	1·98 ± 0·03	0·789 8 ± 0·001 0
20857	G	WR	205	205	1·0 ± 0·01	2·91 ± 0·03	0·783 0 ± 0·000 7
20863A	M	WR	295	120	2·48 ± 0·04	7·3 ± 0·1	0·886 0 ± 0·000 9
		BT	....	....	32·2 ± 0·6	104 ± 2·0	1·939 9 ± 0·001 8
		MT	....	....	11·44 ± 0·22	34·6 ± 0·7	1·192 6 ± 0·001 1
20871B	G	WR	280	95	3·03 ± 0·04	8·94 ± 0·1	0·922 1 ± 0·000 9
20872	G	WR	345	60	5·9 ± 0·1	17·8 ± 0·3	1·123 7 ± 0·000 9
		BT	....	....	133 ± 3	652 ±13	7·840 ± 0·006
		MT	....	....	115 ± 2	532 ±10	6·853 ± 0·004
		MCL	....	....	6·8 ± 0·1	20·5 ± 0·3	1·152 0 ± 0·001 5

Notes : 1. G—granitic rock, M—migmatite, WR—whole rock, BT—biotite, MT—muscovite, MCL—microcline
2. The Rb and Sr concentrations have been determined by comparison with a number of standard rocks using X-ray fluorescence spectrometry. An assessment of the mass absorption coefficient of individual samples was made and it is estimated that the values are accurate to ± 7 per cent, although the accuracy of the Rb/Sr ratios are in general accurate to about ± 1 per cent. The Rb/Sr ratios do not correspond exactly with the ratios that would be derived from the separate Rb and Sr values shown.

EXPERIMENTAL PROCEDURES

About 200 g of each sample was reduced to —200 mesh using a jaw crusher and a Tema mill. Approximately 0.4 g of each powdered sample was then taken into solution using a $HF-HClO_4$ mixture, and the Rb and Sr extracted by ion-exchange chemistry. Details of the chemical extraction and mass spectrometry are given by Lewis and others (1975).

Replicate analyses of Eimer and Amend standard strontium carbonate were made, to give a mean value of $^{87}Sr/^{86}Sr$ of 0.7081 ± 0.0001, normalized to a $^{88}Sr/^{86}Sr$ value of 8.3752. A value of 1.39 x 10^{-11} $year^{-1}$ was used for the decay constant of ^{87}Rb.

X-ray fluorescence was used to select rocks with favourable Rb/Sr ratios for mass spectrometric analysis, and also to determine precise values of the Rb/Sr ratio for the selected whole-rock samples. The Rb/Sr ratios of the mineral separates were determined by isotope dilution. Accurately weighed quantities of ^{87}Rb and ^{84}Sr spikes were added to the samples prior to dissolution. Each sample was then dissolved in a $HF-HClO_4$ mixture and the rubidium and strontium separated by cation-exchange chemistry as before. Blank determinations using the isotope dilution technique showed that the Rb and Sr contamination introduced by the chemical processing was less than 10^{-9} g and 10^{-8} g respectively. Full details of the isotope dilution techniques used in this laboratory are given by de Laeter and Abercrombie (1970).

RESULTS AND DISCUSSION

The analytical results are listed in Table 35. The errors accompanying the ratios are at the 95 per cent confidence level. The isotopic data from the 14 whole-rock samples are plotted at different scales, together with selected isochrons, in Figure 68A and B.

Regression analyses of the $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ data were carried out using the programme of McIntyre and others (1966). All the data (except 20852) were regressed to give an apparent age of 1 626 ± 73 m.y. (95 per cent limits) and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7190 ± 0.0060. The fit of the data is worse than predicted for experimental error alone. The programme examined the data for geological variation and indicated that the distribution of the residuals suggests that the rocks have the same age but different initial $^{87}Sr/^{86}Sr$ ratios. This is not surprising in view of the large geographical distribution of the samples and the geology of the province.

Sample 20852 was excluded from the regression analysis because of its high $^{87}Sr/^{86}Sr$ value. If this sample point is joined to an assumed initial ratio of 0.71 it gives a model age of 2 842 m.y. It is possible that this sample is a remnant of the initial Archaean association of greenstones and granitic rocks which has survived the full effects of the metamorphic and magmatic events described above.

The subset of samples 20872, 20871B, 20863A, 20857 and 20846 gives an isochron which, if fitted to experimental errors alone, has an apparent age of 1 672 ± 18 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7131 ± 0.0002. These samples have been collected over a large area in the same general location as Yinnietharra and Minnie Creek homestead, where ages of 1 730 ± 240 m.y. and 1 690 m.y. were obtained by Compston and Arriens (1968) on gneisses and granites respectively. The age of 1 672 m.y. as measured in this project is therefore a more precise estimate of the age in this locality.

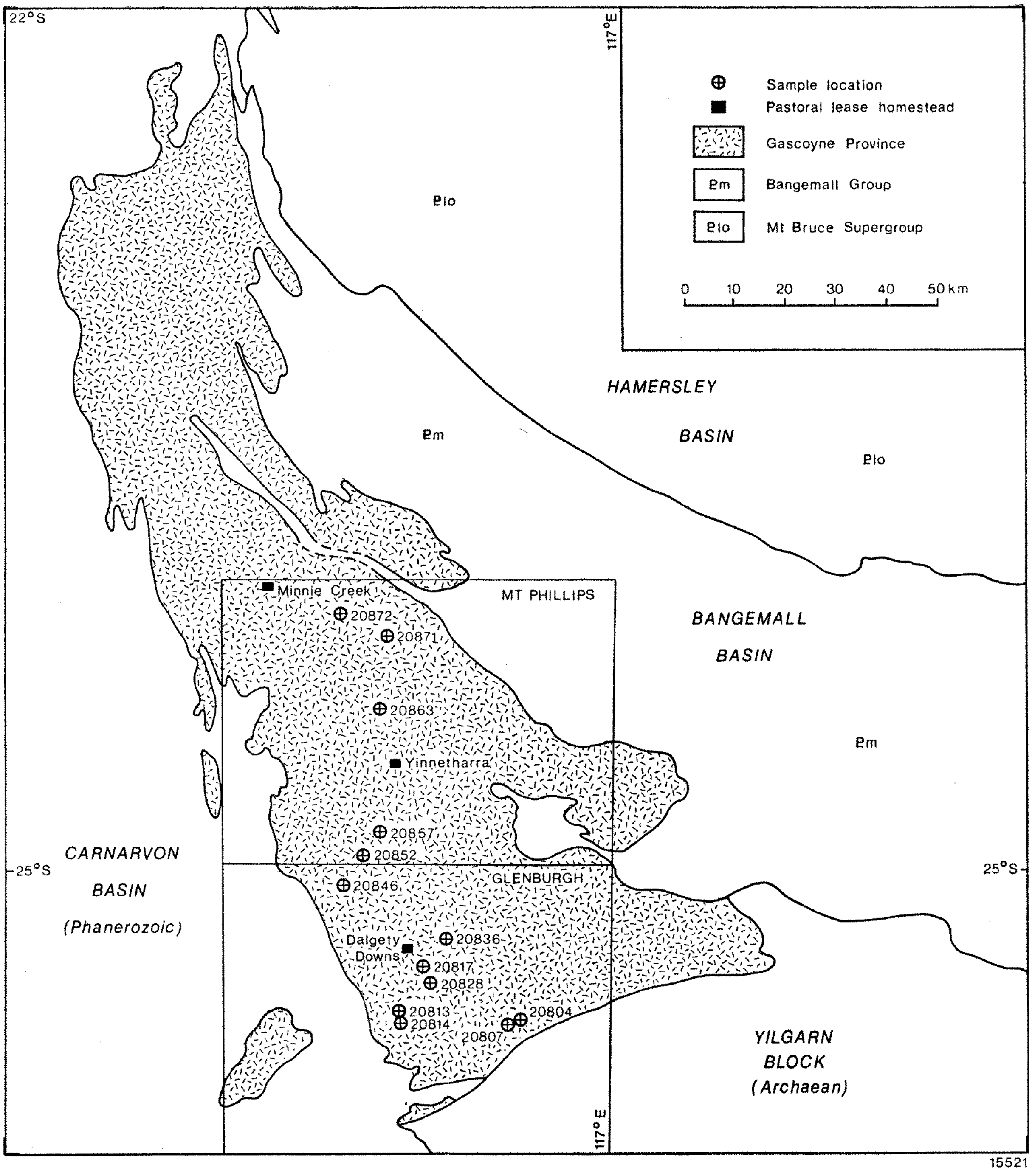


Figure 67. Map showing the position and extent of the Gascoyne Province, the boundaries of the Mount Phillips and Glenburgh 1 : 250 000 Sheet areas, and locations of analysed samples.

The four samples 20807, 20804, 10814B and 20813B, which are located in the southern portion of the Gascoyne Province, give an isochron (labelled II in Fig. 68) and regress within the assigned limits for experimental error to give an apparent age of 1 776 ± 18 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7152 ± 0.00034. This age is significantly older than the 1 672 m.y. isochron (labelled I in Fig. 68). The initial ratios of these two suites of samples are consistent with the hypothesis that these samples have been derived from older Archaean rocks, admixed with younger magmatic or supercrustally reworked material.

Three of the four remaining samples (20817B, 20836D and 20836B) have an excellent fit to an isochron (labelled III in Fig. 68) which regresses to give an apparent age of 2 208 m.y. and an initial $^{87}Sr/^{86}Sr$ ratio of 0.7136. These samples were collected from the Dalgety Downs area, (see Fig. 67) and this age is significantly older than the rocks to the south and north, again reflecting the complex geological history of the province.

The 11 mineral separates listed in Table 35 have been plotted with their corresponding whole rocks in Figure 69. A visual inspection of the resulting seven mineral isochrons indicate a uniformity of ages throughout this series of analyses. The mineral ages range from 739 m.y. to 809 m.y. with an average value of 780 m.y. There is no significant difference between the mineral ages derived from biotite and those derived from the muscovites and microcline. As the temperature in this region decreased, the minerals became closed systems with respect to Rb and Sr. The temperature decrease must have been rapid to enable all the minerals to reflect essentially the same age (of 780 m.y.).

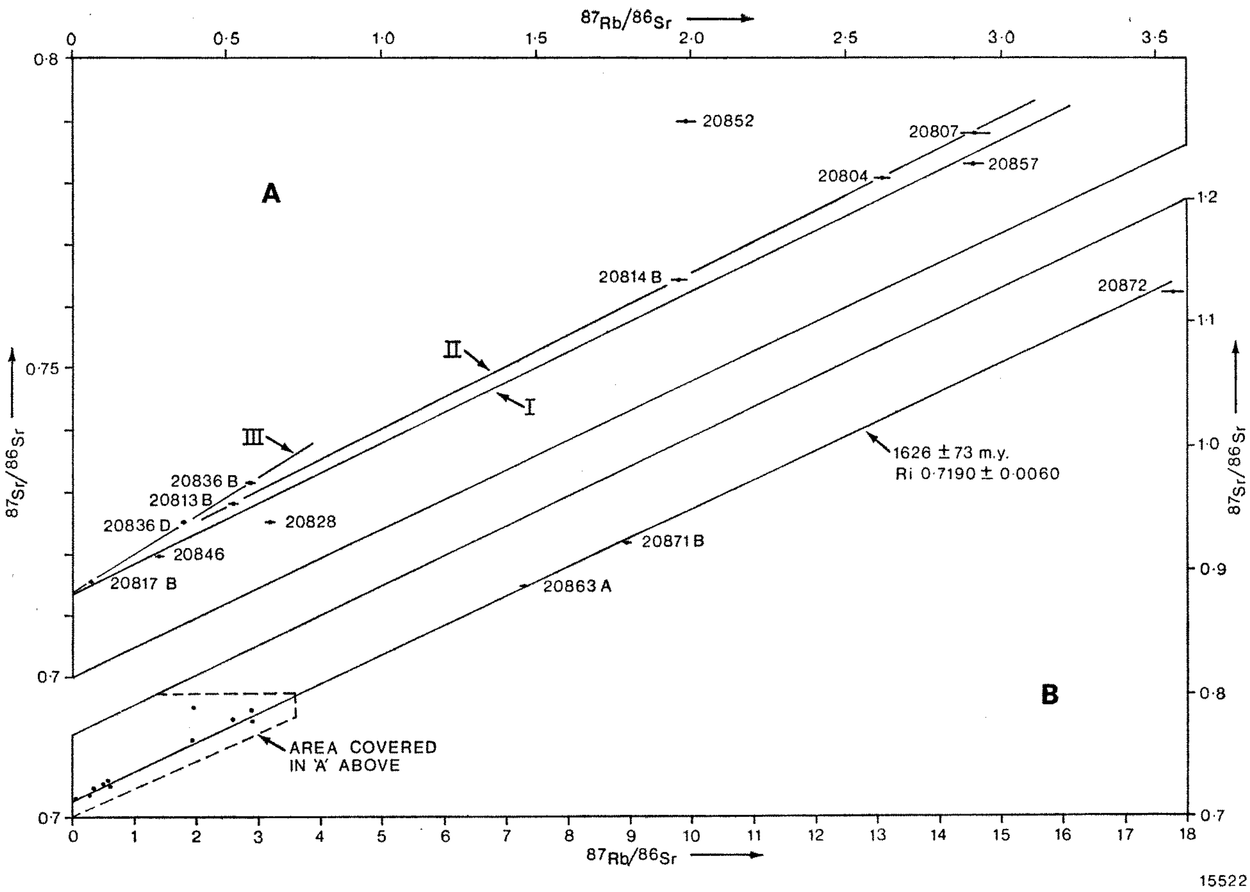


Figure 68. Isochron plot for data of Table 35 ; the upper diagram 'A' is an expanded representation of the small part of 'B' indicated.

