GEOLOGICAL SURVEY of WESTERN AUSTRALIA

ANNUAL REPORT 1973

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1973

EXTRACT FROM REPORT OF THE DEPARTMENT OF MINES

Minister: The Hon. D. G. May, M.L.A.

Under Secretary: G. H. Cooper

Director, Geological Survey: J. H. Lord

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1974

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DIVISION IV

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Annual Report of the Geological Survey Branch of the Mines Department for the Year 1973

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CONTENTS

REPORTS

LIST OF FIGURES

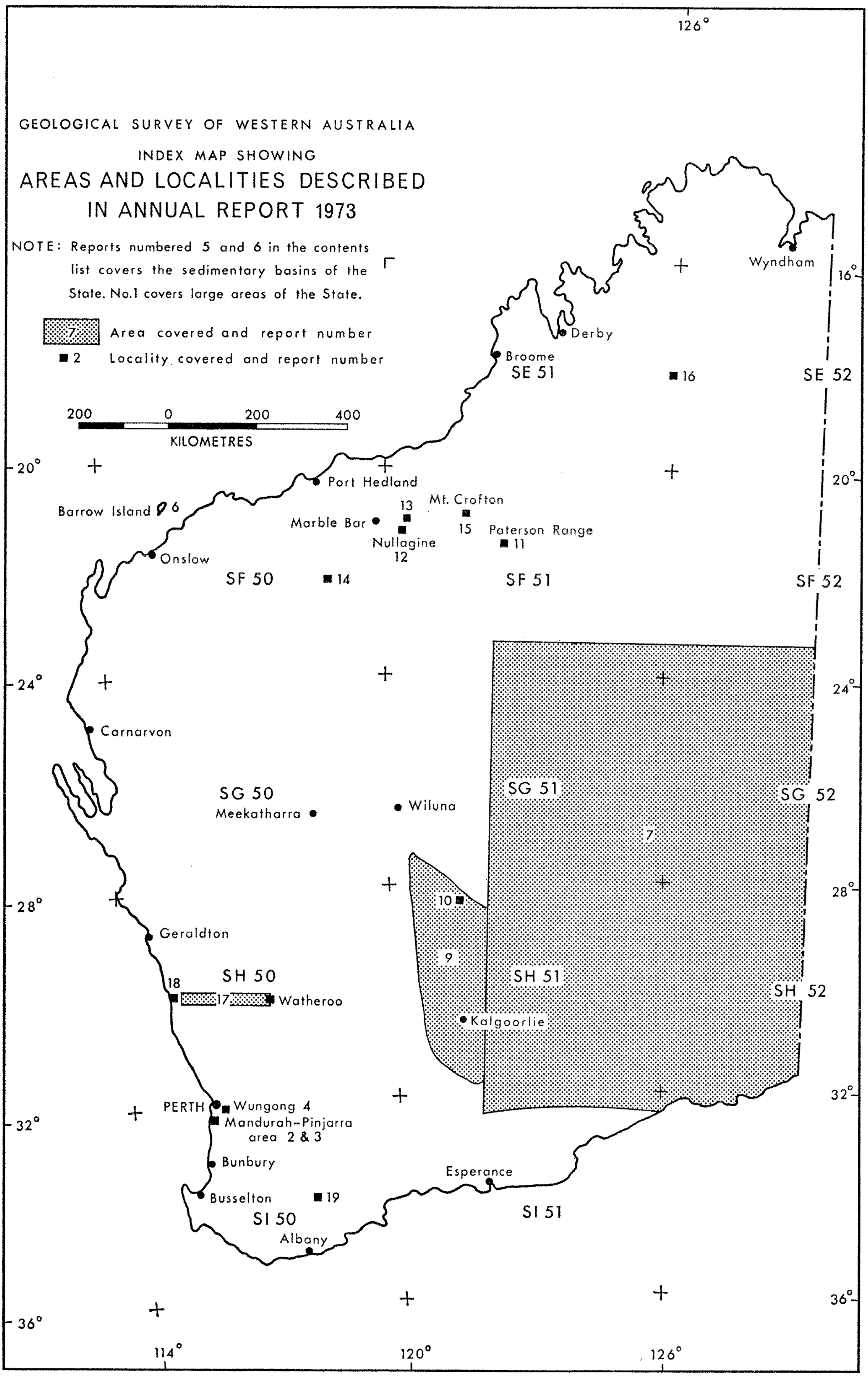


Figure 1. Index map showing areas and localities described in Annual Report for 1973.

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1973

Under Secretary for Mines:

For the information of the Honourable Minister for Mines, I submit my report on the activities of the Geological Survey of Western Australia during 1973, together with some of the reports on investigations made for departmental purposes.

INTRODUCTION

In the early part of 1973 the stability which had developed towards the end of the previous year continued. This was stimulated by the availability of Temporary Reserves for exploration. During the year some 182 such reserves were approved.

In the later part of the year exploration waned for lack of a clear policy from the Commonwealth Government, and a number of companies ceased exploration.

Iron ore exploration continued but declined towards the end of the year because of the lack of new export contracts. Similarly three bauxite projects are waiting on contracts before any further work is done.

Exploration for nickel continued on a greatly reduced scale. Exploration at Agnew was nearly complete and waited on a decision with regard to development. The prospect near Forrestania was being investigated further and a decision was made to develop the mine at Redross.

There was a decline in the tempo of oil exploration. The number of test wells decreased by 30 per cent, while there was a greater decrease in seismic activity both on and off shore.

The only success in exploration was in the northwest shelf, where extensions to the Angel and Goodwyn fields were successfully tested and a discovery of gas, condensate, and oil in the Dockrell structure and oil in the Egret structure were made. The deep hole on Barrow Island was classified a gas well and the gas found on West Tryal Rocks No. 1 remains to be evaluated.

Exploration for uranium attracted more interest than any other mineral during 1973 without any significant finds being made. The search extends throughout the State, involving the sedimentary basins as well as the Precambrian areas. The only possible economic deposit found to date is at Yeelirrie. This deposit has been fully examined and waits on a Commonwealth Government's decision and a contract before development can be planned.

Due to the increase in price, gold was another mineral in which there was renewed interest. Many old prospects were being re-examined and State batteries were kept busy treating prospectors' ore. A new find, made in 1972, was reported in the Paterson Range about 250 km southwest of Marble Bar. This gold mineralization is in a new geological environment and developments should be interesting.

A nugget weighing about 1 340 grams was found a short distance southeast from Mt. Magnet by two lads following a newly graded road. The nugget was photographed (Fig. 2A) shortly before smelting.

Due to the energy crisis exploration for coal continued, particularly in the southern portion of the Perth Basin and in the Fitzroy Basin.

Exploration continued at a reduced scale for other metallic and non-metallic minerals.

Two lectures, followed by field excursions, were arranged during the year. The first was at Laverton covering the Laverton and Leonora 1 : 250 000 geological sheets. About 140 persons from private enterprise, Universities and C.S.I.R.O. attended, as illustrated in Figure 2 B, C. The second was at Dongara covering the Dongara and Hill River 1 : 250 000 geological sheets. This was entirely on sedimentary geology and about 35 persons participated (Fig. 2 D).

STAFF

Although employment opportunities for geologists were reputedly scarce, a number of geologists at Level 1 resigned during the year.

Difficulty was experienced in recruiting geologists in sedimentary geology and a senior position in this Division has not been filled for nearly two years.

Approval was received to establish a section with two geologists to deal with environmental geology and conservation.

Miss G. Solomon resigned after 8 years as a typist with the Branch when she married and moved to another State. Difficulty has been experienced in obtaining a satisfactory replacement because of the technical nature of the work involved.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Brakel, A. T., B.Sc. (Hons.) Ph.D.	Geologist, Level 1	3/1/73
Chin, R., B.Sc. (Hons.)	Geologist, Level 1	5/1/73
Hill, W. B., B.Sc. (Hons.)	Geologist Level 1	5/1/73
Thompson, J. H., B.Sc. (Hons.)	Senior Geologist, Level 3	7/5/73
Barnett, J. C., B.Sc.	Geologist, Level 1	18/6/73
Wenham, M. E., B.Sc.	Geologist, Level 1	15/10/73
Green, K. H., B.Ed. (Hons.)	Geologist, Level 1	15/10/73
Klenowski, G., B.Sc. (Hons.)	Geologist, Level 1	17/12/73

Resignations

Vogwill, R.	Geologist, Level 1	2/3/73
Nicholson, J....	Geologist, Level 1	8/6/73
Commander, S. J.	Geologist, Level 1	19/7/73
Thom, J. H.	Geologist, Level 1	20/7/73
Balleau, W. P.	Geologist, Level 1	17/8/73
Gower, C. F.	Geologist, Level 1	24/8/73
Thompson, J. H.	Senior Geologist, Level 3	1/9/73
Cochrane, R. H. A.	Geochemist, Level 2	16/11/73

CLERICAL AND GENERAL

Appointments

Name	Position	Effective Date
Mouritzen, C.	Geological Assistant	7/3/73
Spring, A. L.	Geological Assistant	12/3/73
Darby, N. D.	Geological Assistant	28/3/73
Dawson, H.	Technical Assistant	30/4/73
Formato, E.	Geophysical Assistant	10/7/73
Nolan, G. D.	Technical Assistant	12/7/73
Daly, B.	Typist	6/8/73
Larsson, G.	Typist	15/8/73
Nutt, M.	Typist	24/8/73
Blundell, C.	Geological Assistant	3/9/73
Marrell, G. W.	Technical Assistant	12/11/73

Resignations

Hadley, P.	Technical Assistant	9/2/73
McGilligan, M.	Geological Assistant	13/4/73
Branson, G.	Technical Assistant	20/7/73
Solomon, G.	Typist	26/7/73
Daly, B.	Typist	9/8/73
Larsson, G.	Typist	23/8/73
Nolan, G.	Technical Assistant	24/8/73
Spring, A. L.	Geological Assistant	16/11/73

Transfers out

Nichols, T. J.	Geological Assistant	2/3/73
Neil, J.	Geological Assistant	19/11/73

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), C. C. Sanders, J. R. Forth, G. W. A. Marcos, W. A. Davidson, A. S. Harley, R. E. J. Leech, D. P. Commander, R. G. Barnes, J. M. Campbell, J. C. Barnett, G. Klenowski.

Hydrogeology

Deep exploratory drilling continued along the cross section of the Perth Basin sediments on the Eneabba line, extending between Winchester and the coast near Beagle Island. Four sites were drilled during 1973 and potable water was obtained at each site.

Contractors to the Metropolitan Water Board also drilled ten other deep bores in the Perth Basin north of Perth, some having yielded up to 53 litres per second of water with a total salinity in the 300 to 450 ppm range.

In conjunction with the Metropolitan Water Board, investigation of shallow groundwater around Perth progressed, and separate projects at Yanchep, Gingin, Lake Thompson, Wanneroo, and Joondalup, continued. A major production bore field was also being developed at Wanneroo, on the western flank of the Gnangara mound.

In the Canning Basin further seismic work was done to delineate bedrock, and 10 exploratory bores were drilled at 8 sites along two section lines. Potable water occurs in Mezosoic sediments but the salinity increases with distance northward, and not all groundwater is suitable for public water supply. Several bores flowed strongly. More work is planned to delineate the extent of the potable water and to find the intake.

Seven exploratory bores were also drilled into the Lyre Creek Agglomerate in the catchment area of the Harding River at Cooya Pooya, south of Roebourne. The groundwater is of low salinity, and although a calculation of the water balance suggests that the area should have valuable potential, pumping results have been disappointing.

The Branch continued to provide advice in connexion with work done by groundwater consultants for mining and other companies, but activity was at a lower level than previously. Officers were also engaged in environmental studies in co-operation with other departments.

Field inspections were made and written advice given to 126 private landholders; 22 reports were written for other departments including Public Works Department, Metropolitan Water Board, Town Planning Department and the Aboriginal Affairs Planning Authority. In addition assessments of groundwater prospects were written for the Pilbara Region and the Southwest Region as a guide to the planning of future development.

Continued assistance was provided to the Public Works Department with the progressive exploration and development of groundwater supplies from the Gascoyne River bed for Carnarvon water supply and irrigation scheme.

Engineering Geology

The following investigations were carried out on proposed dam sites for the Department of Public Works:

(i) North Pole. Completion of field mapping, and geophysics. A report was written on the spillway sites and construction materials, completing that phase of investigations.

(ii) Kangan Pool. Some geophysics was done on the site itself, and on the stilling basin below a spillway proposed on the left bank.

(iii) Bullinnarwa. Geological mapping of the whole site was completed, together with drilling, geophysics, pits and costeans thus completing the geological feasibility studies. A report was commenced.

(iv) Preliminary inspections and assessments were made at Dogger's Gorge, Gregory Gorge and on the Robe River.

(v) Harvey. Two dam sites downstream of the existing weir were investigated by detailed geological mapping, drilling, and geophysics, and a report written.

(vi) Burekup. Reconnaissance mapping only; work will continue.

Investigations for the Metropolitan Water Board included:

(i) South Dandalup Dam. Geological advice was provided during construction, which is now complete. A final detailed geological report was commenced.

(ii) Lower Wungong Dam Site. A detailed geological investigation of the site and the borrow areas was made, including drilling, trenching and geophysics. The site geological investigation phase was completed.

(iii) Canning Dam tunnel. Periodic inspections were made, and a photographic record of the tunnel was compiled in conjunction with the University of Western Australia.

(iv) Carralong Brook. Geological inspections of suggested dam sites and tunnel lines were made in the Carralong Brook—Serpentine Falls area.

(v) Mullaloo Tunnel. A field reconnaissance was made and reported.

Advice was also given to other Departments such as the Government Railways and the Department of Main Roads.

SEDIMENTARY (OIL) DIVISION

P. E. Playford (Supervising Geologist), R. N. Cope (Production Geologist), G. H. Low (Senior Geologist), W. J. E. van de Graaff, J.-C. Boegli and R. W. A. Crowe.

Information received from petroleum exploration permittees and production licence-holders was evaluated and collated. Procedures for accession, storage, retrieval and distribution of data were further stream-lined and developed. The Division dealt with numerous petroleum exploration enquiries. Evaluation of coal exploration on the Collie Coalfield and on other prospective areas was continued.

A compilation report on the petroleum reserves of the entire northern Carnarvon Basin, as on 30th June, 1973 was prepared for the Pilbara Study Group. Technical advice was provided to the Fuel and Power Commission on numerous occasions.

Compilation of map sheets and explanatory notes of the Officer Basin continued throughout the year, and the preliminary editions of the Madley, Warri, Cobb, Herbert, Browne, Yowalga, Westwood, Seemore, Vernon and Mason sheets were issued. Writing of a bulletin on the Officer Basin was commenced.

Regional mapping of the northeastern Canning Basin, jointly with the Bureau of Mineral Resources, was continued, with the mapping of the Cornish, Crossland, Dummer, Helena, Mount Bannerman and Webb 1 : 250 000 sheets. In addition a drilling programme was carried out to clarify stratigraphic problems. Compilation of explanatory notes and maps for the Billiluna, Lucas and Stansmore sheets continued.

Studies of the Devonian reef complexes on the Lennard Shelf continued, with special emphasis on facies relationships in the fore-reef environment. A bulletin on "The Geology of the Perth Basin" has been completed in manuscript.

REGIONAL GEOLOGY DIVISION

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

The programme of regional mapping of the Precambrian area of the State for publication on a scale of 1 : 250 000 continued. The progress is shown in Figure 3.

Field mapping commenced on the Nullagine, Mount Phillips and Southern Cross sheets. Field mapping of the Laverton, Duketon, Throssell and Mount Egerton sheets was completed.

Work continued on compilation of a bulletin on the geology of the southeastern part of the Yilgarn block covering the Kalgoorlie and Esperance 1 : 1 000 000 sheets.

A geological excursion of the Leonora and Laverton sheets was conducted.

MINERAL RESOURCES DIVISION

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

Field and office work continued for the production of a bulletin on the State's resources of chrome, vanadium, tungsten and molybdenum, and for the revision of the copper bulletin. Writing of the bulletin on tin and mineral sands continued.

Further tests on the application of a new geophysical technique to Western Australian conditions were made.

Compilation of the Marble Bar sheet was completed and about 75 per cent of the Nullagine sheet was mapped in conjunction with the Regional Geology Division.

Mapping of the Precambrian portion of the Perth sheet was completed and compilation commenced. A start was made on the Pinjarra sheet, and work on the Moora sheet continued.

Inspections were made of a number of kaolin deposits in the southern part of the State in order to establish the resources of this mineral. Other inspections of talc, fluorite, limestone, lead, zinc, uranium, beryl and gold deposits were made as required.

About 315 general enquiries from the public and 120 requests for data from reports on relinquished tenements received attention.

A two week field trip with a guide was arranged for Colombo Plan fellows in association with the Department of Foreign Affairs in June and July.

COMMON SERVICES DIVISION

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

The rise in demand for petrological services during 1973 increased the production of petrological reports to 92 covering 1 353 samples. Means of streamlining reporting procedures are being considered in order to handle the increased load.

A petrological and geochronological study of sills in the Weeli Wolli Formation and a petrological and field study of ultramafic lavas in the Mount Clifford area were completed. A study of the petrology of the Eastern Goldfields and a project on syenite and other alkali granitic rocks of Western Australia were continued. The computerized retrieval system for rock data was nearly ready for operation.

The capability of the section in the fields of low-grade metamorphic, fine-grained volcanic, and other fine-grained rocks was greatly increased by direct access to a new X-ray diffractometer at the Government Chemical Laboratories. Results are being reported regularly in petrological reports. Some of the more striking discoveries were that a rock from the Bangemall Beds which has been generally accepted as a chert, is in fact a K-feldspar rock and that a supposed feldspathic volcanic rock from Gregory Gorge is silicified.

The Government Chemical Laboratories continued to provide valuable chemical analyses, mineral determinations and X-ray mineral identifications.

The laboratory prepared 1873 petrological thin sections, 50 polished mounts, 35 polished slabs, 34 mineral separations, 25 sieve analyses and 120 crushings (for various analytical requirements).

The co-operative geochronological programme with the Western Australian Institute of Technology continued involving a number of projects.

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

Seventy file reports were written during the year. The table below shows that the bulk of these reports were written at the request of the Hydrology and Engineering Geology Division and dealt with palynology.

Report requested by	Field of palaeontology		
	Palynology	Micropalaeontology	Macropalaeontology
Hydrology and Engineering Geology Division	30	1	2
Sedimentary Division	5	2	7
Regional Mapping and Mineral Resources Divisions	6	2	3
Other Organizations	3	1	5

A project on Devonian brachiopods from the Lennard Shelf was completed and a start was made on the bivalves and gastropods from the same area. A preliminary study of Devonian spores from boreholes in the Gogo Formation was finished. Work continued on the Mesozoic palynology of the Perth Basin and a tentative zonation for the Upper Jurassic and Lower Cretaceous sequence in the Watheroo Line boreholes was produced. A general survey of the palaeontology of the Perth Basin was made and work started on the planktonic foraminifera from the Gingin Chalk.

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

During 1973 there was a substantial increase in the number of shallow water bores geophysically logged in the Perth Basin. However this was offset by a decrease in logging operations elsewhere and the total number of bores logged amounted to only 138 compared with 151 in 1972. Correspondingly the total logged length for all runs decreased from 31 600 to 27 000 m.

Seismic refraction surveys were carried out at the Harvey, North Pole, Bullinnarwa and Kangan Pool dam sites at the request of the Engineering Geology group. A further 40 refraction and resistivity depth soundings were made in the West Canning hydrology investigation. Exploratory drilling in the basin in 1974, whilst mainly confirming the earlier seismic bedrock depths, in one bore highlighted a velocity inversion problem and afforded the necessary control to resolve it with fair reliability.

The usual laboratory services, field salinity determinations, equipment calibration and repair, were maintained.

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

Although there were several staff changes during the year, the editorial duties connected with the items listed below and the production of twenty-eight Records indicate that the amount of material for publication passing through the Section continued to grow. In addition fourteen publications, mainly Explanatory Notes, were issued. Distribution of geological information to both public and staff continued to be a major function of the group. The preparation of a pamphlet to serve as a guide to the layout of the Geological Museum was commenced.

Requisitions raised on the Surveys and Mapping Branch for drafting services and photography for the Survey totalled 1 132. Photocopying for the public of out-of-print publications numbered 900 requisitions. Many of these contained more than one entry.

During the year 2 985 members of the public used the facilities of the library. Loans to outside organizations were 63, while loans to departmental staff totalled 4 826.

The establishment of a microfilm library was commenced and all Geological Survey publications are now available on 16 mm film in cassettes, supplemented by 35 mm aperture-card mounts for large maps. Reading and print out facilities are available at the library.

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 the 1 : 250 000 geological sheets and bulletins on the Kimberley Division as a joint project with the Survey.

(ii) Compilation of the geological mapping of the Officer Basin and preparation of a bulletin as a joint project with the Survey.

(iii) Continuation of mapping in the Canning Basin as a joint project with the Survey including stratigraphic drilling.

(iv) Continuation of the aeromagnetic survey of W.A., confined to the Officer Basin.

PROGRAMME FOR 1974

HYDROGEOLOGY AND ENGINEERING DIVISION

A. *Hydrogeology*

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling.
2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas:
   (a) Cooya Pooya, Millstream, George River and Lower Harding.
   (b) West Canning Basin.
   (c) Murchison and East Murchison—regional assessments.
   (d) Town water supply Halls Creek.
   (e) Carnarvon Basin—Gascoyne River sands.
3. Hydrogeological investigations for Metropolitan Water Board.
   (a) Regional studies.
   (b) Deep drilling at Wanneroo, Whitfords.
   (c) Shallow drilling at Salvado, Wanneroo, Gwelup, Yanchep, Joondalup and Lake Thompson.
4. Kimberley Division—hydrogeological assistance to pastoralists as required.
5. Continuation of bore census work in selected areas.
6. Miscellaneous investigations and inspections as requested by Government departments and the public.