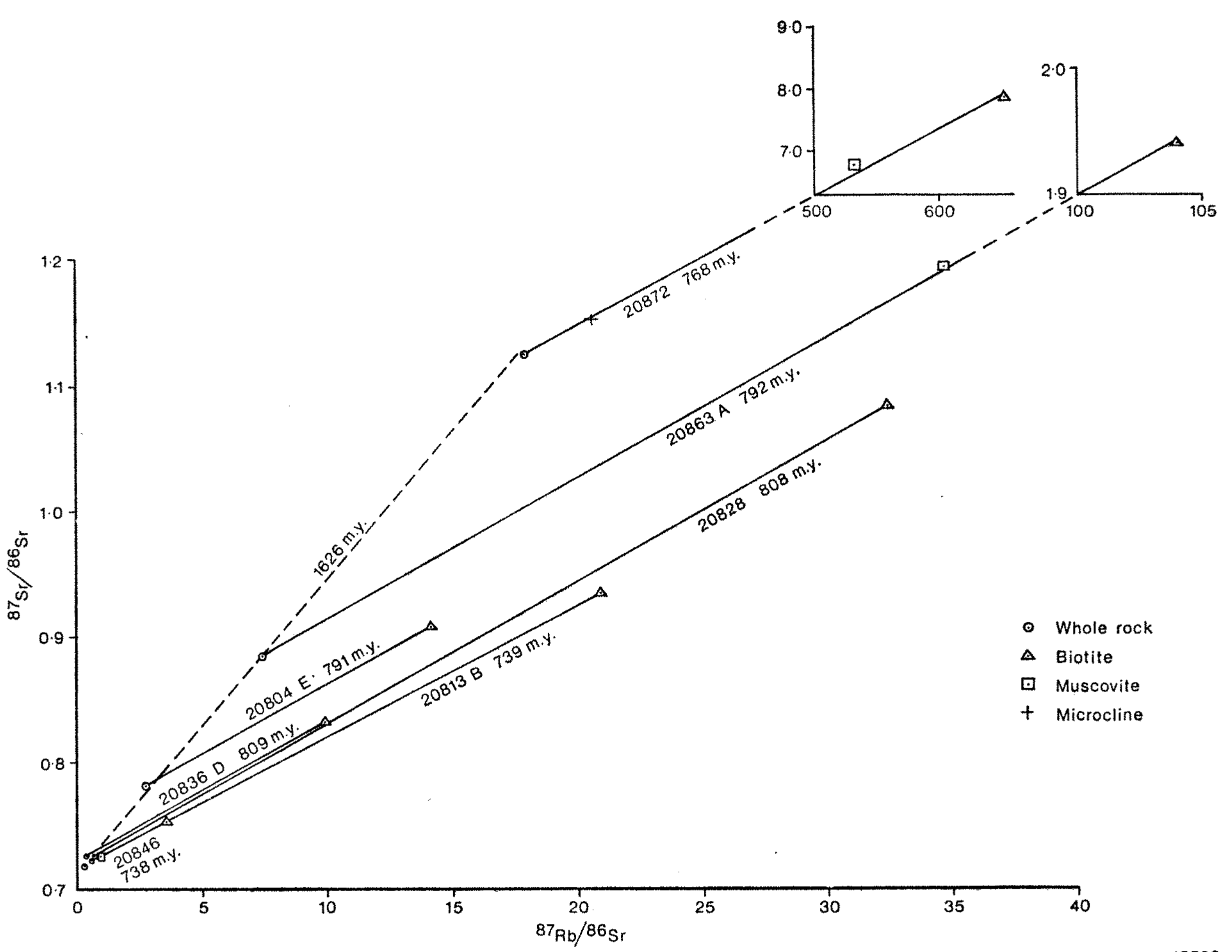


Figure 69. Mineral ages for seven of the samples plotted in Figure 68. The lower five lines each join a single mineral analysis with its parental total rock sample (two of these lines are in fact superposed). The two upper lines represent the mean ages derived from the two or more mineral analyses shown.

The data do not allow a distinction to be made between a short later regional thermal event and the final termination of a period of elevated temperature which had persisted since initial metamorphism. However, it possible that more rapid cooling took place at this time in association with the uplift and folding of the Bangemall Basin.

ACKNOWLEDGEMENTS

This project was initiated at the suggestion of Dr. J. L. Daniels, who collected the samples used and offered much valuable advice during the course of the work. The author would also like to thank Mr. I. D. Abercrombie and Mr. W. W. Thomas of the Department of Physics, Western Australian Institute of Technology, for technical assistance during this project.

REFERENCES

Aldrich, L. T., Wetherill, G. W., Bass, M. N., Compston, W., Davis, G. L., and Tilton, G. R., 1959, Mineral age measurements, *in* Year Book 1958: Carnegie Institution of Washington, p. 237-250.

Compston, W., and Arriens, P. A., 1968, The Precambrian Geochronology of Australia: Canadian Jour. Earth Sciences, v. 5, p. 561-583.

Daniels, J. L., 1975, Gascoyne Province, *in* Geology of Western Australia: West. Australia Geol. Survey Mem. 2, p. 107-114.

Daniels, J. L., and Horwitz, R. C., 1969, Precambrian tectonic units of Western Australia: West Australia Geol. Survey Ann. Rept. 1968, p. 37-38.

De Laeter, J. R., and Abercrombie, I. D., 1970, Mass spectrometric isotope dilution analyses of rubidium and strontium in standard rocks: Earth and Planetary Science Letter, v. 9, p. 327-330.

Leggo, P. J., Compston, W., and Trendall, A. F., 1965, Radiometric ages of some Precambrian rocks from the Northwest Division of Western Australia: Geol. Soc. Australia Jour., v. 12, p. 53-65.

Lewis, J. D., Rosman, K. J. R., and de Laeter, J. R., 1975, The age and metamorphic effects of the Black Range dolerite dyke: West. Australia Geol. Survey Ann. Rept. 1974, p. 80-88.

McIntyre, G. A., Brooks, C., Compston, W., and Turek, A., 1966, The statistical assessment of Rb-Sr isochrons: Jour. Geophys. Research, v. 71, p. 5459-5468.

Muhling, P. C., and de Laeter, J. R., 1971, Ages of granitic rocks in the Poona-Dalgaranga area of the Yilgran Block, Western Australia: Geol. Soc. Australia Special Publication, v. 3, p. 25-31.

ZONED ULTRAMAFIC ROCKS FROM THE CANNING TUNNEL

by J. R. Drake

ABSTRACT

Small (5 to 40 cm) mineralogically and texturally zoned ultramafic bodies occur in Archaean banded gneiss in the Canning Tunnel, near Roleystone. They consist of an outer layer of tangential biotite, followed by layers of massive and/or radial tremolite prisms around cores composed either of intergrown talc and calcite, or of decussate tremolite with interstitial chlorite. The ultramafic bodies formed by boudinage of ultramafic layers during deformation, accompanied by amphibolite facies metamorphism, of a mafic/ultramafic igneous sequence. A static greenschist facies metamorphism/metasomatism followed the tectonism, and under these conditions reaction, by cation diffusion, took place across the chemical gradient between the mafic and ultramafic rocks. Reaction was incomplete, which left the zoned ultramafic pods as metastable inclusions in the banded gneiss.

INTRODUCTION

In 1972, the Perth Metropolitan Water Supply, Sewerage and Drainage Board decided to amplify the Perth water supply by driving a tunnel from Canning Dam (one of the two major reservoirs providing water for Perth) to Roleystone. The tunnel was constructed during 1973-74, and passed through the Darling Range, the physical expression of the Darling Fault which forms the western margin of the Yilgarn Block (see Fig. 70). The Yilgarn Block is a stable Archaean nucleus consisting of elongate "greenstone" belts enclosed by granites and gneisses. In the eastern half, metamorphic grade is generally low, but in the west, rocks of high metamorphic grade are found and granites, gneisses, and migmatites predominate.

The major rock types encountered during excavation of the Canning Tunnel were banded gneiss and massive granite of Archaean age, and altered dolerite of younger Precambrian age. Zoned ellipsoidal ultramafic bodies from 5 to 40 cm across were found in the banded gneiss, and a project to determine the origin of these bodies was undertaken.

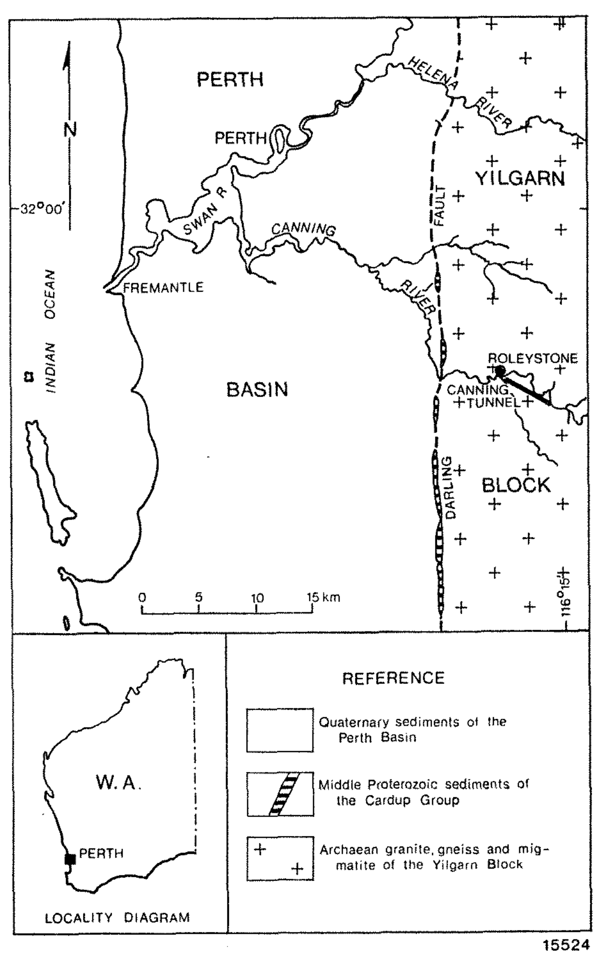


Figure 70. Locality map showing the position of the Canning Tunnel.

Previous work in the area dates from 1915, when Feldtmann (1916) reported on the geology of the Canning Dam site. Other studies were those of Clarke and Williams (1926) in the Roleystone area; of Prider (1940 and 1942) at Armadale and Canning Dam respectively; more recently of Klenowski (1973) who worked on the geology, particularly the engineering geology, of part of the Canning Tunnel; and of Wilde (in prep.) who mapped the area at a scale of 1:250 000.

GEOLOGY

The general geology of the Canning Tunnel area was determined by Prider (1940 and 1942). The oldest rocks are mafic xenoliths which occur in Archaean banded gneiss termed "hybrid gneisses" by Prider. The banded gneiss consists of alternating mafic and felsic bands, and is discordantly intruded by massive granite; both gneiss and granite are cut by aplites, pegmatites, and quartz veins which are probably late phases of the massive granite. The youngest rocks in the area are altered dolerite dykes which cut across all other rock types.

PETROLOGY OF THE BANDED GNEISS

Description

The gneiss is banded on a macroscopic scale, with bands greater than 5 cm (see Fig. 71), and a mesoscopic scale with bands of approximately 1 cm width. The mesoscopic bands are mafic, felsic or porphyroblastic, and although each macroscopic band contains all three types, each is dominated by one. Some of the felsic bands, however, such as the prominent ones in Figure 71, may be veins which were intruded parallel to the banding during or after metamorphism, and they are composed predominantly of quartz and oligoclase.

The mafic bands consist of intergrown subhedral prisms of green-brown hornblende, which are commonly rimmed or almost completely replaced along cleavages by khaki biotite; biotite not obviously after hornblende is also common. Albite, packed with epidote, may be a minor constituent in the mafic bands; sphene, apatite, and pyrite are typical accessories.

Intergrown anhedral albite crystals about 1 mm across are the major components of the felsic bands. The albite crystals are invariably crammed with epidote inclusions; minor hornblende and biotite, and accessory sphene, apatite, and pyrite are generally present.

The porphyroblastic bands contain porphyroblasts and glomeroporphyroblasts of albite more than 5 mm across, in a mafic groundmass. The plagioclase, as in the other bands, has been heavily epidotized and may also have been sericitized. The groundmass is predominantly green-brown hornblende showing minor replacement by actinolite and biotite; sphene, apatite, and pyrite are disseminated accessories.

Origin

The banded gneiss is a deformed and metamorphosed sequence of mafic igneous rocks. The rocks recrystallized as hornblende-plagioclase amphibolites under amphibolite facies conditions, but were subsequently retrogressed and metasomatized in the greenschist facies, with partial replacement of hornblende by biotite and actinolite, and calcic plagioclase by albite and epidote.

The banding is due to metamorphic differentiation, but when and how differentiation took place is not clear. It could have been a mechanical segregation during tectonism, a diffusive segregation during amphibolite facies metamorphism, or a diffusive segregation during metasomatism and greenschist facies metamorphism. The last mentioned is the most likely mechanism as diffusion would have been aided by the presence of a fluid phase.

ULTRAMAFITES

OCCURRENCE

Ultramafic rocks in the gneiss of the Roleystone area have only been found in the Canning Tunnel; however, this may be a function of preservation, as such rocks would probably have weathered out of surface exposures.

Distribution

The ultramafic rocks are not found in the gneiss throughout the length of the tunnel, but only occur in the 1 100 ft (330 m) section from 6 800 ft (2 070 m) to 7 900 ft (2 400 m) which is approximately the middle of the tunnel. The ultramafites are irregularly distributed through the gneiss in this section, but generally occur in the mafic bands. However, where the banding in the gneiss is finer they may be in contact with several bands, including felsic and porphyroblastic ones (see Fig. 71).

Size and shape

The size and shape of the ultramafic bodies are variable; however, most are triaxial ellipsoids with their two longest axes lying in the plane of the banding of the enclosing gneiss. In size, the pods range from rounded bodies about 5 cm across, to ellipsoids with longest axes up to 40 cm, with a fairly even distribution between these limits.