B. *Engineering*

1. Kimberley Area—investigation for the raising of the Moochalabra dam.
2. Pilbara area—further investigations at the following dam sites: Kangan Pool, Robe River, Gregory Gorge and Dogger's Gorge—completion of work at Bullinnarwa and North Pole (spillway).
3. Darling Range area—completion of work at South Dandalup dam site—continuation of work at Lower Wungong dam site—Burekup dam site, South Canning and North Dandalup dam site—commencement of work on the proposed tunnels at Lower Wungong and Mullaloo and aqueduct route from Collie River to Harvey Dam.

SEDIMENTARY (OIL) DIVISION

1. Maintain an active interest in the progress and assessment of oil exploration in Western Australia.
2. Evaluate oil and gas discoveries and assess the resources of the State.
3. Completion of the Bulletin on the Perth Basin.
4. Preparation of the Bulletin on the Officer Basin.
5. Mapping of the Canning Basin in conjunction with the Bureau of Mineral Resources.
6. Commence surface and sub-surface study of the Carnarvon Basin.

REGIONAL GEOLOGY DIVISION

1. Completion of Throssell, Duketon, Nullagine, Mount Egerton 1 : 250 000 sheets.
2. Continuation of mapping of the Bangemall Basin on the Collier and Robinson Range 1: 250 000 sheets.
3. Commencement of mapping on the Sir Samuel, Paterson Range and Yarrie sheets.
4. Continuation of mapping on the Southern Cross and Mount Bannerman sheets.
5. Continuation of the re-assessment of the regional geology of the Eastern Goldfields.

MINERAL RESOURCES DIVISION

1. Maintain records and assess mineral exploration in Western Australia.
2. Completion of mineral resources bulletins on tin, mineral sands, copper and vanadium, chromium, tungsten and molydbenum deposits of Western Australia.
3. Completion of re-mapping of the Nullagine 1 : 250 000 sheet.
4. Regional mapping of the Darling Range on 1 : 250 000 scale and study of the bauxite occurrences.
5. Miscellaneous mineral investigations as required.

PUBLICATIONS AND RECORDS

Issued during 1973

Annual Report, 1972.

Publications Catalogue, 1973.

Report 2:

A reappraisal of the Yule River area:
Port Hedland Town water supply, and
An appraisal of the effects of longterm pumping in the Lake Allanooka area.

Mineral Resources Bulletin 9: The lead, zinc and silver deposits of Western Australia.

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

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

Geological map of Forrest 1 : 250 000 Sheet (SH/52-10 International Grid) with explanatory notes.

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

Geological map of Jubilee 1 : 250 000 Sheet (SH/52-5 International Grid) with explanatory notes.

Geological map of Kurnalpi 1 : 250 000 Sheet (SH/51-10 International Grid) with explanatory notes.

Geological map of Lennard River 1 : 250 000 Sheet (SE/58-8 International Grid) with explanatory notes.

Geological map of Madura-Burnabbie 1 : 250 000 Sheet (SI/52-1 International Grid) with explanatory notes.

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

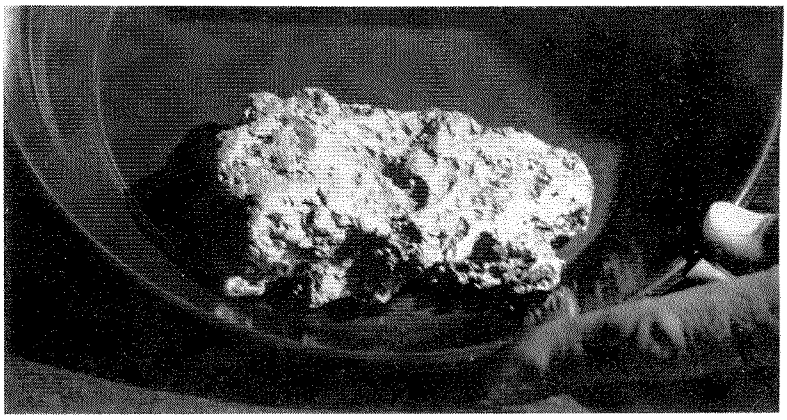
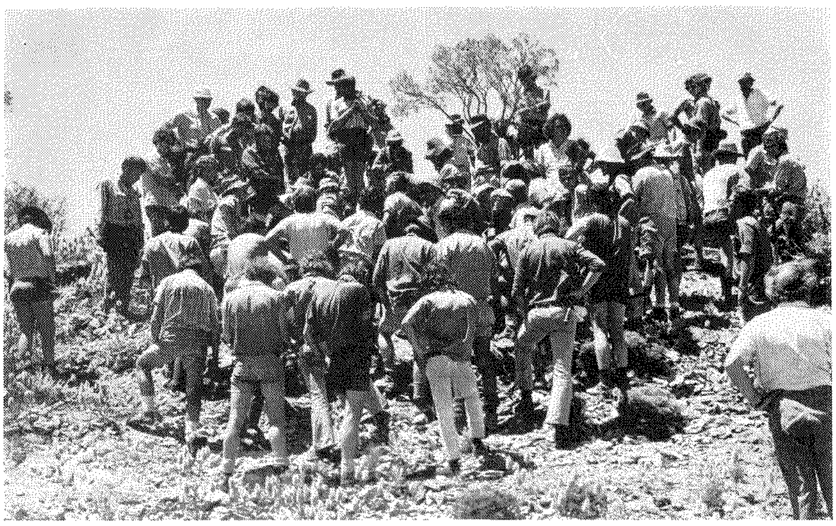


Figure 2. Photographs of field excursions held during 1973

A. Photograph of a gold nugget found within a few kilometres of Mt. Magnet on 24th November, 1973.

B. Photograph of vehicles assembled at the start of the Leonora-Laverton geological field excursion.



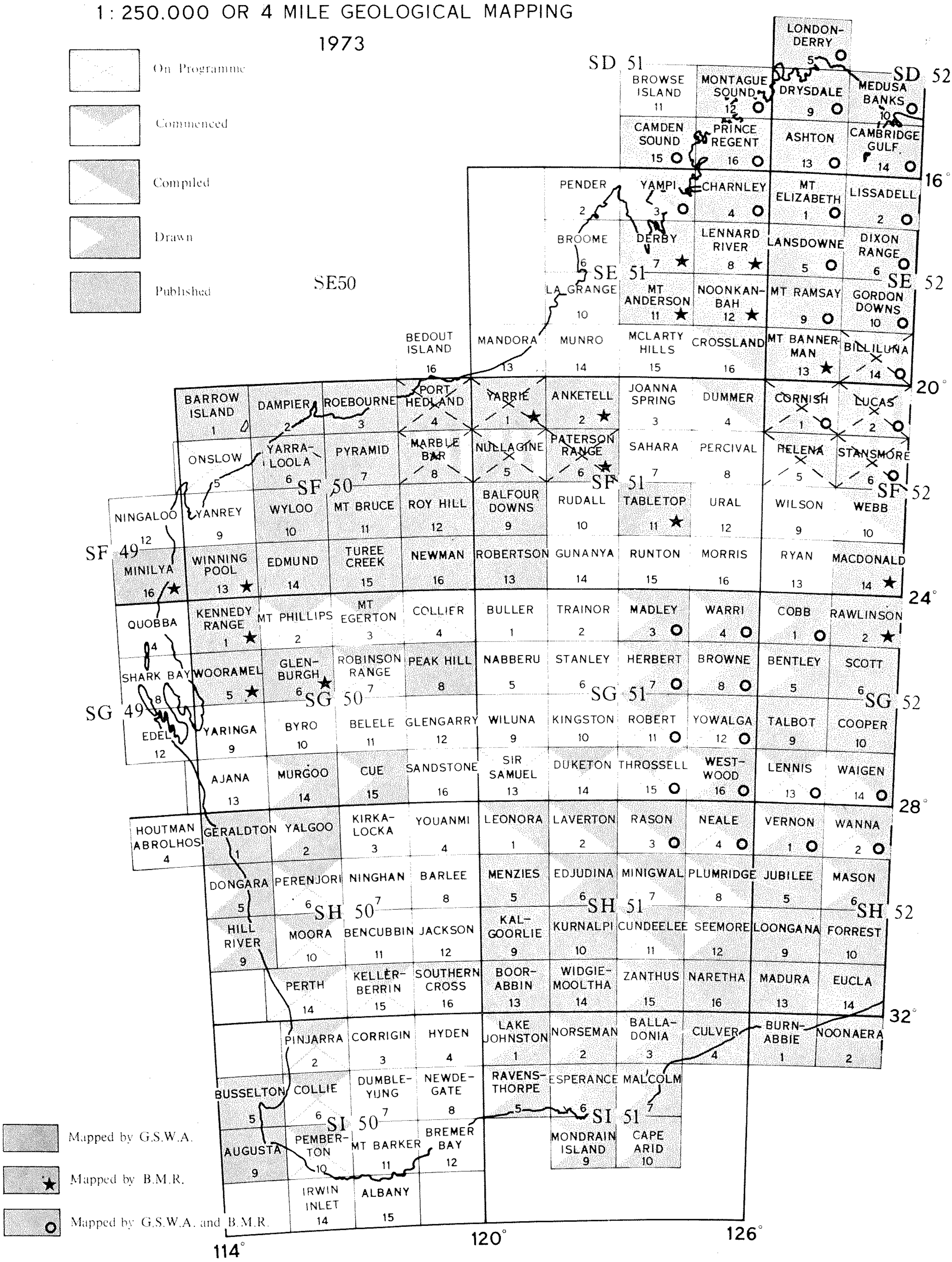
C Photograph of part of the 140 strong group that attended the Leonora-Laverton excursion on 1st November, 1973.

D Photograph of group examining the type section of the Yarragadee Formation, 8 km north of Mingenew on the Dongara-Hill River geological excursion.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

1 : 250.000 OR 4 MILE GEOLOGICAL MAPPING

1973



Broken lines or shading indicates remapping

Figure 3

Geological map of Peak Hill 1 : 250 000 Sheet (SG/50-8 International Grid) with explanatory notes.

In Press

Bulletin 123: The geology of the Blackstone Region, Western Australia.
Geological map of Balladonia 1 : 250 000 Sheet (SI/51-3 International Grid) with explanatory notes.
Geological map of Bentley 1 : 250 000 Sheet (SG/52-5 International Grid) with explanatory notes.
Geological map of Cue 1 : 250 000 Sheet (SG/50-15 International Grid) with explanatory notes.
Geological map of Edjudina 1 : 250 000 Sheet (SH/51-6 International Grid) with explanatory notes.
Geological map of Esperance-Mondrain Island 1 : 250 000 Sheet (SH/51-6 and 10 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 Lake Johnston 1 : 250 000 Sheet (SI/51-1 International Grid) with explanatory notes.
Geological map of Malcolm-Cape Arid 1 : 250 000 Sheet (SI/51-7 and 11 International Grid) with explanatory notes.
Geological map of Murgoo 1 : 250 000 Sheet (SG/50-14 International Grid) with explanatory notes.
Geological map of Norseman 1 : 250 000 Sheet (SI/51-2 International Grid) with explanatory notes.
Geological map of Ravensthorpe 1 : 250 000 Sheet (SI/51-5 International Grid) with explanatory notes.
Geological map of Seemore 1 : 250 000 Sheet (SH/51-12 International Grid) with explanatory notes.
Geological map of Yalgoo 1 : 250 000 Sheet (SH/50-2 International Grid) with explanatory notes.
Geological map of Yampi 1 : 250 000 Sheet (SE/51-3 International Grid) with explanatory notes.
Geological map of Zanthus 1 : 250 000 Sheet (SH/51-15 International Grid) with explanatory notes.

In Preparation

Bulletin 124: The geology of the Perth Basin.
Mineral Resources Bulletin: Tin.
Mineral Resources Bulletin: Heavy mineral sands.
Geological maps 1 : 250 000 with explanatory notes, the field work having been completed:

Billiluna, Browne, Cobb, Cundeelee, Duketon, Herbert, Laverton, Lennis, Leonora, Lucas, Madley, Marble Bar, Mason, Minigwal, Neale, Perth, Rason, Robert, Stansmore, Throssell, Vernon, Waigen, Wanna, Warri, Westwood, Yowalga.

Geological map 1 : 2 500 000 Western Australia.
Geological map 1 . 1 000 000 Kalgoorlie.
Geological map 1 : 1 000 000 Esperance.

Records Produced

1966/6 Geology of the Darling Scarp between latitudes 32° and 33° South, W.A., by J. L. Baxter and J. J. G. Doepel.
1973/1 Lalla Rookh proposed dam site and spillway, Shaw River—foundation geology, by J. Nicholson (restricted).
1973/2 The geology of the peninsula west of Leschenault Inlet, by R. W. A. Crowe (restricted).
1973/3 Report on the geology of the Fitzgerald River lignite, by A. E. Cockbain and W. J. E. van de Graaff (restricted).
1973/4 Kangan Pool dam site, Sherlock River, geological investigation—progress report, by J. M. Campbell (restricted).
1973/5 Wells drilled for petroleum exploration in W.A. to the end of 1972, by G. H. Low.
1973/6 Explanatory notes on the Yalgoo 1 : 250 000 geological sheet, W.A., by P. C. Muhling and G. H. Low.
1973/7 West Canning Basin hydrology investigation, geophysics 1972—progress report, by D. L. Rowston (restricted).
1973/8 A proposed structural subdivision for the Eastern Goldfields Province of the Archaean Yilgarn Block, Western Australia, by I. R. Williams.
1973/9 Explanatory notes on the Ravensthorpe 1 : 250 000 geological sheet, W.A., by R. Thom and S. Lipple.
1973/10 Lower Wungong proposed dam site: brief geological report of investigations March 1973, by G. Marcos.
1973/11 A review of the geological investigations of the Eastern Goldfields Province including bibliography to December 1972, by I. R. Williams.
1973/12 Summary of progress on the Precambrian stratigraphy of W.A., by R. D. Gee.
1973/13 B.M.R. Billiluna No. 1 stratigraphic test bore, by R. W. A. Crowe.
1973/14 Explanatory notes on the Rason 1 : 250 000 geological sheet, W.A., by C. F. Gower and J.-C. Boegli.
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1973/18 Explanatory notes on the Warri 1 : 250 000 geological sheet, W.A., by W. J. E. van de Graaff.
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1st February, 1974. J. H. LORD, Director.

CALCRETE IN WESTERN AUSTRALIA

by C. C. Sanders

ABSTRACT

Calcrete is a carbonate rock occurring in association with fluvial sediments in the ancestral river valleys of arid regions in Western Australia. It has formed by the *in situ* replacement of valley-fill debris by carbonate precipitated from percolating carbonate-saturated ground and soil water. In Australia it frequently attains a thickness of 10 m, but may rarely be as much as 30 m thick.

Calcrete has a well developed secondary porosity and high permeability, and in places it forms excellent aquifers. Some calcretes close to Archaean granites are selectively mineralized by uranium.

In the arid zone there are also widespread soil carbonates which are termed kankar, but these are superficial and unlike calcrete are not valley controlled.

INTRODUCTION

Calcretes have been shown to be the most productive aquifers in the arid zone of Western Australia, because of the shallow depth to water in the deposits and their high permeability. Commonly the groundwater is potable, but where the water is brackish to saline it can usually be extracted in sufficient quantities to be suitable for industrial uses, e.g. the beneficiation of minerals. Furthermore, some calcretes, because of their closeness to uranium-bearing provenance rocks, have become hosts for uranium mineralization. The established and potential economic importance of these carbonate rocks makes necessary a better understanding of the nature of calcrete and prompts comparison with other arid zone carbonate rocks such as travertine, kankar, and calcareous paleosols.

Exploration of calcretes both for groundwater supplies and possible uranium mineralization is at present taking place in the Pilbara region in the northwest, and the East Murchison District in the central part of the State (Fig. 4).

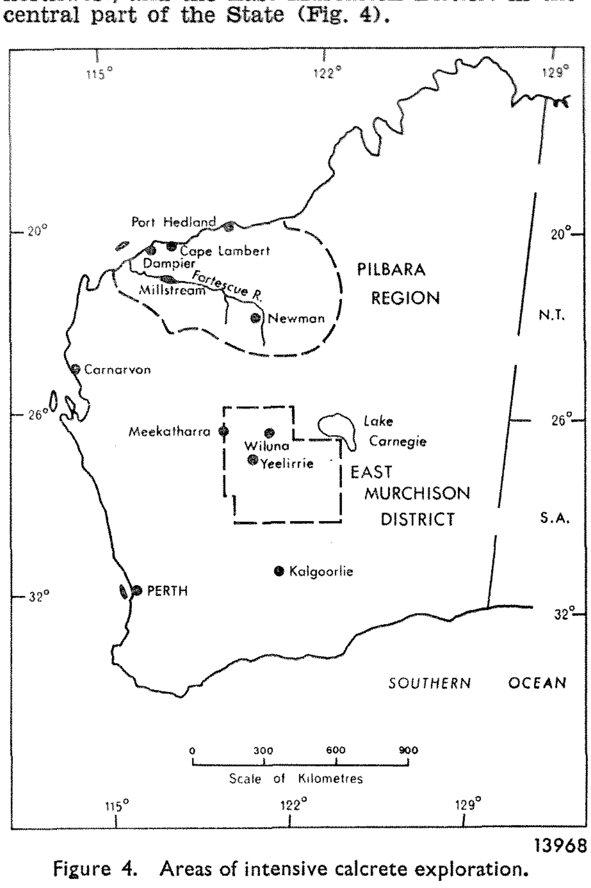

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Figure 4. Areas of intensive calcrete exploration.

CALCRETE

OCCURRENCE AND DESCRIPTION

The main rivers of the inland follow ancestral courses with alluvial, and in places calcrete infilled valleys, up to 30 m thick. The topography is mainly subdued with gentle gradients averaging 1 : 1 000, the water courses generally being poorly defined. Some of the valleys in the Pilbara Region, where drainage is to the coast from the Hamersley Range, have been subjected to rejuvenation and consequent renewed erosion. In the East Murchison drainage is internal towards large salt lakes, which now occupy parts of an extensive Tertiary river system that flowed southeastward to the Eucla Basin (Mabbutt and others, 1963; Morgan 1966). Other writers have presented reconstructions of the palaeodrainages of the region based on photo-interpretation, soils and vegetation evidence; Bunting and others (1974) have used altimetric data.

Calcrete crops out along the valley floors mainly as low mounds of nodular calcium carbonate dispersed in a brown calcareous soil, the mounds being separated by a network of narrow alluvial channels. In places it forms indurated sheets of calcium carbonate, frequently having karstic features such as sink holes (Fig. 5), cavities and solution pipes. Calcrete is restricted to ancestral or existing water courses, although these may not be apparent at ground level because of the low relief and a lack of indentifiable trunk drainage tracts. Air-photographs, however, usually show a distinctive residual dendritic drainage pattern, the calcrete being visible as whitish crenulated platforms ("brain pattern" Fig. 6). Furthermore, in some places the calcrete is overlain by thin alluvial wash and eolian sand, but its presence may be discerned on air-photographs from a conspicuous pock-mark pattern (gilgai), caused by carbonate solution and soil collapse. Colluvial debris also tends to mask any surface radioactivity associated with uranium within the calcrete.

Calcrete most commonly occurs along flat reaches of the drainage and around salt lakes (Morgan, 1966; Sanders 1969). The water table is usually at a depth of 3 to 6 m below ground level, except in areas where the base level of valleys has been lowered by renewed erosion, as along the Oakover River in the Pilbara region. Here the water table rests between 20 and 30 m below the calcrete surface.

Subsurface calcrete is of nodular and blocky limestone, which is friable and permeable in places, elsewhere it may occur as massive impermeable sheets a square metre or so in area. The level of the water table is marked by horizontal layers of brown pebbly detrital debris. Where the groundwater has a salinity generally less than about 5 000 mg/l massive opaline silica (chert) bands up to 0.5 m thick may occur. Past higher or lower elevations of the water table are often marked by various levels of opaline silica, but these are rarely more than a metre above or below the present water table. Often the opaline rock is fractured and fissured, the joints being encrusted with concretionary secondary carbonate. Some of the larger fissures have become avenues for groundwater movement and have been enlarged by water action to 0.3 m or more in width. Occasionally large caverns have formed, and these may connect with the surface (de la Hunty, 1958). Calcrete has a high secondary porosity, and in zones of uranium mineralization carnotite and some other exotic radioactive minerals may occupy pores and fractures mainly at the water table.

Beneath the silica layer the calcrete has variable lithology, from hard limestone to fine calcareous sand, with occasional brown detrital silt, sand and gravel layers cemented by ferroan carbonate. Where calcreted valleys occur in granite

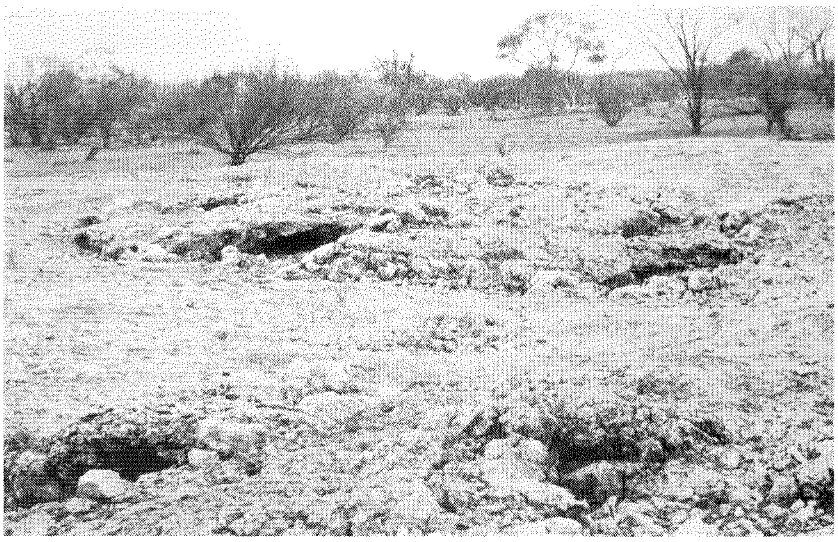

Figure 5. Cavernous calcrete surface at Paroo Station, Wiluna. The sink hole at left of centre is 0·8 m deep and 3·2 m wide. Note the mound development.