MINERALOGY AND TEXTURE

The most interesting feature of the ultramafic bodies is that they are mineralogically and texturally zoned (see Fig. 72). All of them have an outer layer of tangential biotite, usually about 1 cm thick, with minor though variable amounts of hornblende and chlorite, and accessory sphene, apatite, and pyrite. In most of the specimens examined, the biotite layer is drawn out into a flange in the plane of the two longest axes, which indicates that the ultramafic pods have been tectonically flattened.

The ultramafites usually have three or four layers from 1 mm to 2 cm across, of alternately massive and radial tremolite around cores of either talc and calcite, or tremolite with chlorite.

The massive layers are made up of acicular or equant tremolite prisms about 1 mm long, with interstitial chlorite, and scattered magnetite and pyrite. The radial layers have elongate tremolite prisms up to 1 cm long, and again interstitial chlorite, and scattered magnetite and pyrite. The total width of the outer tremolite layers varies from approximately 1 to 5 cm for different bodies. In the talcose ultramafites, the outer tremolite layers may grade, with increasing talc and calcite and decreasing tremolite content, into massive talc-calcite rocks, while in others the boundaries of the tremolite and talc-calcite layers are sharp. In some specimens, the talcose cores are also zoned into talc-rich and calcite-rich layers. Partially replaced euhedral tremolite prisms are present in minor amounts in the talc-calcite cores, and magnetite and pyrite are accessories.

In the predominantly tremolitic ultramafites, an outer massive layer is followed by a layer composed of radial tremolite prisms 2 to 3 cm long, which branch slightly towards the centre, indicating that they grew inwards from the margin. The cores of these ultramafites are made up of decussate tremolite prisms 2 to 3 mm long, with minor interstitial chlorite, and accessory magnetite and pyrite (see Fig. 72).

ORIGIN

The ultramafic rocks represent parts of original ultramafic flows or intrusions which were interlayered in a predominantly mafic sequence. The sequence was deformed and metamorphosed in the amphibolite facies, and during deformation the ultramafic rocks broke up into small pods due to boudinage. Static greenschist facies metamorphism/metasomatism followed the tectonism, and under these conditions reaction, probably by cation diffusion, took place across the chemical gradient between the mafic and ultramafic rocks. Unfortunately, the mineralogical composition of the ultramafic rocks before reaction is not known, so it is impossible to estimate the exact movements of elements during the reaction. However, it is likely that the ultramafic rocks gained silicon, aluminium, potassium, and calcium from aqueous solution and the enclosing mafic rocks, while their chief loss was of magnesium. Reaction was incomplete, and the mineralogically zoned ultramafic rocks remained as metastable pods in banded gneiss. A fluid phase was probably necessary to allow the reaction to proceed at all, since activation energies of liquid diffusion processes are orders of magnitude lower than those of corresponding solid state processes (Curtis and Brown, 1969), and evidence for such a phase is provided by the metasomatism, and perhaps also by the metamorphic differentiation of the banded gneiss. The presence of a fluid phase may account for the size and radial structure of some of the tremolite prisms, as it does, for example, in igneous pegmatites.

Mineralogical zoning around the borders of metamorphosed ultramafic rocks has been reported from many parts of the world and from several metamorphic environments. Gillson (1927), Hess (1933), Phillips and Hess (1936), Chidester (1962), and Jahns (1967) described zoning attributed to metamorphic reaction and differentiation around serpentinites in greenschist facies rocks from vermont. Misar (1973) and Sørensen (1954) found and documented metamorphic reaction zones around ultramafites in amphibolite and granulite facies rocks respectively, while Kalsbeek (1970) found similar reaction zones where ultramafic rocks were cut by pegmatites, and Bondesen (1964) found reaction zones where ultramafic inclusions occurred in an intrusion breccia.

The most recent account of the chemical processes and kinetics involved in forming zoned ultramafic bodies is that of Curtis and Brown (1969). They describe the ultramafites from Unst, Shetland, which were originally described by Read (1934). The idealized zonal sequence at Unst is from country rock, through phlogopite, chlorite, actinolite, and talc, to antigorite, although the chlorite zone is rarely developed, and in some cases antigorite has been completely replaced. Therefore, although the bodies at Unst are larger (30 cm to 6 m), they are very like those of the Canning Tunnel, and the chemical processes responsible for the two occurrences are likely to have been very similar.

CONCLUSION

The zoned ultramafic pods from the Canning Tunnel formed by boudinage of ultramafic layers during deformation of a mafic/ultramafic igneous sequence. Deformation was accompanied by amphibolite facies metamorphism, which was followed by retrogressive greenschist facies metamorphism in the presence of a fluid phase which caused diffusive reaction across the chemical gradient between the mafic and ultramafic rocks. Unfavourable reaction kinetics prevented the reaction from going to completion, which left the zoned ultramafic rocks as metastable pods in the enclosing mafic gneiss.

ACKNOWLEDGEMENT

I am indebted to Mr. W. L. Powe of Dampier Mining Co. Ltd., formerly of the Metropolitan Water Supply, Sewerage and Drainage Board, who first drew my attention to the ultramafic rocks in the Canning Tunnel, and who helped me with sample collecting on subsequent excursions.

REFERENCES

Bondesen, E., 1964, An intrusion breccia with associated ultrabasics from Sermersût, South-West Greenland: Grønlands Geologiske Undersøgelse Bull. 41, 36p.

Chidester, A. H., 1962, Petrology and geochemistry of selected talc-bearing ultramafic rocks and adjacent country rocks in north-central Vermont: U.S. Geol. Survey Prof. Paper 345, 207p.

Clarke, E. de C., and Williams, F. A., 1926, The geology and physiography of parts of the Darling Range near Perth: Royal Soc. West. Australia Jour., v. 12, p. 161-178.

Curtis, C. D., and Brown, P. E., 1969, The metasomatic development of zoned ultramafic bodies in Unst, Shetland: Contributions to Minerology and Petrology, v. 24, p. 275-292.

Feldtmann, F. R., 1916, Geological report on the Canning River dam site No. 2: West. Australia Dept. Mines Ann. Rept. 1915, p. 133-135.

Gillson, J. L., 1927, Origin of the Vermont talc deposits: Econ. Geol., v. 22, p. 246-287.

Hess, H. H., 1933, The problem of serpentinisation and the origin of certain chrysotile asbestos, talc and soapstone deposits: Econ. Geol., v. 28, p. 634-657.

Jahns, R. H., 1967, Serpentinites of the Roxbury district, Vermont, *in* P. J. Wyllie (ed.), Ultramafic and related rocks: New York, John Wiley and Sons, p. 137-160.

Kalsbeek, F., 1970, The petrography and origin of gneisses, amphibolites and migmatites in the Qasigialik area, South-West Greenland: Grønlands Geologiske Undersøgelse Bull. 83, 70p.

Klenowski, G., 1973, The geology of the Canning Dam-Roleystone Tunnel, Western Australia: Univ. West. Australia Hons. thesis (unpublished).

Misar, Z., 1973, Precambrian ultramafic rocks south of Sermilik, Frederikshab district, South-West Greenland: Grønlands Geologiske Undersøgelse Bull. 107, 60p.

Phillips, A. H., and Hess, H. H., 1936, Metamorphic differientation at contacts between serpentinite and siliceous country rocks: Am. Mineralogist v. 21, p. 333-362.

Prider, R. T., 1940, The contact between the granitic rocks and the Cardup Series at Armadale: Royal Soc. West. Australia Jour., v. 27, p. 137-147.

——1942, Granitic rocks from Canning Dam: Royal Soc. West. Australia Jour., v. 29, p. 137-149.

Read, H. H., 1934, On the zoned association of antigorite, talc, actinolite, chlorite and biotite in Unst, Shetland Islands: Mineralog. Mag., v. 23, p. 519-540.

Sorensen, H., 1954, The border relations of the dunite at Siorarssuit, Sukkertoppen district, West Greenland: Grønlands Geologiske Undersøgelse Bull. 6, 47p.

Wilde, S. A., in prep., Explanatory notes on the Pinjarra 1:250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. (unpublished).

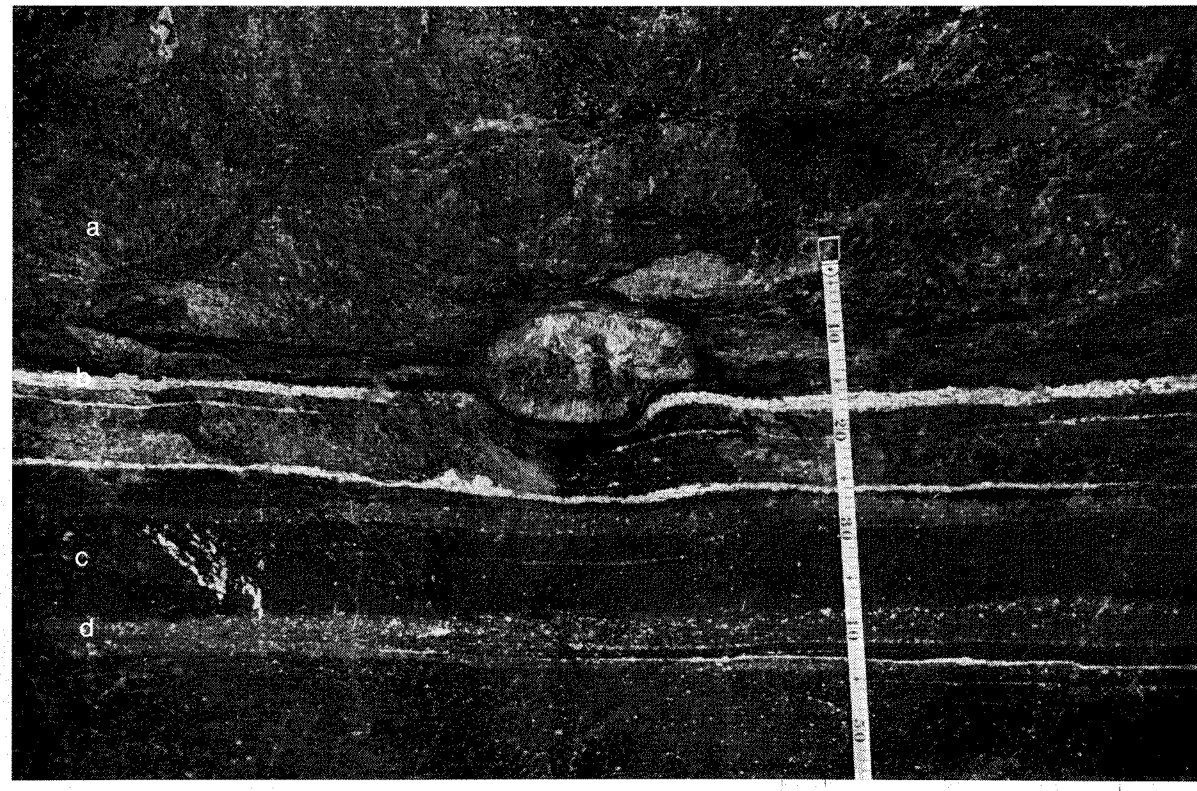


Figure 71. Zoned tremolitic ultramafic body within banded gneiss, south wall of tunnel at 7 600 feet (2 300 m).

a. is a broad mafic macroband.
b. is a thin quartz-oligoclase vein.
c. is a hornblende-biotite mafic microband.
d. is an albitic felsic/porphyroblastic macroband. The scale is in centimetres.

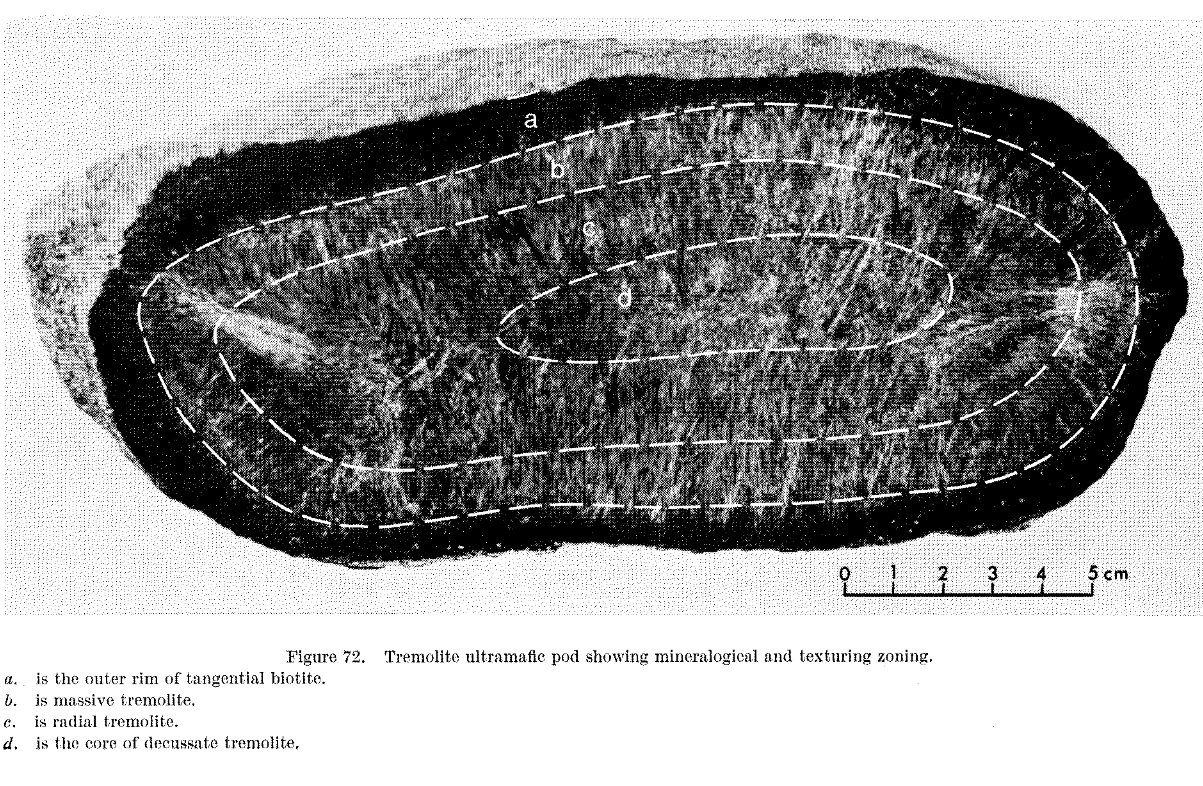


Figure 72. Tremolite ultramafic pod showing mineralogical and texturing zoning.

a. is the outer rim of tangential biotite.
b. is massive tremolite.
c. is radial tremolite.
d. is the core of decussate tremolite.