Figure 6. Air-photograph of typical calcrete area—white area interspersed by dendritic streams leading to a trunk drainage (Weeli Wolli Creek, Pilbara Region). Lands Department of W.A. photo 373 Roy Hill run 18. No. S123. Scale 10 mm=400 m.

terrains white kaolinitic clays are commonly dispersed in the limestone profile. The materials are usually sufficiently well cemented to permit bores to remain uncased. The permeability of the deposit varies greatly depending on the degree of cementation, the amount of residual clay and fine debris, and the development of conduits by solution.

The full calcrete sequence may range in thickness from 5 to 30 m, but is usually of the order of 5 to 10 m. Its origin has been discussed in a number of papers, the general concensus being that the limestone was formed by the slow replacement of fluviatile silt, sand and gravel by carbonate, mainly in the calcitic form, precipitated from high pH, carbonate-saturated ground and soil water. Neither the mineralogy of the limestone nor the replacement mechanism are as yet fully documented. However calcrete groundwaters have a positive Langelier index (see Hem, 1970), indicating supersaturation with respect to calcite. Silica carried in solution is presumably reconstituted into chert at the water table, where oxidization and consequently a reduction in pH occurs.

NOMENCLATURE PROBLEMS

Elsewhere in the semi-arid and arid areas of Australia and other continents there are widespread superficial calcium carbonate deposits that are usually in the form of fine-grained unconsolidated material, nodules, and indurated sheets and commonly contain varying amounts of terrigenous materials and chert. They are known by various local terms, such as caliche, croûte calcaire, nari, kankar or kunkar, etc. Goudie (1971, 1972) gives a bibliography of such deposits, and argues that an acceptable international term for them all would be "calcrete". Generally they bear no relationship to distinct drainages, and are often found in the unsaturated zone well above the water table, where they are formed by cementation and/or *in situ* replacement of pre-existing soil material, mainly by calcium carbonate. In Western Australia these limestone soils are very extensive, especially in the Kalgoorlie region, where they are termed kankar. Heath (1966) points out that this is a more acceptable spelling than kunkar.

It seems that these pedogenic carbonates deserve a standard term of their own that is universally applicable. Thus if a rational term is chosen for kankar, caliche, etc., it should be chosen from the more common synonyms, and not from a term that possibly implies something quite different. "Calcrete" as coined by Lamplugh (1902) is poorly described, but appears to refer to the carbonate cement. Further, Lamplugh (1907) used calcrete to describe carbonate deposits occurring along part of the Zambesi River, and these are probably similar to the Australian valley-controlled calcretes.

The Geological Survey of Western Australia intends to retain both the terms calcrete and kankar for the time being.

AGE

The age of calcrete development in Western Australia is given in the literature as being late Tertiary to Holocene (Traves and others, 1956, Sofoulis, 1963, Sanders, 1973).

There are no reports of isotope age dating having been done, and no datable fossil remains have been found. Calcrete chronology is based on stratigraphic evidence, for instance in the East Murchison, calcrete is part of the uppermost sequence in valley-filled drainages which demonstrably lead southeastward to the Tertiary Eucla Basin. Moreover, calcrete development is enhanced under arid climatic conditions, which from geomorphological evidence, such as peneplanation and alluviation of trunk drainages and development of salt lakes (Mabbutt and others, 1963), commenced in the late Tertiary and have persisted to the present.

ECONOMIC IMPORTANCE

A calcrete at Millstream on the Fortescue River is described by Davidson (1969), and is reported by Collett and Sadler (1973) as yielding 22.5 megalitres (22.5×10^3 m^3*) per day of potable water suitable for developing towns in the Pilbara. At least 350×10^6 m^3 is estimated to be in storage. Further, these authors predict for Dampier-Cape Lambert a daily water requirement by 1990 of 450 megalitres (450×10^3 m^3) if the concept of an integrated industrial complex becomes a reality; much of this water must come from underground sources.

Balleau (1973) examined the hydraulics of many of the Pilbara river basins. He concluded that calcreted aquifers in association with local alluvial reservoirs along river valleys are recharged from intermittent rainfall and catchment runoff at an average overall rate of 300×10^3 m^3 per day. If the rate of abstraction is made equal to the recharge rate any alteration of the water balance will be minimized and the prospect exists of meeting much of the projected 1990 water demand from groundwater sources.

In the East Murchison District, north of Kalgoorlie, a number of calcretes are being investigated for their groundwater resources. One, at Paroo Station near Wiluna, could yield at least 12.3×10^3 m^3 per day of potable water (Sanders, 1973). Other calcretes should provide industrial quality water at salinities greater than 1 500 milligrams per litre total dissolved solids. The predicted combined daily demand of companies in this region is given by Collett and Sadler (1973) as upward of 160 megalitres (160×10^3 m^3), but 75 per cent of the water may be of industrial quality at salinities ranging from 3 000 to 100 000 mg/l TDS, depending on company requirements.

Intensive uranium prospecting of calcrete followed the January 1972 announcement by Western Mining Corporation of a significant discovery at Yeelirrie 90 km south of Wiluna. The Corporations 1973 Annual Report records the proven ore resources for the explored area at Yeelirrie as 32×10^6 tonnes containing 0.15 per cent uranium oxide (3.3 lbs. per long ton). Discoveries by other exploration companies working in the region have also been announced in the press.

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RECHARGE TO THE JURASSIC AQUIFER OF PINJARRA

by J. R. Forth

ABSTRACT

The term "Jurassic aquifer" is informally applied to a thickness of water-producing sands contained within a greater thickness of saturated clays, silts and sands of Jurassic, Cretaceous and Quaternary age at Pinjarra (70 km south of Perth, Western Australia).

Pinjarra is on the coastal plain westward of the Darling Fault. The land surface slopes gently westward to the sea and is drained by minor streams.

Drilling has shown that the coastal plain deposits consist of interfingering layers and lenses of sand, silts and clays. The block-faulted Jurassic sediments are unconformably overlain at the surface by westward-dipping Cretaceous strata and up to 15 m of Quaternary sands and silts.

Groundwater flow in the confined Jurassic aquifer is westward from an impermeable fault boundary towards the sea 20 km distant.

The aquifer is about 150 m below the ground surface and is 25 m thick. Its transmissivity is shown to be in the range 150 to 180 m^2/d, and aquifer recharge, prior to pumpage, is shown to be about 2 640 m^3/d.

When head changes in the cone of depression, resulting from long term abstraction, are analysed, then it is clear that leakage to the aquifer is not by vertical percolation from the water table, but is mined from water stored in sediments above and below the aquifer.

Aquifer recharge is apparently restricted to a very small part of the total potential recharge area of 8.2×10^6 m^2, and abstraction from the Jurassic aquifer can only lead to small increases in recharge by capture.

INTRODUCTION

The alumina refinery site at Pinjarra (70 km south of Perth) is underlain by a thick sequence of fine sediments. Present water production is from bores (the locations of which are given in Commander, 1974) whose screens have been emplaced in sands of Jurassic age, loosely referred to as the "Jurassic aquifer".

There has been extensive testing of the main producing aquifer, and a substantial body of information has been derived from the many observation bores sited within the cone of influence. In the ensuing discussion data collected during long term abstraction are applied to the problem of describing the locus of the water pumped, and the possible effect of pumping of the recharge regime.

SYMBOLS

Symbols used are those of Hantush, 1964.

A	=	area
B	=	leakage factor = $\sqrt{Kb/(K'/b')}$
b	=	uniform thickness of an aquifer
b'	=	uniform thickness of a semipervious layer
d	=	day
H (u,β)	=	an indefinite integral
H	=	head
i	=	hydraulic gradient
K	=	hydraulic conductivity of an aquifer
K'	=	hydraulic conductivity of a semi-pervious layer
Ko(x)	=	zero-order modified Bessel function of the second kind
m	=	metres
Q	=	discharge
r	=	radial distance
r_w	=	effective radius of a well
S	=	storage coefficient of an aquifer
S'	=	storage coefficient of a semipervious layer
s	=	drawdown
T	=	transmissivity
t	=	time
u	=	$r^2/4vt$
W(u)	=	well function for a non-leaky aquifer
β	=	$(r/4B)\sqrt{S'/S}$ = a parameter in formulae pertaining to leaky aquifers with storage in the semipervious layer
δ	=	$1 + S'/3S$
v	=	T/S
Δh	=	head difference

HYDROGEOLOGICAL SETTING

The principal aquifer systems are in Jurassic and Cretaceous sediments consisting of interfingering layers and lenses of sand, sandy clay and clay, which are covered by a relatively thin layer of more recent sandy and clayey sediments. The detailed stratigraphy and structure of the area has been described by Commander, 1974. The Jurassic sands tapped for production are typically 150 to 200 m below the ground surface, which is about 20 m above sea level.

Water in the Jurassic and Cretaceous sediments has a pressure head, while in the uppermost surficial sediments there is a water table. Recharge to the generally confined Jurassic aquifer is restricted to a small area bounded on one side by an unnamed fault parallel to and westward of the Darling Fault, and on the other, approximately by the 24 m potentiometric contour (Figs. 7 and 8).

The potential recharge area is limited to the zone in which potentiometric levels in the Jurassic aquifer are lower than the elevation of the water table. Hence there appears to be a possibility of increasing the area of recharge by pumping water from the Jurassic and Cretaceous sediments, thereby reducing their potentiometric levels.

Production from 1970 to 1974 has been from bores whose screens are set in Jurassic sands, selected because of their potential for supporting sustained production at high rates. The screened intervals have been chosen as the best that exist within an economic depth range. Water could be pumped from other depth intervals at the production bore sites, though yields might not necessarily be as great as those presently obtained. All the sediments are fully saturated, including those that are classified as aquifers and those that are not. This is important when considering the likely behaviour of bores in this area.