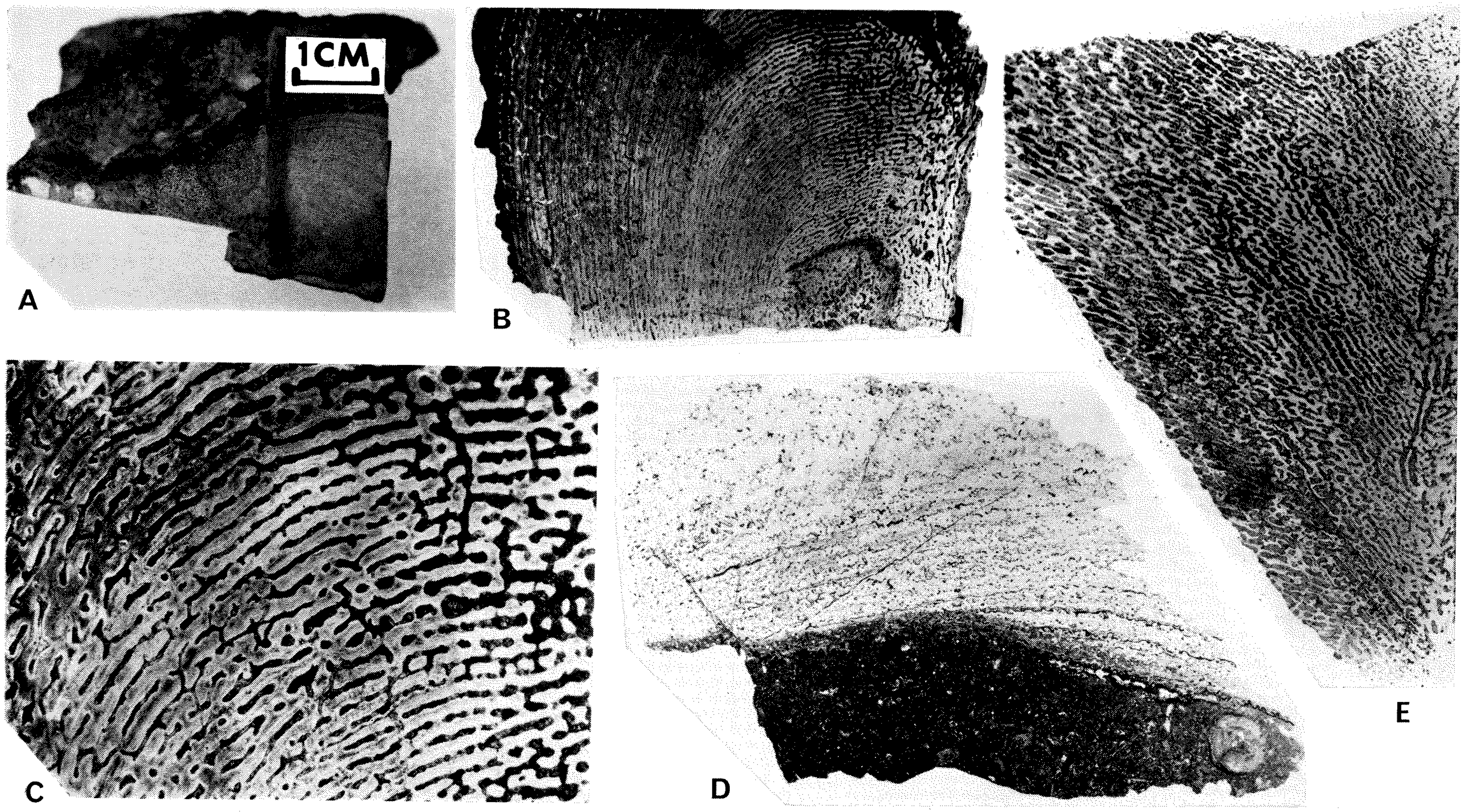

1CM
A
B
C
D
E

Figure 73. *Stromatoporella kimberleyensis* Etheridge Jr. All figures are of the holotype (Australian Museum registered numbers F16810 and AM990) collected from the Napier Formation near old Napier Downs homestead, Napier Range, by Dr. H. Basedow in 1916.

A. General view of holotype : F16810.

B. Longitudinal section, x4 : AM990a.

C. Enlargement of part of AM990a, x15.

D. Longitudinal section, x4 : AM990b.

E. Tangential section, x4 : AM990c.

STROMATOPORELLA KIMBERLEYENSIS ETHERIDGE Jr. 1918 IS A PIECE OF BONE

by A. E. Cockbain

ABSTRACT

The species *Stromatoporella kimberleyensis* Etheridge Jr. 1918 is shown to be a piece of arthrodire bone and is figured for the first time. Kimberleyensis bone has only been found in rocks of Famennian age belonging to the Napier Formation and Nullara Limestone.

INTRODUCTION

In 1918, Etheridge Jr. described, but did not figure, three new species from the Devonian of the Lennard Shelf under the names *Actinostroma subclathratum*, *Stachyodes dendroidea*, and *Stromatoporella kimberleyensis*. The types of all three species are housed in The Australian Museum, Sydney. Through the kindness of Dr A. Ritchie, Curator of Palaeontology, I have been able to examine the specimens. *Actinostroma subclathratum* and *Stachyodes dendroidea* are typical representatives of their respective genera and will be described and figured as part of a study of the stromatoporoids from the Lennard Shelf Devonian reef complexes. However, *Stromatoporella kimberleyensis* is not a stromatoporoid and the purpose of this note is to figure the species and show that it is arthrodire bone.

SYSTEMATIC PALAEONTOLOGY

"*Stromatoporella kimberleyensis*" Etheridge Jr.
Figure 73.

1910 coccostean bone: A. Smith Woodward in Glauert, p. 112, 113.

1918 *Stromatoporella kimberleyensis* Etheridge Jr.: p. 259.

1919 *Stromatoporella kimberleyensis* Etheridge Jr.; Maitland: p. 29, 32.

1922 *Stromatoporella kimberleyensis* Etheridge Jr.; Benson: p. 167.

1966 *Stromatoporella kimberleyensis* Etheridge Jr.; Playford and Lowry: p. 61, 70.

1968 *Stromatoporella kimberleyensis* Etheridge Jr.; Flügel and Flügel-Kahler: p. 221.

Type material: One specimen, Australian Museum registered number F16810, and 3 slides (all Australian Museum registered number AM990) in The Australian Museum; Napier Formation, Napier Range near Old Napier Downs homestead (LNR1); collected by Dr H. Basedow in 1916.

Other material: G.S.W.A. registered number F327, Napier Formation, Barker Gorge (LNR2); G.S.W.A. registered number F5727, Napier Formation, 4 km northwest of Windjana Gorge (LNR3); G.S.W.A. registered number F5728, Napier Formation, Cycad Hill (LNR4) (see Fig. 74 for localities).

Description: The original description of *kimberleyensis* by Etheridge Jr. (1918, p. 259-260) is as follows:—

"*Sp. Chars.*—Coenosteum apparently forming a thick laminar expansion (25 mm), but whether incrusting, or attached by a peduncle evidence is lacking. Concentric laminae gently undulated (thereby probably indicating the absence of mamelons on the surface), averaging from four to five in the space of one millimetre, and possessing a peculiar structure of their own, in that they are composed of parallel wavy fibres concentric around the interlaminar spaces, but without any median clear line; interlaminar spaces appear to be quite subordinate to the concentric laminae, are oval or circular, without septa; radial pillars stout, short, and confined to their respective interlaminar spaces; zooidal tubes not observed. A tangential section displays the cut ends of radial pillars, or sections of the concentric laminae, thereby indicating a considerable degree of reticulation."

If the stromatoporoid terminology is omitted, then Etheridge's description is entirely appropriate for bone structure.

The holotype is a piece of bone 60 x 50 x 25 mm in size. The bone has a spongy texture and consists of a network of trabeculae 0.13 to 0.2 mm in diameter, with a ramifying system of canals 0.05 to 0.2 mm in diameter between them. The trabeculae tend to be arranged in layers (about 4 per mm) parallel to the outer surface of the bone; the layers are not continuous sheets but are themselves reticulate networks. However, the layering and networks are far from regular. The trabeculae have a concentric lamellation around the canals and contain lens-like specks or lacunae.

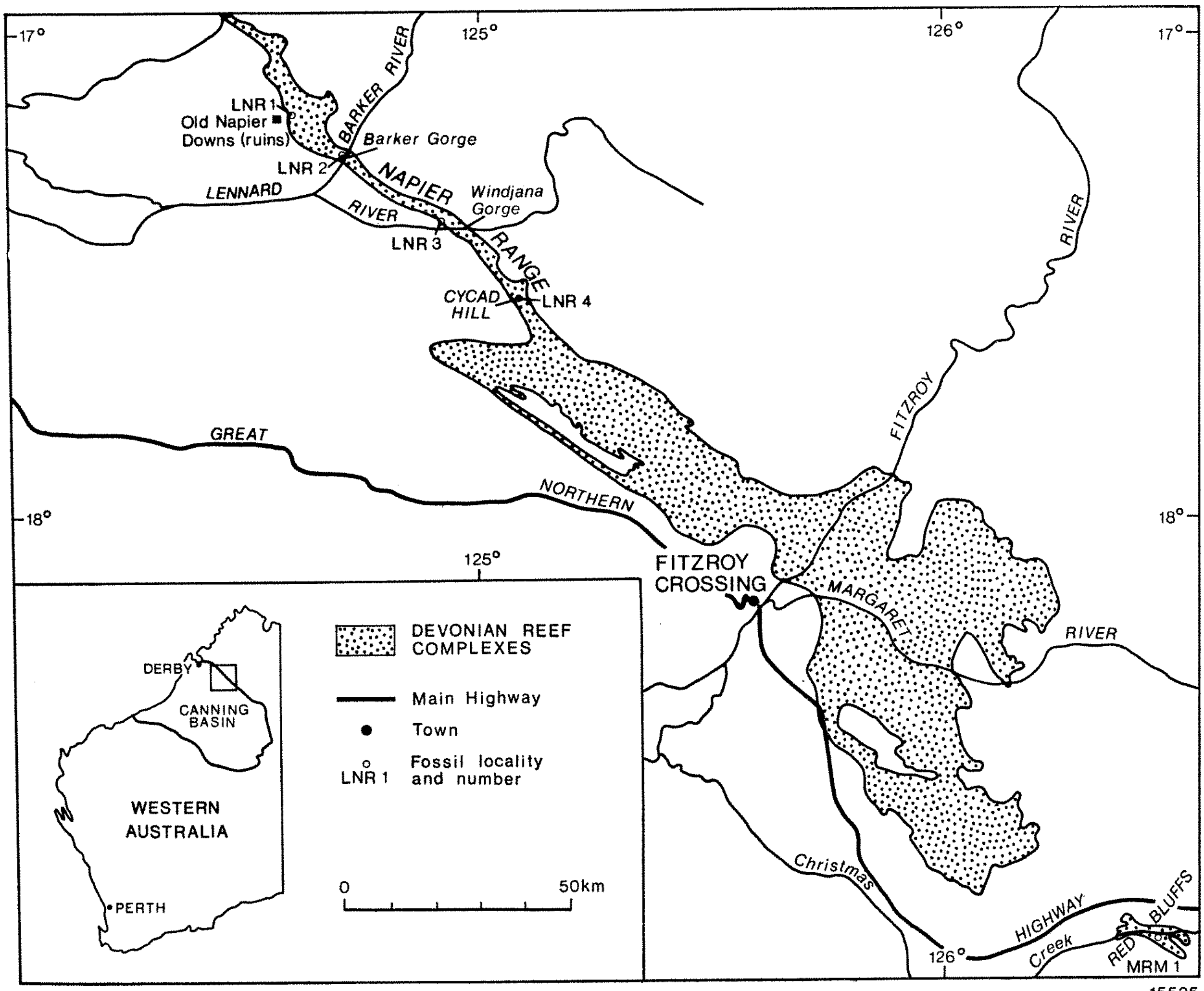
X-ray diffraction analysis of G.S.W.A. registered number F5727 shows that the bone consists of apatite and the canals between the trabeculae are filled with calcite and a little common opal (Western Australian Government Chemical Laboratories, written comm., October, 1975). The apatite has a fibrous habit. In holotype slide AM990a (Fig. 73) the bone has been extensively replaced by carbonate, although patches of fibrous apatite do occur.

Remarks: Etheridge's comments on the species are given below (1918, p. 260):

"*Obs.*—The state of preservation of the tissues is very uneven. In one radial or longitudinal section the structure of the concentric laminae is preserved, but in a second taken close to the first the whole of the tissues are obliterated, and represented by clear mineral matter, and in a tangential section the same occurs.

"Nicholson's description of the structure of *S. eifelensis* [sic] so aptly fits that of this form I am feign to quote it: —'owing to the thickness of the laminae, the interlaminar spaces are comparatively narrow, and the correspondingly thick radial pillars usually run from lamina to lamina, but do not extend beyond the interlaminar space within which each originates.'

"There is another aspect of this fossil seen in longitudinal sections difficult of interpretation, viz., large branching canals, or tubes, vertical or oblique, often running through more than one concentric lamina, in fact passing through four or five direct, and filled with clear mineral matter. For a long time I was much puzzled to account for these passages, and I can only do so now on the hypothesis of structural decay, whereby the tissue of certain of the radial pillars has decayed and the channels thus formed 'ran together' with some of the interlaminar spaces, and so formed these unsymmetrical tubular spaces. Here and there it is possible to see one, or perhaps two superimposed replaced radial pillars combining with a similarly infilled interlaminar space."



15525

Figure 74. Localities with *kimberleyensis* bone.

He was obviously puzzled by the structure of *kimberleyensis,* suggesting "structural decay" to account for the appearance in thin section. Similarly, Flügel and Flügel-Kahler (1968, p. 221) commenting on photographs of the material stated: "Der Vertikalschliff zeigt eine mit *Stromatoporella* vergleichbare Struktur, wobei jedoch extrem dicke Skelettelemente auffallen." ("The vertical section shows a structure comparable to *Stromatoporella,* but extremely thick skeletal components are a striking feature".) The peculiar appearance of "*Stromatoporella kimberleyensis*" is at once resolved when it is realized that the type specimen is a piece of bone.

Photographs of slides cut from the type specimen and of a polished surface of G.S.W.A. registered number F327 were sent to Dr R. S. Miles of the British Museum (Natural History) who stated (written comm., July, 1975): "All of your photographs clearly show pieces of arthrodire bone . . . How many species in all are involved cannot be judged, as bone varies in character from one part of the armour to another, and yet may look alike in different species."

TABLE 36. LOCALITY DATA

Fossil locality no.	Co-ordinates E	Co-ordinates N	Locality	Formation	Sample no. and collector
Lennard River 1:250 000 map sheet					
LNR 1	Precise locality not known		Napier Range, near Old Napier Downs homestead	Napier Formation	H. Basedow, 1916 ; AM 990 F16810
LNR 2	Precise locality not known		Napier Range, Barker Gorge	Napier Formation	H. P. Woodward, 1906 ; F327
LNR 3	273 400	2 812 500	Napier Range 4 km N.W. of Windjana Gorge	Napier Formation	P. E. Playford, 1962 ; sample 11653
LNR 4	293 100	2 793 500	Napier Range, Cycad Hill	Napier Formation	P.E. Playford, 1962 ; sample 11654
Mount Ramsay 1:250 000 map sheet					
MRM 1	453 000	2 635 000	Red Bluffs, 2·5 km S.S.W. of Nippers bore	Nullara Limestone	P.E. Playford, 1966 ; sample 3428

Distribution: (Fig. 74 and Table 36) *kimberleyensis* bone has been recorded from the Napier Formation near Old Napier Downs homestead (LNR 1) (Etheridge Jr., 1918), at Cycad Hill (LNR 4), and 4 km northwest of Windjana Gorge (LNR 3) (Playford and Lowry, 1966), and from Barker Gorge (LNR 2) (Glauert, 1910). Near Windjana Gorge the bone fragments are up to 37 cm long (P. E. Playford, pers. comm., October, 1975). Playford and Lowry (1966) also record the bone from the Nullara Limestone (formerly mapped as Pillara Limestone) at Red Bluffs (MRM 1). The rocks at all these localities are of Famennian age.

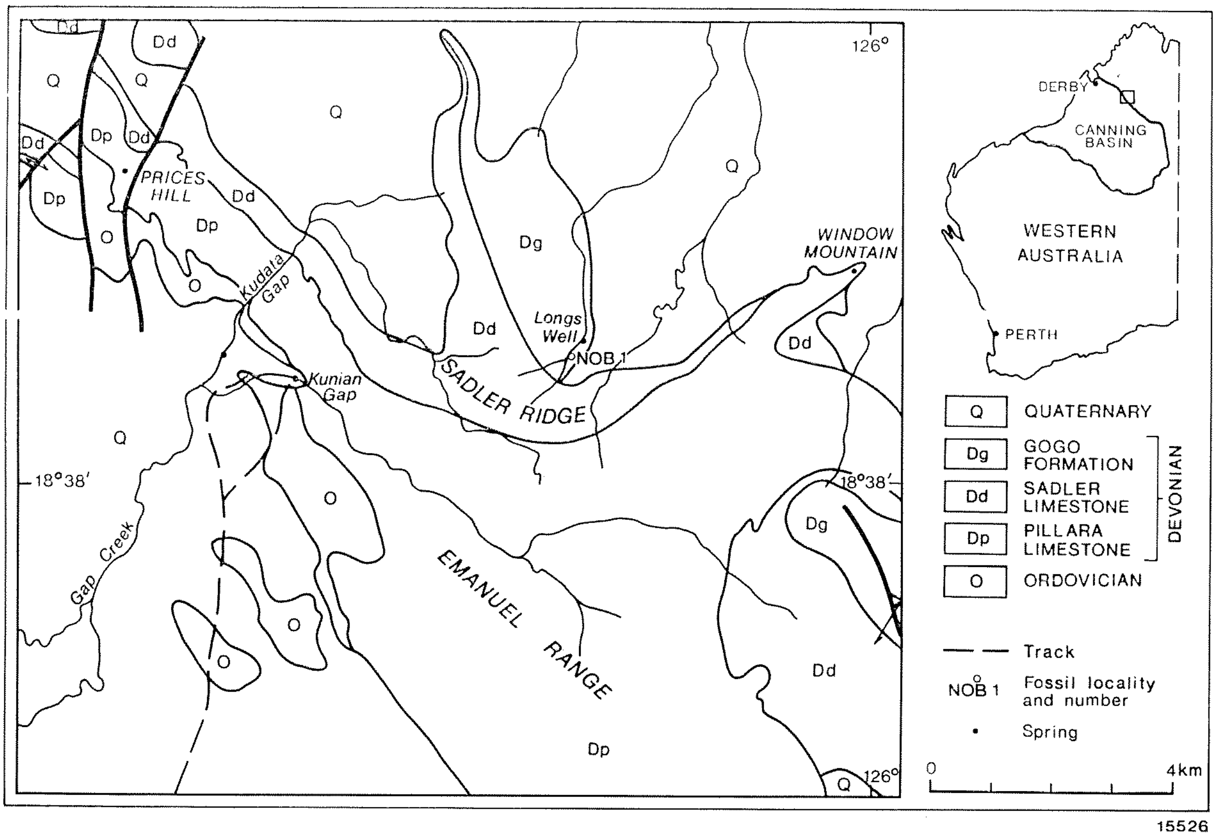


Figure 75. Locality map.

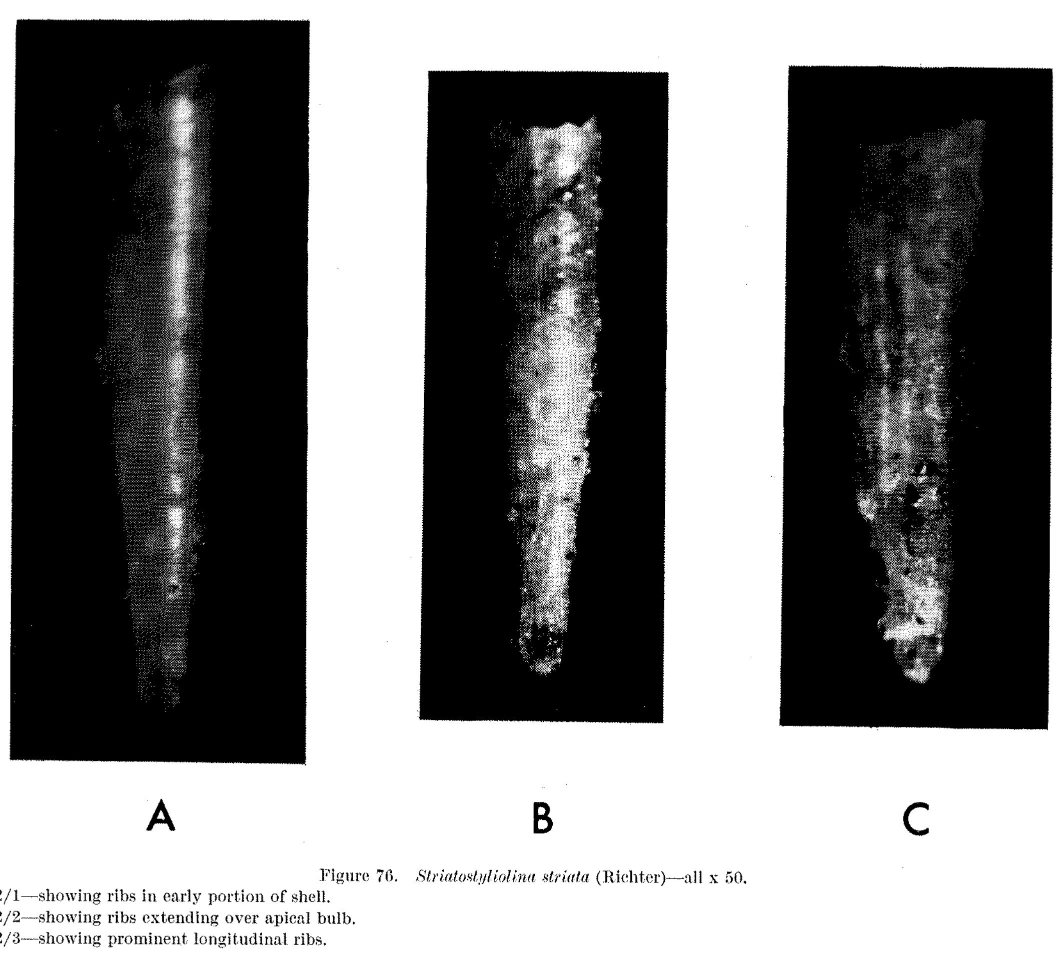


Figure 76. *Striatostyliolina striata* (Richter)—all x 50.

A. F9262/1—showing ribs in early portion of shell.
B. F9262/2—showing ribs extending over apical bulb.
C. F9262/3—showing prominent longitudinal ribs.

REFERENCES

Benson, W. N., 1922, Materials for the study of the Devonian palaeontology of Australia: New South Wales Geol. Survey Recs., v. 10, p. 83-204.

Etheridge, R. Jr., 1918, Observations on Carboniferous and other fossils, *in* Basedow, H., Narrative of an expedition of exploration in northwestern Australia: Royal Geographical Soc. Australasia, South Australia Branch, Trans., v. 18, p. 250-262.

Flügel, E., and Flügel-Kahler, E., 1968, Stromatoporoidea (Hydrozoa palaeozoica), *in* Westphal, F. (ed.), Fossilium catalogus 1: Animalia, parts 115 and 116; 's Gravenhage, Dr W. Junk N. V.

Glauert, L., 1910, New fossils from Barker Gorge, Napier Range, Kimberley: West. Australia Geol. Survey Bull. 36, p. 111-114.

Maitland, A. G., 1919, Geology of Western Australia: West. Australia Geol. Survey Mem. No. 1.

Playford, P. E., and Lowry, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: West. Australia Geol. Survey Bull. 118.

DEVONIAN TENTACULITIDS FROM THE CANNING BASIN REEF COMPLEXES

by A. E. Cockbain

ABSTRACT

The first Australian record of *Striatostyliolina striata* is from Gogo Formation strata of 1α age. This is in broad agreement with the lower Adorfian occurrence of the species in Germany. The age of some of Sherrard's (1975) tentaculitid records is reassessed and her Givetian species are considered to be probably Frasnian in age.

INTRODUCTION

Tentaculitids are small conical shells of uncertain affinities which have been shuffled back and forth between several phyla. Lately, they have been considered to belong to a new class of Mollusca (Fisher, 1962). Although tentaculitids have been studied for many years, it is only within the last two decades that their biostratigraphic potential has been tested (see, for example, Boucek, 1964, 1967; Zagora, 1964; Lyashenko, 1967; and references therein).

The earliest record of tentaculitids from the Devonian reef complexes of the Canning Basin is probably that of Teichert (1949) who listed *Tentaculites* sp. from the *Manticoceras* zone. Recently, Sherrard (1975) has recorded 9 species in open nomenclature from 4 formations in the reef complexes. Sherrard's specimens came from samples collected by West Australian Petroleum Pty. Ltd. (Wapet). None of them came from the Gogo Formation. This unit frequently contains tentaculitids (Glenister and Crespin, 1959; Playford and Lowry, 1966) which are silicified at some localities. This report documents one such locality where specimens of *Striatostyliolina striata* are associated with abundant radiolarians.

The locality (NOB 1) is situated about 0.4 km southwest of Longs Well near Sadler Ridge and is on a section line measured through the Gogo Formation (Fig. 75). Conodonts collected from this section belong to the lower and/or middle *asymmetricus* zone (1α) (Druce, 1971).

SYSTEMATIC PALAEONTOLOGY

Class TENTACULITA Boucek (1964)

There seems to be no universally accepted name for the tentaculitids. Lyashenko (1959) placed them and the hyolithids in the new Class Coniconchia; Fisher (1962) considered the tentaculitids and hyolithids to be unrelated and erected two new classes, the Cricoconarida for the tentaculitids and the Calyptoptomatida for the hyolithids. Boucek (1964) accepted the separation of these two groups but united the tentaculitids and the cornulitids in the Class Tentaculita. There is a good case for retaining a familiar name for the class which includes the tentaculitids and as the law of priority is not binding at the class level, I prefer Boucek's name Tentaculita.

Order DACRYOCONARIDA
Family STYLIOLINIDAE

Striatostyliolina striata (Richter)

Figure 76.

1854 *Tentaculites striatus* Richter: p. 288, pl. 3, figs. 30-33.

1864 *Styliola richteri* Ludwig: p. 321, pl. 50, figs. 16a-c (new name for *S. striatus* (Richter) not Rang).

1964 *Striatostyliolina striata* (Richter); Boucek: p. 134.

1964 *Striatostyliolina striata* (Richter); Zagora: p. 1246.