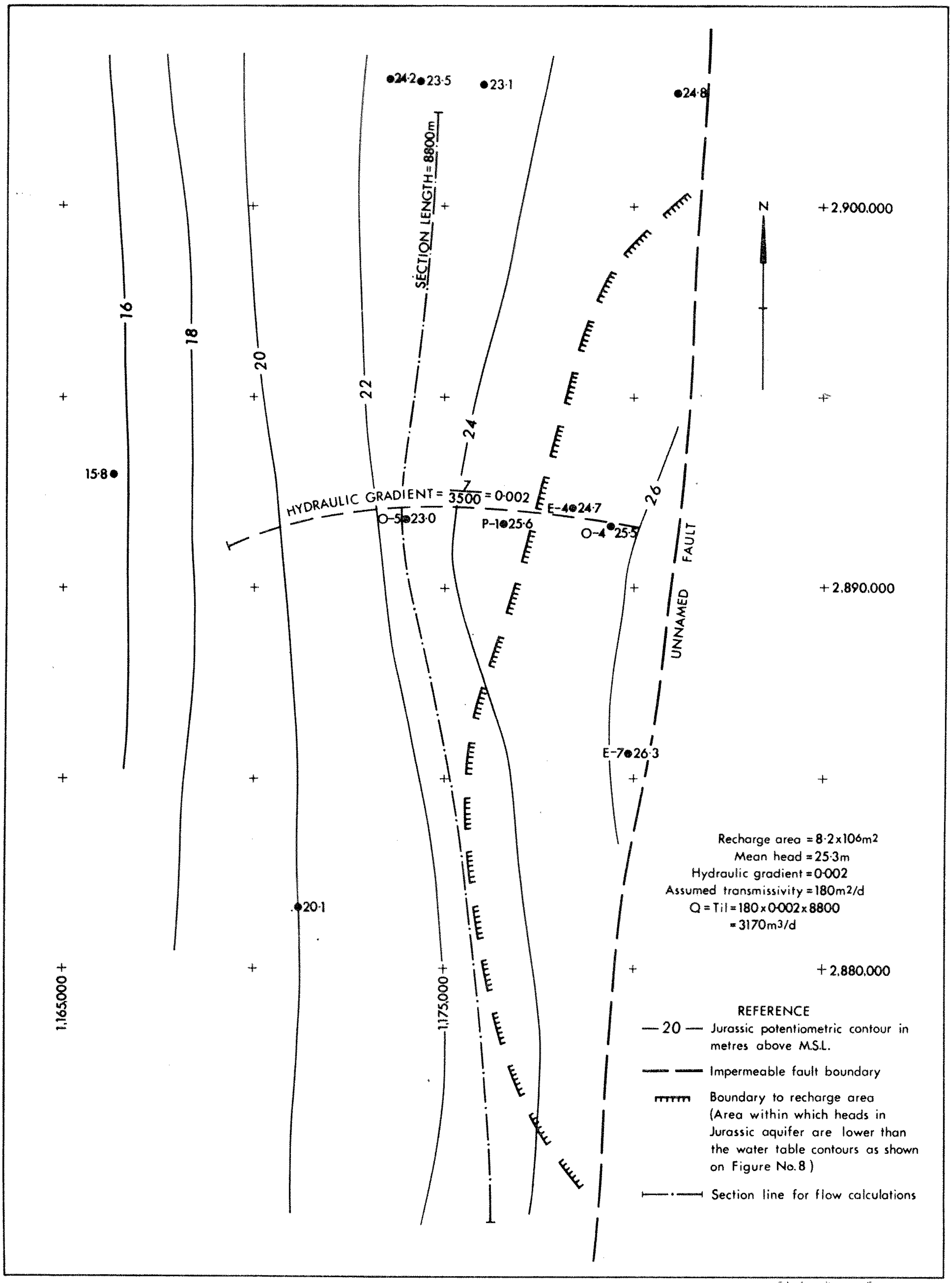

Figure 7. Potentiometric map for Jurassic aquifer prior to long term pump test.

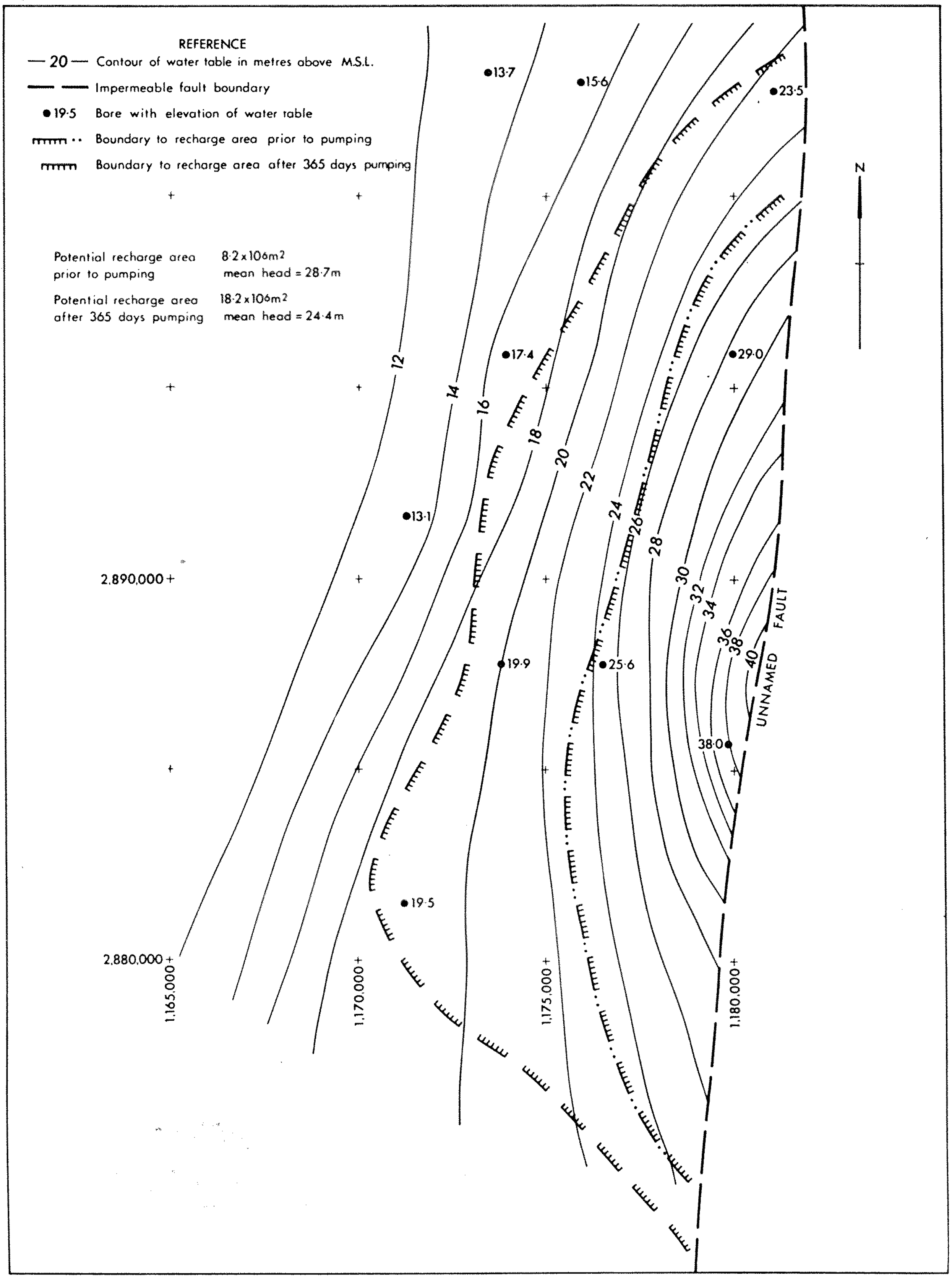

Figure 8. Contours of elevation of water table.

THEORETICAL AQUIFER RESPONSE.

With a knowledge of the hydrological setting it is possible to discuss the behaviour of a pumping bore having screens set in the Jurassic or Cretaceous aquifers. Hantush (1964) has given the mathematical theory of flow under conditions similar to those pertaining at Pinjarra. The following equations are all taken from his work and are not individually acknowledged.

The aquifers being pumped are confined, and from what is known of the geology of the area it can be said that they are "leaky".

Hantush, (1964) states, that for pumping bores in such systems "the discharge . . . is supplied from local storage in the main artesian aquifer, as well as leakage, if any, originating in and/or passing through the semipervious confining beds. The confining beds of an artesian aquifer are rarely completely impermeable. Frequently, the artesian sand is confined above and/or below by a semipervious elastic clay or silt that yields significant amounts of water from storage. In certain instances, the water released from storage in these semipervious layers is much more significant than that released from storage in the artesian sand they confine. These semipervious layers may . . . be over/or underlain by aquifers whose capacity for lateral flow is sufficient that the head distribution therein is not affected by flow conditions in the main artesian aquifer in spite of the leakage from or into them".

The flow equations for wells discharging from confined aquifers have been detailed by Hantush and are summarized here. For a short time interval $\left(t < \frac{S'b'}{10K'}\right)$ and with steady flow, the general flow equation for confined aquifers is:

$$S = (Q/4\pi T)\ H(u,\beta) \quad \ldots \quad (1)$$

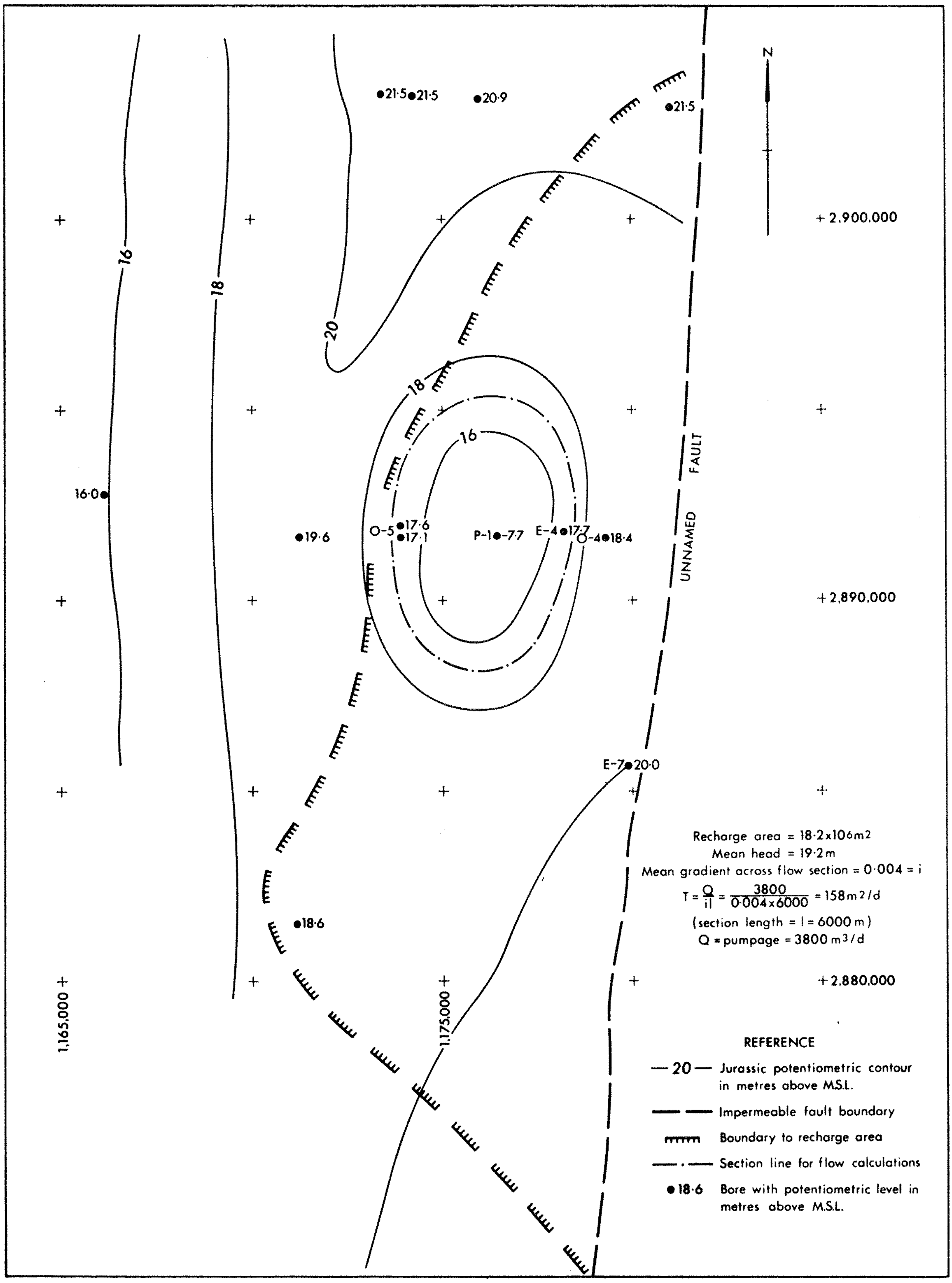

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Figure 9. Potentiometric map for Jurassic aquifer after 365 days pumping.