Material: G.S.W.A. registered number F9262 (about 20 specimens) from G.S.W.A. sample number 19656, Gogo Formation. Fossil locality NOB 1, Noonkanbah 1 : 250 000 Map Sheet, co-ordinates (yards) 394 640 E, 2 663 820 S, 0.4 km southwest of Longs Well.

Description: The conical shell is up to 2.7 mm in length, 0.5 mm in diameter at the apertural end and 0.15 mm in diameter at the apical end. The apical bulb is bluntly rounded; the shell is initially cylindrical for a short distance and then becomes conical, the angle of the cone being about 7 to 8 degrees. Internally the shell is smooth. On the outside are up to 14 widely spaced, thin, prominent longitudinal ribs which continue over the apical bulb. No growth lines can be seen.

Remarks: All specimens are silicified and were extracted from the rock using hydrochloric acid. The longitudinal ribs are poorly preserved, possibly as a result of the extraction technique. The species has not been recorded previously from Australia.

Distribution: *S. striata* occurs in the Gogo Formation from strata which have yielded a lower-middle *asymmetricus* zone (1α) conodont fauna. The species occurs in the lower Adorfian of Germany (Boucek, 1967). Zagora (1964) shows it to range through the upper part of the *asymmetricus* zone (*dubia* zone on his chart) into the lower part of the *triangularis* zone, (that is, upper 1α/β to lower 1γ) in Thuringia; its absence from the lower part of the *asymmetricus* zone is probably due to unsuitable facies.

TENTACULITID DISTRIBUTION IN THE REEF COMPLEXES

The tentaculitids identified by Sherrard (1975) came from the Pillara and Sadler Limestones and the Virgin Hills and Napier Formations. On the basis of Lyashenko's work she compiled a table showing the age of the tentaculitid species occurring in the reef complexes. Using the data given by Sherrard together with some further locality details in Seddon (1970) and provided by Wapet (written comm., October 1975), Table 37 has been drawn up summarizing the distribution of tentaculitids in the reef complexes of the Canning Basin.

TABLE 37. DISTRIBUTION OF TENTACULITIDS IN DEVONIAN FORMATIONS, CANNING BASIN

Species	Formations: Dg	Dp	Dd	Dr	Dn	Tentaculitid ages (Sherrard, 1975)	Conodont datings (Sherrard, 1975)	Age suggested herein
Uniconus aff. *livnensis*					X	Upper Frasnian	1δ-post 1δ	
Tentaculites aff. *donensis*		X			X	Middle Frasnian	1β/γ-1γ	
Uniconus aff. *kremsi*		X				Middle Frasnian	1β/γ-1γ	
Multiconus cf. *schimanskii*			X			Middle Frasnian	none	Frasnian
Dicricoconus aff. *lansiformis*		X	X			Middle Frasnian	none	Frasnian
Homoctenus aff. *krestovnikovi*		X	X	X	X	Middle Frasnian	1γ (Dr)	Dn-probably Famennian ; rest Frasnian
Dicricoconus aff. *tagangaevi*		X	X			Upper Givetian	1α (β)	Frasnian
Tentaculites aff. *maslovi*		X				Middle Givetian	none	Frasnian
Dicricoconus aff. *mesodevonicus*		X	X			Middle Givetian	none	Frasnian
Striatostyliolina striata	X					Not recorded		1α

Dg Gogo Formation
Dp Pillara Limestone
Dd Sadler Limestone
Dr Virgin Hills Formation
Dn Napier Formation

Whilst the ages suggested by the tentaculitids agree in general with those indicated by the conodonts (as Sherrard pointed out), there are some discrepancies. Most noteworthy are the species considered Middle Givetian by Sherrard; the localities from which these were collected (BC 83 and 85 in the Lawford Range) are more likely to be Frasnian on stratigraphical grounds. The record of *H. krestovnikovi* from Lloyd Hill (BC 21) is probably 1α in age (Druce, 1971) whereas the Napier Formation occurrence of this species (BC 128, near Windjana Gorge) is possibly Famennian, and the species has a long range. The BC numbers are those of the Wapet localities from which Sherrard's specimens came.

In the present state of our knowledge it is too early to state how precise a tentaculitid time scale may prove to be. Some species are obviously quite good (for example, *S. striata, U. livnensis*); others appear to be ambiguous (for example, *H. krestovnikovi, T. maslovi*). The fact that some tentaculitid species were widespread (presumably because they were pelagic organisms) and had a limited vertical range (for example, *S. striata*) offers hope that they may be useful in interregional correlation.

REFERENCES

Boucek, B., 1964, The Tentaculites of Bohemia; their morphology, taxonomy, ecology, phylogeny and biostratigraphy: Czechoslovakia Acad. Sci., Prague, 215p.

———1967, Significance of dacryoconarid tentaculites and graptolites for the stratigraphy and palaeogeography of the Devonian System, *in* Oswald, D. H. (ed.), International symposium on the Devonian System: Alberta Soc. Petroleum Geologists, Calgary, v. 2, p. 1275-1281.

Druce, E. C., 1971, Conodont biostratigraphy of the Upper Devonian reef complexes of the Canning Basin, Western Australia: Univ. Michigan thesis (unpublished).

Fisher, D. W., 1962, Small conoidal shells of uncertain affinities, *in* Moore, R. C. (ed.), Treatise on invertebrate paleontology: Geol. Soc. America and Univ. Kansas Press, part W, p. W98-W143.

Glenister, B. F., and Crespin, I., 1959, Upper Devonian microfaunas from the Fitzroy Basin, Western Australia: Australian Jour. Sci., v. 21, p. 222-223.

Ludwig, R., 1864, Pteropoden aus dem Devon in Hessen und Nassau sowie aus dem Tertiär-Thon des Mainzer Beckens: Palaeontographica, v. 11, p. 311-323.

Lyashenko, G. P., 1959, Devonian Coniconchia of the central and eastern districts of the Russian Platform (in Russian): Works of the All-Union Petroleum Scientific Research Geological Prospecting Unit, p. 1-220 (not seen).

———1967, Coniconchia (Tentaculitida, Nowakiida, Styliolinida) and their importance in Devonian biostratigraphy, *in* Oswald, D. H. (ed.), International symposium on the Devonian System: Alberta Soc. Petroleum Geologists, Calgary, v. 2, p. 897-903.

Playford, P. E., and Lowry, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: West. Australia Geol. Survey Bull. 118.

Richter, R., 1854, Thüringische Tentaculiten: Deutsche Geol. Gesell. Zeitscher, v. 6, p. 275-290.

Seddon, G., 1970, Frasnian conodonts from the Sadler Ridge-Bugle Gap area, Canning Basin, Western Australia: Geol. Soc. Australia Jour., v. 16, p. 723-753.

Sherrard, K., 1975, Devonian tentaculitids from north-west Australia: Royal Soc. Victoria Proc., v. 87, p. 179-186.

Teichert, C., 1949, Observations on stratigraphy and palaeontology of Devonian western portion of Kimberley Division Western Australia: Australia Bur. Mineral Resources Rept. 2.

Zagora, K., 1964, Tentaculiten aus dem thüringischen Devon: Geologie, v. 13, p. 1235-1273.

GEOCHEMICAL VARIATIONS IN ARCHAEAN GRANITOIDS IN PART OF THE NORTHEAST YILGARN BLOCK

by R. Davy

ABSTRACT

Regional variations in Archaean granitoids have been identified during the course of a regional rock geochemical programme on the Rason, Laverton, and Leonora 1 : 250 000 Sheet areas. The mean values of magnesium, nickel, and vanadium rise consistently from east to west across lineament boundaries from the Sefton to the Ida Lineaments, whilst potassium and rubidium reach a peak between the Sefton and Laverton Lineaments, falling away on either side. The causes of these systematic variations are as yet unknown, but they may be related either to crustal thinning (from east to west) or to deeper penetration of the crust by major disruption zones.

INTRODUCTION

In 1972, the Geological Survey of Western Australia initiated a programme of regional sampling to investigate the potential of bed-rock geochemistry as a strategic exploration tool and as an adjunct to regional mapping. The area chosen for preliminary study included the Archaean rocks, in particular the Archaean igneous rocks (or their metamorphosed equivalents), from parts of the Rason, Laverton, and Leonora 1 : 250 000 Sheet areas (Fig. 77). During the programme some 1 200 "fresh" samples and 300 altered or weathered samples were collected, emphasis being given to the collection of samples from major outcrop zones with the proviso that the samples should be as representative of the various rock types as possible. Seventeen elements and oxides* were determined by X-ray fluorescence analysis on compressed powder briquettes, and one element, uranium, was determined by chromatography (Plamonden, 1968). All analyses were carried out by the Western Australian Government Laboratories.

A detailed report is in preparation and will be published elsewhere (Davy, in prep.). The present report is confined to an examination of regional variations, particularly in granitoids, which have become apparent during interpretation of the results.

Williams (1974) discussed the structural subdivision of the Eastern Goldfields Province, splitting it into three subprovinces. The Kalgoorlie (central) and Laverton (eastern) Subprovinces are relevant to this paper. Williams postulated that a number of major linear zones (hereafter called lineaments) trend generally north (or up to 45° west of north) through the area. Major lineaments recognized in the area under study are, from east to west:—

(1) Sefton.
(2) Laverton.
(3) Celia.
(4) Keith-Kilkenny.
(5) Ida.

For the purposes of this paper it is assumed that the lineaments are real and that the rocks sampled can be considered grouped in inter-lineament zones. Additional granitoids were sampled from within the Keith-Kilkenny greenstone belt, separate from the main inter-lineament zones. In this paper the inter-lineament and greenstone zones discussed are referred to (from east to west) by zone letters:—

(1) east of the Sefton Lineament — zone A
(2) Sefton to Laverton Lineaments — zone B
(3) Laverton to Celia Lineaments — zone C
(4) Celia to Keith-Kilkenny Lineaments — zone D
(5) Keith-Kilkenny greenstones — zone E
(6) Keith-Kilkenny to Ida Lineaments — zone F

*Ba, CaO, Cr, Cu, total iron as Fe_2O_3, K_2O, MgO, Na_2O, Ni, Pb, Rb, SiO_2 (Laverton and Leonora Sheet areas only), Sr, TiO_2, V, Zn, Zr.

RESULTS

Weathering conditions, with associated formation of silcrete, laterite or kaolinized rocks, did not allow for the collection of samples from every available outcrop.

Analyses of those samples which were obtained have been considered in two ways:—

(1) allowing an equal weighting to each sample, and
(2) with samples grouped either by outcrop area or by rock type.

In the latter case, where a batholith has been sampled, distinction was made between the same rock type recurring at widely spaced outcrops, and different types of rock (for example, a porphyritic and an even-grained phase) occurring at the same outcrop. Equal weighting for each sample can create problems of over-emphasis where excessive sampling has occurred in a small area. The second approach reduces this bias but it is realized that neither treatment gives a truly representative picture of the chemistry as a whole.

A summary of the results as applied to K_2O and MgO is given in Table 38. It will be seen that when the mean values are considered there is a peak of K_2O in zone B with a sharp falling off of K_2O content to the west, and with some tendency for the value to fall eastwards in zone A. The same trend is shown when the results are considered by rock type-outcrop area, though the fall-off to the west is less smooth, with a minor rise shown in zone D. By contrast, the MgO contents of the granitoids rise from east to west.

TABLE 38. A COMPARISON OF K_2O AND MgO VALUES IN GRANITOIDS IN THE RASON, LAVERTON, AND LEONORA SHEET AREAS.

			Average % K_2O in Granitoids		Average % MgO in Granitoids	
Zone	No. of samples (n)	No. of rock types/outcrop zones (t)	$\frac{\Sigma x}{n}$	$\frac{\Sigma \bar{x}}{t}$	$\frac{\Sigma x}{n}$	$\frac{\Sigma \bar{x}}{t}$
A	58	15	4·4	4·2	0·27	0·25
B	71	23	4·9	5·0	0·51	0·58
C	58	15	3·5	3·3	1·2	1·3
D	53	12	3·2	3·5	1·5	1·4
E	8	5	3·1	2·5	1·7	2·3*
F	8	2	2·3	2·6	1·8	1·3

Note : The granitoids are grouped in inter-lineament zones.

*1·4 if one high value is excluded.

Σx = the sum of values for n samples.

$\bar{x}$ = the mean value for any particular rock type at any single outcrop zone.

$\Sigma \bar{x}$ = the sum of $\bar{x}$ values.

t = the number of rock types and/or outcrop zones considered as separate entities for this assessment.

Any sample taken at random may, or may not, be higher than a sample taken from an adjacent zone. However, taken as a whole, the results show that regional trends are present.

Table 38 makes no allowance for the standard deviation or the scatter of results. Various methods have been used to overcome this, the two most successful being Na_2O-K_2O-CaO triangular diagrams, and cumulative frequency probability curves. To illustrate this, Na_2O-K_2O-CaO diagrams are given for the granitoids in zone C (Fig. 78A) and zone B (Fig. 78B). In these diagrams the variations within individual rock types can be assessed by the scatter of the points. Again, though there is overlap, particularly of adamellitic rocks, there is a marked shift from K_2O-rich samples in zone B to Na_2O-rich samples in zone C.