37038 (2)

The equation holds whether leakage is from elastic storage in overlying or underlying beds, or if the leakage is by flow through semipervious confining beds without a contribution from elastic storage. If there is no leakage then $\beta = O$ and the function of $H(u,\beta)$ is identical with the Theis well function $W(u)$.

Hantush has also provided solutions for long times:

(i) Leakage with storage in the semipervious layer

where $r_w/b < 0.1$

and $t > 2b'S'/K'$

and $t > 30 \ \delta_1 r^2_w/\nu \left\{1 - (10r_w/B)^2\right\}$

$$s = (Q/4\pi T) \ W \ (\delta_1 u, r/B) \quad \text{.... ....} \quad (2)$$

(ii) Leakage without storage in the semipervious layer

$$s = (Q/4\pi T) \ W(u, r/\beta) \quad \text{.... ....} \quad (3)$$

For both long time solutions (equations 2 and 3), as time becomes effectively long the yield of the well is sustained almost entirely by leakage through the semipervious layer (a steady state of flow will be essentially realized) and the steady drawdown is given by

$$s = (Q/2\pi T) \ Ko(r/B) \quad \text{.... ....} \quad (4)$$

which is the Jacob (1946) steady state leaky artesian equation.

This very brief summary of the principal radial flow equations for confined aquifers is given to point out some of the problems that must be faced before pump test data from confined aquifers can be analysed. At Pinjarra it is almost certain that there is leakage to the Jurassic aquifer. It follows then that aquifer behaviour cannot be analysed by the Theis equation or the Jacob straight line modification. If very early time data are available then equation 1 could be used, or if late time steady state data are available, analysis by equation 4 could be used. There are some difficulties in applying equations 2 and 3 (mainly in establishing which is applicable) and their use would not be strongly recommended at Pinjarra. In those cases where the Theis or Jacob modifications have been used for analysis, the resultant calculated transmissivites will be too large.

JURASSIC AQUIFER TRANSMISSIVITY

An estimate of aquifer transmissivity can be made by flow net analysis of the mapped cone of depression (Fig. 9). The resultant value (158 m^2/d) should be slightly too high because of leakage to that portion of the aquifer between the section line used for the calculation, and the pumping bore, P-1.

Data collected during a long term pump testing have also been analysed using standard type curves. The time-drawdown observations have the apparent form of the Theis curve and if so matched, as demonstrated in Figure 10, yield a resultant transmissivity of 348 m^2/d and a storage coefficient of 3.48×10^{-4}. The data show that after 365 days pumping the aquifer had not reached an equilibrium state and that drawdowns were still increasing.

Curve matching to the Theis non-leaky curve obviously implies that there is no leakage and as long as drawdowns continue, the pumped water is being derived from storage in the induced cone of depression. The volume of the cone of depression (Fig. 9) is approximately 170×10^6 m^3 after 365 days pumping. The derived storage coefficient is 3.48×10^{-4}, so the volume of water abstracted from the cone of depression in the pumped aquifer should be $3.48 \times 10^{-4} \times 170 \times 10^6 = 5.92 \times 10^4 \, m^3$ of water. Pumpage during the same period was $3\,800 \times 365 + 1.39 \times 10^6 \, m^3$. The proportion of pumped water taken from the cone of depression is $5.92 \times 10^4/1.39 \times 10^6$ or approximately 4 per cent of the total pumpage. Therefore, 95 per cent of the pumped water must have come from sources other than that cone. This can only be by leakage from water bearing beds above or below those pumped. In this case the drawdown pattern cannot be described by the Theis curve and another form of analysis must be used.

On Figure 11, observed drawdowns from four observation bores are shown matched to the $H(u,\beta)$ "leakage from storage" curves (equation 1 of previous section). A reasonable match can be made, and the resultant transmissivity is 180 m^2/d which is in fair accordance wth the flow net result of 158m $^2/d$. The 180 m^2/d result has been used in subsequent calculations to illustrate some features of the aquifer's response to long term pumping.

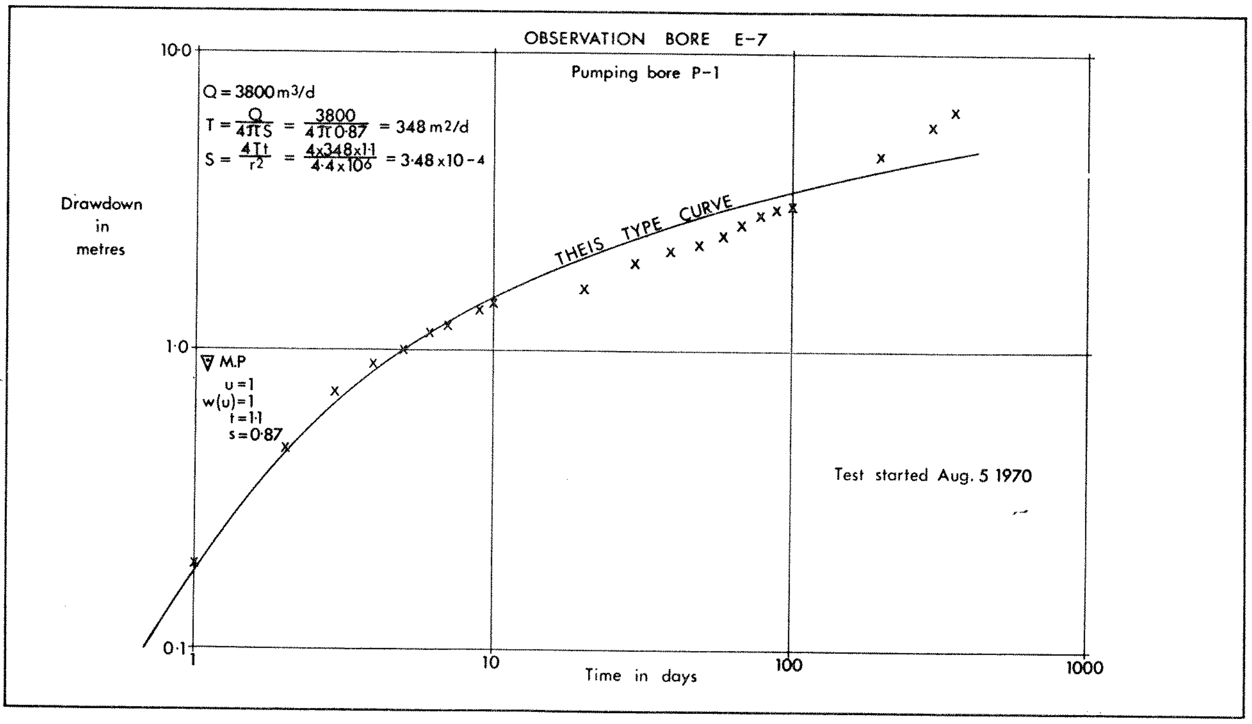

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Figure 10. Pump test analysis of observation bore E-7 by Theis Curve.

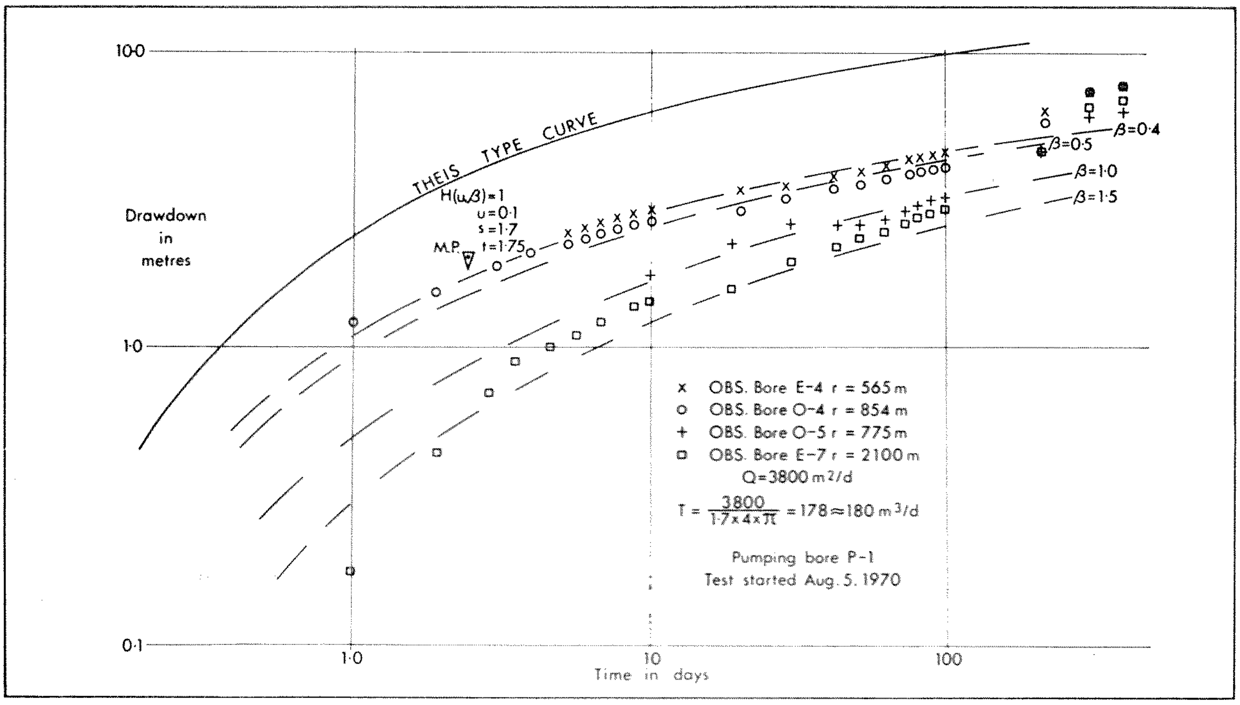

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Figure 11. Pump test analysis of observation bores E-4, 0-4, 0-5 and E-7, by Hantush H(u,β) " leakage from storage " curves.