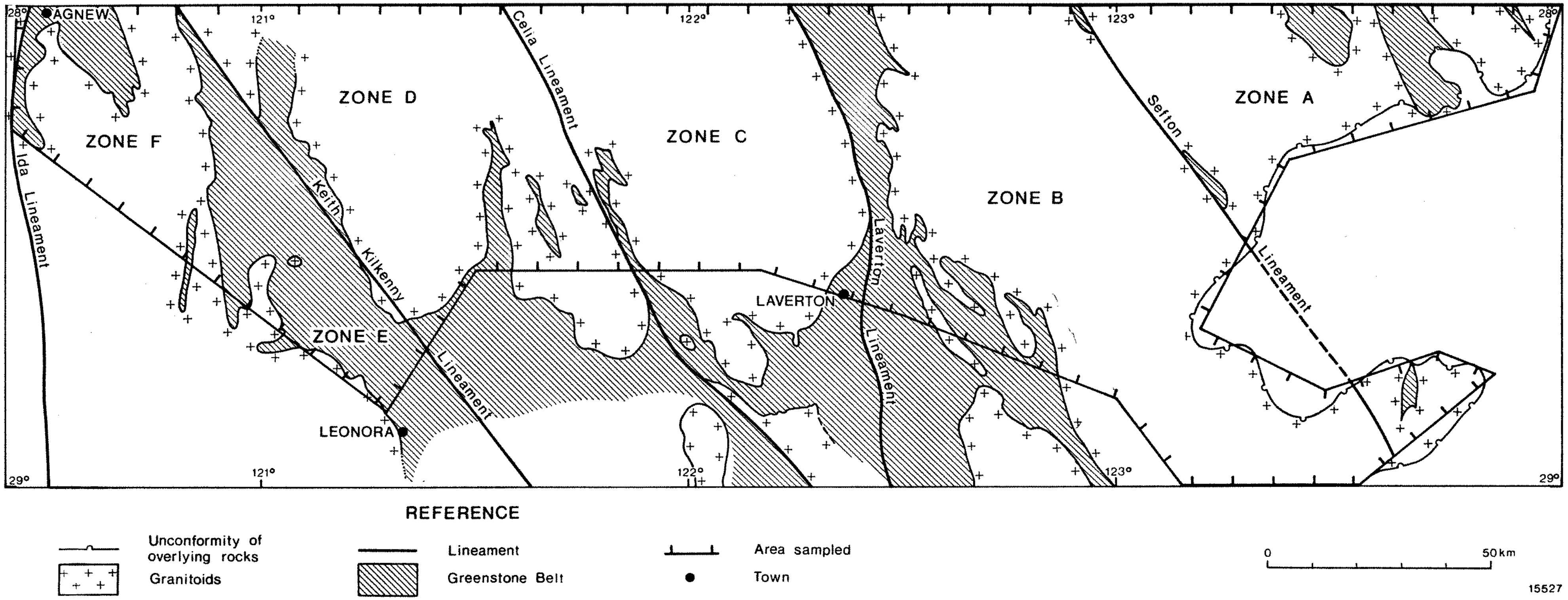


Figure 77. Generalized geology of the Leonora, Laverton and Rason Sheet areas showing approximate areas sampled. Base maps taken from Thom and Barnes, 1974 ; Gower, 1974 ; Gower and Boegli, 1973.

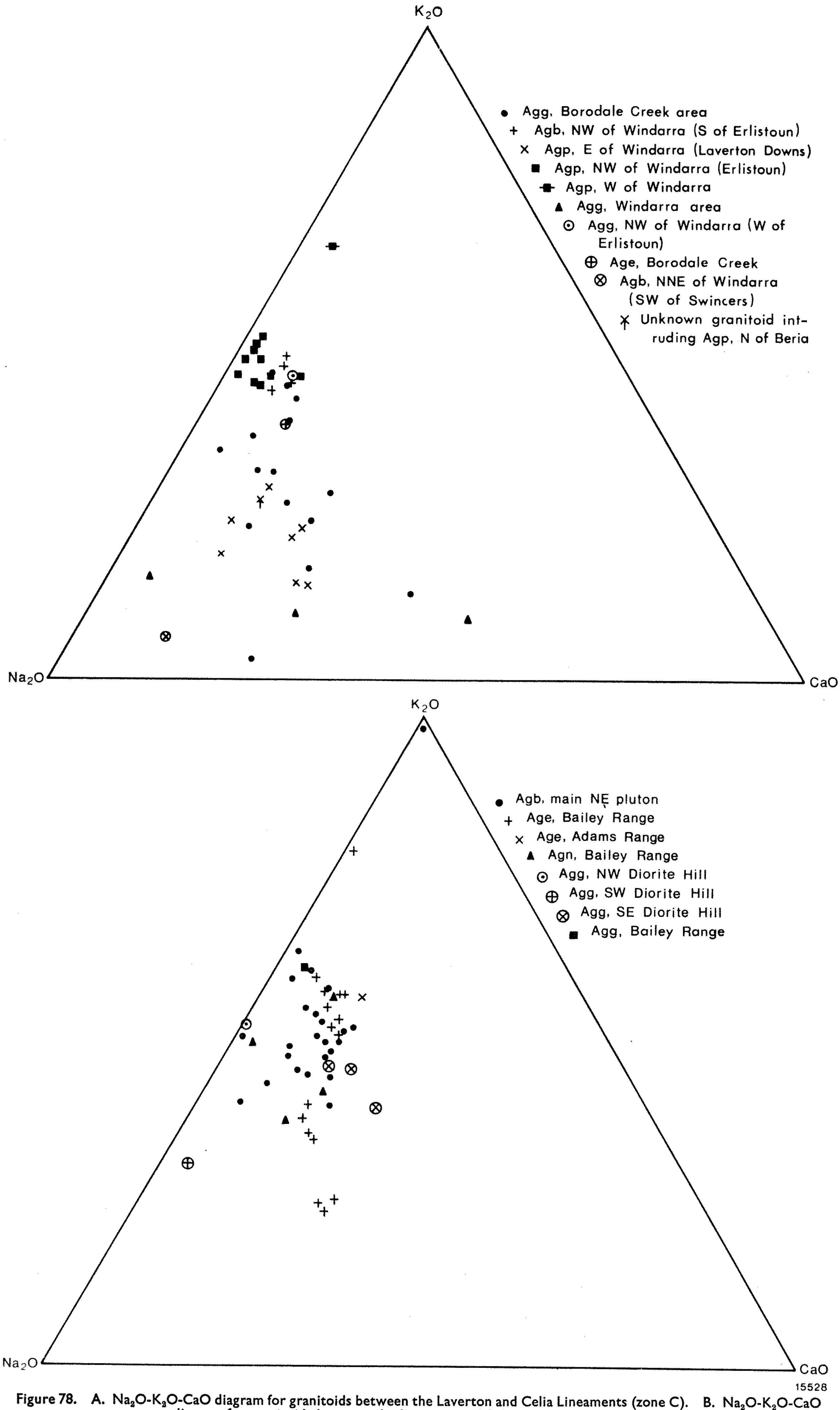


Figure 78. A. Na_2O-K_2O-CaO diagram for granitoids between the Laverton and Celia Lineaments (zone C). B. Na_2O-K_2O-CaO diagram for granitoids between the Laverton and Sefton Lineaments (zone B).

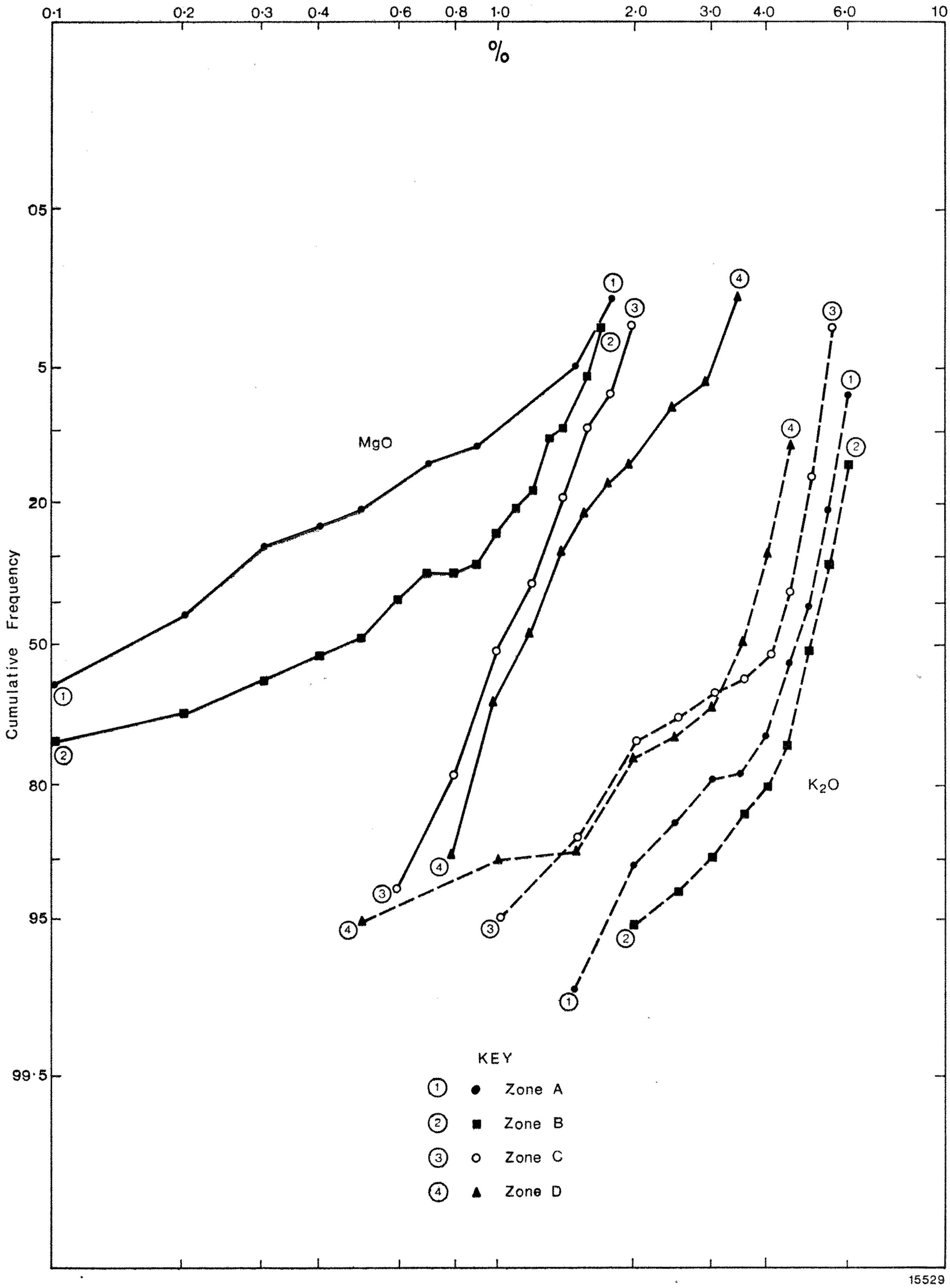


Figure 79. Cumulative frequency probability curves for K_2O and MgO for granitoids on the Rason, Laverton, and Leonora 1 : 250 000 Sheet areas.

Cumulative frequency probability curves have been drawn for the four eastern inter-lineament zones (A, B, C, and D). Of these the diagrams for K_2O and MgO are reproduced here (Fig. 79). These diagrams show clearly the increasing magnesium content of the inter-lineament zones as they are traversed from east to west. The two eastern zones have similar profiles for MgO but the curve for zone B is transposed towards the higher MgO values compared with that for zone A. Many of these rocks contain no detectable magnesium, they are in sharp contrast with the rocks west of the Laverton Lineament which contain at least 0.5 per cent MgO and overall are much higher in magnesium.

The patterns for K_2O are slightly less clear. The curve for zone A lies between the curves for zone B and zone C (suggested by the mean values) and does not overlap either. Zone D has lower (and fewer) high values than zone C but for a short distance this curve overlaps the zone C curve. The diagram shows that on both a mean and a cumulative basis the maximum potassium values occur in zone B, with values falling off on either side.

Cumulative frequency probability curves could not be drawn for zone F because of insufficient samples. A few samples were collected from granitoids within the greenstones of the Keith-Kilkenny greenstone belt (zone E). Though the results from these samples cannot be considered as representative of the whole zones, they support the general trends (see Table 39).

TABLE 39. MEAN VALUES FOR GRANITOIDS IN THE RASON, LAVERTON, AND LEONORA SHEET AREAS.

Zone	A	B	C	D	E	F
No. of samples	58	71	54†	53	8	8
Ba	970	1 200	870	640	860	780
CaO	1·2	1·1	1·2	1·1	1·9	2·4
Cu	11	14	11	17	24	13
Fe_2O_3*	1·9	1·8	1·7	2·1	2·4	2·3
K_2O	4·4	4·9	3·5	3·2	3·1	2·3
MgO	0·3	0·5	1·2	1·5	1·7	1·8
Na_2O	4·0	4·1	4·9	4·8	5·5	4·8
Ni	17	18	22	22‡	63	27
Pb	32	44	24	19	29	26
Rb	180	190	120	120	89	88
SiO_2	72	71	71	72	70	69
Sr	270	270	320	240	330	380
TiO_2	0·3	0·3	0·2	0·2	0·3	0·4
U	2	2	1	1	2	4‡
V	16	18	22	22	32	36
Zn	47	47	33	33	41	94
Zr	170	200	110	170	195	150

Values are expressed in % (oxides) and ppm (elements).

* Total iron as Fe_2O_3.

† Values of the Mount Boreas adamellite taken from Gower (1974) are included for Ba, CaO, Fe_2O_3, K_2O, MgO, Na_2O, Rb, SiO_2, Sr, TiO_2 and the total number of samples is 58.

‡ Excluding in each case, one grossly anomalous value.

Other elements (Table 39; showing mean values only) do not show the same regularities of behaviour, though rubidium closely follows potassium, and nickel and vanadium closely follow magnesium. Iron, titanium, and zinc are low in zone C (with similar values for titanium and zinc in the adjacent zone D) with an apparent rise on either side. Other elements are quite variable though calcium possibly rises towards zone F.

It is notable that the SiO_2 values, though rather variable, maintain consistently high values in the vicinity of 69 to 71 per cent and that there is no evidence that the systematic variations noted above are related to differentiation trends. Plots of the data on a spatial basis reveal neither general trends nor zonations within the inter-lineament zones. However, discrete fractionated phases of separate plutons can sometimes be recognized; thus the biotite granite and the porphyritic microgranite northwest of Mount Windarra appear to be related chemically, with high potassium values. Though texturally similar to these rocks, the biotite granite and porphyritic microgranite east of Mount Windarra (west of Laverton Downs station) are chemically unrelated and have low potassium values. These two groups of granitoids appear to have undergone parallel evolution.

This paper is concerned mainly with the granitoids. However, it is worth mentioning that the trend to increased magnesium to the west is shown not only by the granitoids but also by mafic and ultramafic rocks. Cumulative frequency probability curves for MgO for all rocks analyzed from the Leonora Sheet area are compared with the same curves drawn for all rocks analyzed from the Laverton Sheet area in Figure 80. For all three types of rock the curve for Leonora samples is offset towards higher magnesium values.

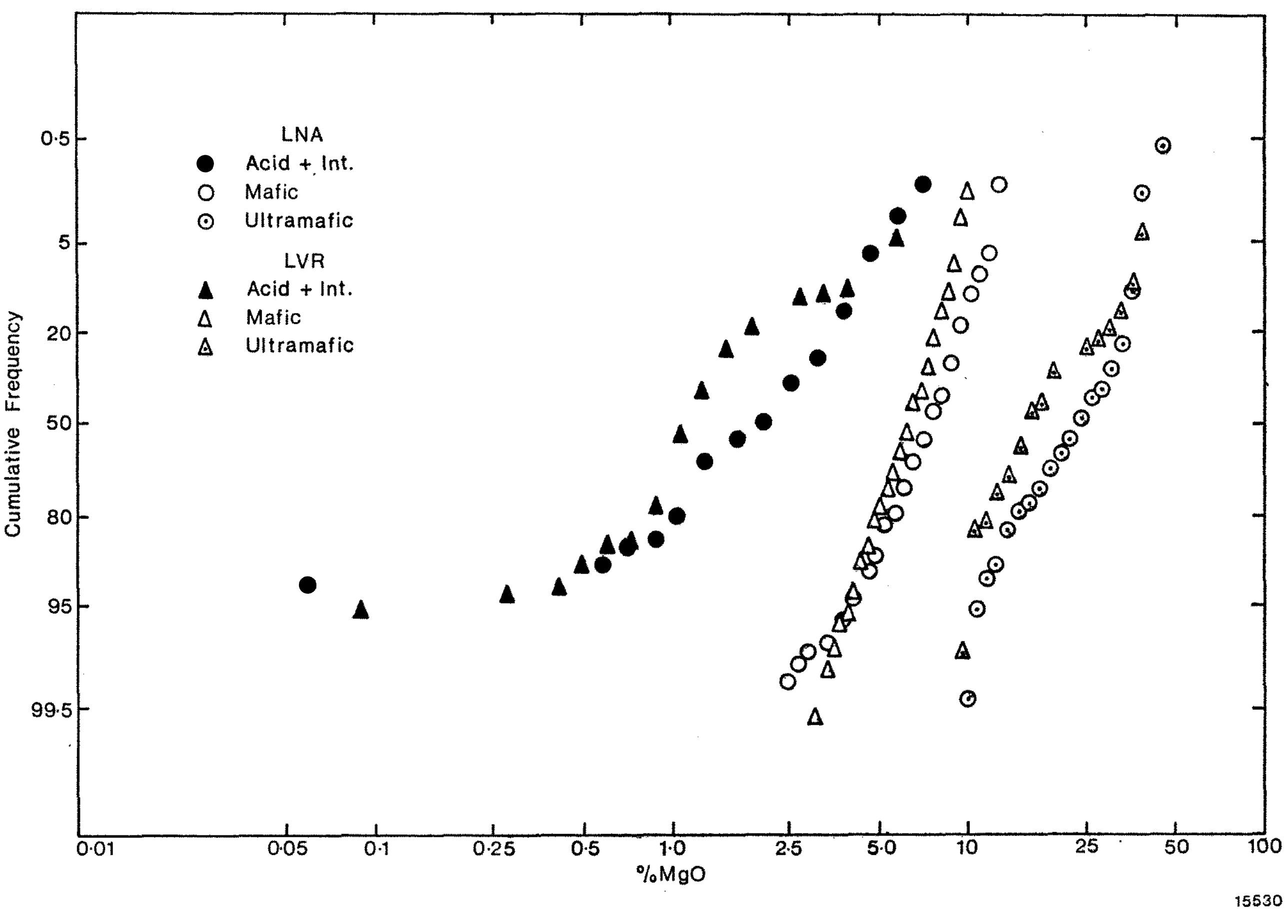


Figure 80. Cumulative frequency probability curve for MgO.

DISCUSSION

It seems clear that two opposing regional trends are shown by the analyses. Potassium and rubidium increase to the east reaching a peak in zone A. Magnesium, nickel, and vanadium increase steadily from the east to west. Though other elements show a more variable distribution there is no reason to doubt that these are genuine trends reflecting major changes in the crustal composition. As far as is known no regional variations such as these have been reported from other Archaean cratonic areas.

Differences caused by weathering have been considered as causes of the chemical changes but have been rejected as the more obviously weathered samples have been excluded from these results. Moreover, in most normal weathering situations calcium, magnesium, potassium, and sodium are among the first of the major elements to be leached. This feature is clearly seen in analyses of kaolinized or silicified granitoids (Davy, in prep.).

The presence of highly magnesian ultramafic rocks with associated nickel mineralization in zone F might suggest the higher values of magnesium and nickel in the adjacent granitoids are caused by contamination. Contamination by nickel has been recognized in granitoids near Mount Windarra but high nickel values are not conspicuous elsewhere, and the highest values of magnesium, nickel, and vanadium are not necessarily found adjacent to greenstones. If contamination has taken place it must have occurred prior to the intrusion of the granitoids.

Williams (1974) considers that the lineaments reflect deep-seated faults and postulates that, in the area studied for this paper, west-down block faulting is the most common form of faulting. This might suggest that the rocks of the Agnew-Leonora area are the youngest rocks represented in the area. He recognized that rocks of differing ages do occur within the inter-lineament zones. Older rocks are exposed in the cores of anticlines, some granitoids are recognizable as intrusive into their host rocks. Few of the rocks in the area have been dated. The Boreas Adamellite (Laverton Sheet area) has been dated at 2 480 ± 30 m.y. (J. C. Roddick, pers. comm.) and granitoids at Isolated Hill (Rason Sheet area), northwest of Mount Windarra (Laverton Sheet area), Borodale Creek (Laverton Sheet area) and at Dodgers Hill (Leonora Sheet area) have been dated at 2 592 ± 25 (Bunting and others, 1976), 2 260 ± 60 (J. C. Roddick, pers. comm.), 2 615 ± 25 (J. C. Roddick, pers. comm.), and 2 580 ± 16 m.y. (Worden and Compston, 1973) respectively. These suggest no regional younging to the west nor, indeed, any regional pattern. If a hypothesis of granitoids younging to the west is correct the granitoids would appear to become less potassic and more magnesian as they get younger, an unusual feature.

The presence of abundant iron formation in the Rason Sheet area and its relative absence from the Leonora Sheet area suggests that the Rason Sheet area was once possibly a shelf environment with relative tectonic stability. The Leonora sediments, on the other hand, were formed in deeper water or an oceanic environment. The majority of the basaltic rocks analyzed are similar in composition to present-day deep oceanic tholeiites. The observed trends may be related either to a thinning of sialic crust or to successively deeper fractures of the crust progressing from the Rason Sheet area towards the Leonora Sheet area. The lesser thickness, or the deeper fractures, may have resulted in a greater contamination of the sialic crust by simatic material.

It seems that, though east-west trends in the granitoids in the Rason, Laverton, and Leonora Sheet areas are real, the origins of these trends are not yet clear. It would be interesting to investigate similar rocks beyond the Ida Lineament to examine whether the trends continue or are reversed (Williams, 1974, postulates east-down block faulting in this area), and to extend the investigation north and south to determine whether the trends are present on an areal rather than a linear basis.

ACKNOWLEDGEMENTS

The assistance of members of the Western Australian Government Chemical Laboratories, particularly Messrs. N. Marsh and A. Thomas in the production of the analytical data and in the computer manipulation of this data, is gratefully acknowledged.

REFERENCES

Bunting, J. A., de Laeter, J. R., and Libby, W. G., 1976, Tectonic subdivisions and geochronology of the northeast part of the Albany-Fraser Province, Western Australia: West. Australia Geol. Survey Ann. Rept. 1976, p.

Davy, R., in prep., A comparative study of the geochemistry of Archaean bed-rock in part of the northeast Yilgarn Block: West. Australia Geol. Survey Report Series.

Gower, C. F., 1974, Explanatory notes on the Laverton 1 : 250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1973/28 (unpublished).

Gower, C. F., and Boegli, J. C., 1973, Explanatory notes on the Rason 1 : 250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1973/14 (unpublished).

Plamonden, J., 1968, Rapid determination of uranium in geochemical samples by paper chromatography: Econ. Geol., v. 63, p. 76-79.

Thom, R., and Barnes, R. G., 1974, Explanatory notes on the Leonora 1 : 250 000 Geological Sheet, W.A.: West. Australia Geol. Survey Rec. 1974/8 (unpublished).

Williams, I. R., 1974, Structural subdivision of the Eastern Goldfields Province, Yilgarn Block: West. Australia Geol. Survey Ann. Rept. 1973, p. 53-59.

Worden, J. A., and Compston, W., 1973, A Rb-Sr isotopic study of weathering in the Mertondale granite, Western Australia: Geochim. et Cosmochim. Acta, v. 37, p. 2567-2576.

SUPPLEMENTARY MINERAL DATA FROM GABBROS OF THE GILES COMPLEX

by M. Pryce*

ABSTRACT

Accurate unit cell dimensions and related data are provided for one amphibole, six olivines, three orthopyroxenes, and three clinopyroxenes from the Jameson Range Gabbro, and for five olivines from the Blackstone Range Gabbro. The data supplement or supersede those previously published in Bulletin 123 of the Geological Survey of Western Australia.

*Government Chemical Laboratories.

SUPPLEMENTARY DATA

In his Bulletin on the geology of the Blackstone region, Daniels (1974) included mineral unit cell dimensions of moderate accuracy based on powder X-ray data together with some highly accurate parameters based on single crystal data. The powder work is now superseded by further single crystal studies, and other supplementary data is presented to be applied to Bulletin 123 as indicated with each group of figures.

Table 15, Analysis of brown amphibole from Jameson Range Gabbro and comparison analyses, p. 160-1, is supplemented in column 1 by:

S.G. 3·276

a 9·907 ± 0·002 5 Å

b 18·097 ± 0·001 5

c 5·332 ± 0·003 5

β 105°56′ ± 2·5′

Table 24, p.175, and accompanying notes are wholly superseded by:

TABLE 24. UNIT CELL DIMENSIONS OF OLIVINES FROM THE GILES COMPLEX.

Specimen No.	Fa	a (Å)	b (Å)	c (Å)
		BLACKSTONE RANGE GABBRO		
519	35·3	4·780 ± 0·001	10·303 ± 0·000 5	6·023 ± 0·000 5
577	41·3	4·784 ± 0·001	10·322 ± 0·001 5	6·029 ± 0·001 5
581	35·2	4·780 ± 0·001	10·300 ± 0·001 5	6·021 ± 0·001
582C	31·6	4·778 ± 0·001	10·295 ± 0·002	6·017 ± 0·002
585	30·5	4·777 ± 0·002	10·292 ± 0·003	6·018 ± 0·003
		JAMESON RANGE GABBRO		
1 241	54·5	4·795 ± 0·001	10·360 ± 0·005	6·045 ± 0·003
1 247	35·99	4·782 ± 0·001 5	10·308 ± 0·003	6·024 ± 0·002 5
1 251	39·0	4·781 ± 0·001	10·310 ± 0·001 5	6·028 ± 0·001 5
1 257	39·5	4·785 ± 0·000 5	10·316 ± 0·001	6·029 ± 0·001
1 259	39·7	4·784 ± 0·001	10·314 ± 0·002	6·027 ± 0·002
1 260	38·2	4·784 ± 0·001	10·314 ± 0·002	6·027 ± 0·002

Notes:

1. Determinations by M. Pryce, Government Chemical Laboratories. The possible error limits are reported as five times the estimated standard deviation.
2. The cell dimensions were obtained from single crystal methods.
3. The localities of the specimens may be found by reference to Figures 43, 51, 52 and 56.

In Table 27, Chemical, physical and optical properties of orthopyroxenes from the Jameson Range Gabbro, p. 180, a, b and c are superseded by:

Specimen No.	1 252	1 253	1 263
a	18·306 ± 0·003	18·315 ± 0·002	18·291 ± 0·001 Å
b	8·905 ± 0·003	8·902 ± 0·001 5	8·875 ± 0·001
c	5·217 ± 0·002	5·215 ± 0·001 5	5·210 ± 0·001 5

and on p. 181, a° (obs), b° (obs) and c° (obs) by:

a° (obs)	18·306 ± 0·003	18·315 ± 0·002	18·291 ± 0·001
b° (obs)	8·905 ± 0·003	8·902 ± 0·001 5	8·875 ± 0·001
c° (obs)	5·217 ± 0·002	5·215 ± 0·001 5	5·210 ± 0·001 5

Table 28, Chemical, physical and optical properties of clinopyroxenes from the Jameson Range Gabbro, p. 182, is supplemented by:

Specimen No.	1 253	1 256	1 263
a	9·758 ± 0·003 5	9·748 ± 0·002	9·749 ± 0·004 5 Å
b	8·934 ± 0·001	8·919 ± 0·000 4	8·924 ± 0·000 5
c	5·278 ± 0·001	5·260 ± 0·001	5·259 ± 0·003
β	105°57′ ± 2′	106°6′ ± 2′	105°59′ ± 5′
S.G.	3·389	3·349	3·368

REFERENCE

Daniels, J. L., 1974, The geology of the Blackstone Region, Western Australia: West. Australia Geol. Survey Bull. 123.

INDEX

54809/7/76

By Authority: WILLIAM C. BROWN, Government Printer