BOUNDARY EFFECTS

At Pinjarra, faults and lithological variations impose an extremely complex set of boundary conditions upon the aquifer's response to pumping. In a previous section the theoretical aquifer response has been discussed. As the period of pumping increases, the complex boundary conditions will steadily cause a divergence between the theoretical and actual response; the net effect being that actual drawdowns will be larger than those calculated. There is no possibility of calculating such effects by using the presently available data. Instead, in these notes, some observed changes in the aquifer's status are presented and an attempt is made to provide some meaning to these observed changes.

SOURCE OF PUMPED WATER

Production Bore P1 (Fig. 7) was pumped at a rate of 3 800 m^3/d for 415 days from 5 August 1970. These notes relate to the observation bore data collected during the first 365 days of that prolonged pumping test. The bore is screened in Jurassic sands from 132.5 to 137.7 and from 166.4 to 187.1 m below the natural surface.

During the early stages of pumping, the water moving to the bore is from elastic storage in the screened aquifer. As heads reduce and a cone of pressure reduction develops, leakage is induced from underlying and overlying beds. If the confining beds (both above and below, it must be stressed) have hydraulic conductivities very much lower than that of the pumped aquifer, then a widespread cone of depression with large changes in head will develop in the screened aquifer. It has already been shown that the reduction of storage in the main aquifer is small, most of the pumped water being taken from storage in the overlying and underlying beds. At the end of 365 days pumping, the cone of depression was still growing. This shows that the aquifer had not reached equilibrium with vertical percolation, but was still drawing upon elastic storage.

Pressure heads in the sediments overlying and underlying the main aquifer will progressively change, as water is given up from elastic storage. If the vertically changing heads intercept a zone with sufficiently high lateral transmissivity, then lateral flows in that zone may be sufficient to satisfy the vertical leakage and the system will stabilize in an equilibrium condition. This zone may or may not be the water table aquifer in the surficial sediments.

Since the induced cone of depression was still growing after 365 days pumping, the vertical permeabilities were likely to be small. The pumped water was therefore being mined from storage, and during that period there had been no direct capture from the water table.

JURASSIC AQUIFER RECHARGE

By comparing the Jurassic aquifer potentiometric map with the water table contour map (Figs. 7 and 8) the potential area of recharge prior to pumpage from the Jurassic aquifer can be delimited. Only where heads in the Jurassic aquifer are lower than the water table can there be recharge to the lower aquifer.

Lateral flow, in the Jurassic aquifer, from the area which can be recharged by the water table can be computed by application of Darcy's Law. With a transmissivity of 180 m^2/d, lateral flow is 3 170 m^3/d (Fig. 7). This flow must come from the water table and is the total recharge to the Jurassic aquifer in the investigated area under natural conditions.

The potential area of recharge is defined on Figures 7 and 8, and for these areas the mean heads have been calculated by planimetry:

	Recharge area prior to pumpage	Mean head
Water table aquifer	8.2 x 10^6 m^2	28.7 m
Jurassic aquifer	8.2 x 10^6 m^2	25.3 m

Thus, the lateral flow of 3 170 m^3/d is from an area of no more than 8.2 x 10^6 m^2 and is in response to a head difference of 28.7—25.3 = 3.4 m. The Jurassic aquifer is about 150 m below the water table. The average vertical permeability through this thickness is therefore:

$$K' = Qb/\Delta hA$$
$$= (3\,170 \times 150) / (3.4 \times 8.2 \times 10^6)$$
$$K' = 1.7 \times 10^{-2} \text{ m/d}$$

Figure 9 shows the potentiometric map for the Jurassic aquifer after 365 days pumping. By comparison with the water table potentiometric map (Fig. 8) the new increased area of potential recharge can be defined (Fig. 8 and 9). The new area is 18.2 x 10^6 m^2 and the new mean head difference between the Jurassic aquifer and the water table is 24.4—19.2 = 5.2 m.

If leakage is directly proportional to the area and head difference between the aquifers, then the potential increase in recharge is: $A_2 H_2/A_1 H_1 = 18.2 \times 5.2 \times 10^6/8.2 \times 3.4 \times 10^6 = 3.4$ where the subscripts 1 and 2 refer to time 1, and time 2. Therefore the potential recharge after 365 days pumping would be $3.4 \times 3\,170 = 10\,760$ m³/d, a value which is unrealistic because it is impossible for the induced leakage to be greater than the pumped rate of 3 800 m³/d. Hence, there must be an error in the data used, or in the assumptions made in the argument.

The estimate of 180 m²/d transmissivity could be too high, but would have to be reduced to about 50 m²/d to account for the above discrepancy. This implies that the Jurassic aquifer has a hydraulic conductivity of less than 2 m/d. It is hardly likely that the sands described as the Jurassic aquifer could have such a low hydraulic conductivity. The calculation of transmissivity for the cone of depression on Figure 9 indicated that the aquifer transmissivity might be slightly less than 158 m²/d. This is equivalent to a hydraulic conductivity of about 6 m/d which seems reasonable.

The most likely explanation would be that at Pinjarra, vertical leakage is not uniform and is not linearly proportional to development of a cone of depression in the Jurassic aquifer. It is possible that leakage is restricted to one or several very small localised areas; unless a pumping bore is sited in or very near that area it will be difficult to substantially increase the rate of leakage unless an extremely large cone of depression is developed in the Jurassic aquifer.

If a transmissivity of 150 m²/d is accepted as being more suitable for the Jurassic aquifer then:

$$\text{throughflow} = \text{recharge} = 150 \times 0.002 \times 8\,800 = 2\,640 \text{ m}^3/\text{d}.$$

If it is further assumed that the area of vertical recharge to the Jurassic aquifer is fixed by some geological control, then the mean head differences can be found for the original potential recharge area, prior to and after 365 days pumping.

Recharge area	Mean head for potential recharge area
Water Table	28.7 m (Fig. 8)
Jurassic aquifer prior to pumping	25.3 m (Fig. 7)
Jurassic aquifer after 365 days pumping	19.2 m

The increased head differential created by pumping is therefore:

$$\frac{28.7 - 19.2}{28.7 - 25.3} = \frac{9.5}{3.4} = 2.79 \text{ times the initial}$$

one.

If the transmissivity were as low as 150 m²/d (see above) then recharge was 2 640 m³/d. With an increased head differential of 2.79 times the initial one, recharge should rise to 7 400 m³/d i.e. 2.74 x x 2 640 m³/d. This is well in excess of pumpage and must therefore be incorrect. The area in which recharge takes place, must therefore be smaller than the potential recharge area of 8.2×10^6 m² shown on Figures 7 and 8.

The Jurassic aquifer potentiometric contours show that recharge may originate from the vicinity of bore E-7, near the unnamed fault boundary (Fig. 7). If it is assumed that head changes at that bore are representative of the actual recharge area, then prior to the onset of pumping the head differential between the water table and the Jurassic aquifer was $38.0 - 26.3 = 11.7$ m. After 365 days pumping the head differential was increased to $38.0 - 20.0 = 18.0$ m. This is equivalent to potential increases in recharge of (18.0/11.7) 2 640 = 3 980 m³/d, which is only slightly greater than the pumpage. The head differential used would be applicable to a very small area (approximately that bounded by the 36 m water table contour and the unnamed fault on Fig. 8). The calculated increase in leakage is sufficiently close to the pumpage rate to show that recharge to the Jurassic aquifer must be limited to a small area in the vicinity of bore E-7. If recharge is assumed to take place over an area larger than that bounded by the 36 m water table contour, then it will be found that the cone of depression should have reached equilibrium before the end of the 365 day pumping period.

CONCLUSIONS

The Jurassic aquifer has a transmissivity of about 150 to 180 m²/d in the vicinity of the pumping bore. Elsewhere it may be lower.

Aquifer recharge and throughflow is estimated to be about 2 640 m³/d.

Recharge to the Jurassic aquifer is limited to an area much smaller than the potential recharge area of 8.2×10^6 m².

During the prolonged pumping test, production bore P-1 drew most of its water from storage in sediments overlying and underlying the aquifer. There is no evidence to show that there has been any significant capture of additional recharge from the water table.

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HYDROGEOLOGY OF THE MANDURAH – PINJARRA AREA

by D. P. Commander

ABSTRACT

Eighteen exploratory water bores were drilled in the Mandurah-Pinjarra area under Government drilling programmes between 1962 and 1969, and a further twenty-three were drilled for industry east of Pinjarra between 1969 and 1972. These bores have provided information on local stratigraphy, water quality, yield and movement. Two major geological formations are present in the area, the Lower Jurassic Cockleshell Gully Formation, and the Lower Cretaceous Warnbro Group. A threefold division of the latter correlates broadly with the Gage Sandstone, the South Perth Shale, and the Leederville Formation of the metropolitan area. The dip of those beds and the slope of the basal Cretaceous unconformity are generally westwards.

A deep sand-filled Quaternary channel, that cuts through the Leederville Formation, has been recognized in one bore and may have a considerable effect on local hydrology.

Variable quantities of potable water containing less than 1 000 ppm TDS have been located under much of the area, and large supplies of brackish water, from 2 000 to 4 000 ppm TDS, are also present. Generally better supplies and lower salinity waters are available in the east of the area.

One intake area has been found to the east of Pinjarra and another is believed to exist in the North Dandalup area. Water movement is in a general westerly direction from these intakes.

INTRODUCTION

The Mandurah-Pinjarra area is about 70 km south of Perth, on the low lying coastal plain. Farming is the dominant land use, and most of the land has been cleared for pasture. The alumina refinery east of Pinjarra is the only heavy industry.

Numerous shallow bores and wells are used by private landholders for domestic, stock and irrigation purposes, and a few deeper bores (to 150 m) have been drilled where larger supplies are required. Mandurah receives water from the Yunderup bores near Ravenswood, and groundwater is also utilised by the alumina refinery.

Until 1962 there was little information on the subsurface geology and hydrology of the area. The nearest deep bores were in the metropolitan area, until drilling by the Geological Survey between Byford and Rockingham commenced in 1961 (Berliat, 1964). Seismic surveys by West Australian Petroleum Pty. Ltd. culminated in the deep oil exploratory well Pinjarra No. 1 (Jones and Nicholls, 1966).

Exploratory drilling for town supply water was commenced in 1962 near the coast at Mandurah. Domestic quality water was first located near Ravenswood (Emmenegger, 1964) and by 1969 a total of eighteen bores had been drilled with an aggregate depth of nearly 4 000 m. These bores range in depth from 610 m (Mandurah No. 1 or M-1) to 96 m (M-15); eleven bores were cased for observation and the remaining seven abandoned.

Detailed correlations between the bores have been made on the basis of lithology, age (by palynology) and the gamma-ray logs. Water samples were collected and static water levels measured wherever possible and resistivity logs run in the rotary drilled holes. Nearly 100 water samples have been chemically analysed.

A further twenty-three deep bores (Pinjarra E-, O-, OW- and P- series) with an aggregate depth of over 5 000 m were drilled to the east of Pinjarra as part of a detailed study of the groundwater being used for the alumina refinery (Fig. 12).

PHYSIOGRAPHY AND CLIMATE

The Swan Coastal Plain has been divided into a number of geomorphic elements which parallel the present coastline (Woolnough, 1920; McArthur and Bettenay, 1960). The Ridge Hill Shelf forms a narrow belt up to 4 km wide at the base of the Darling Scarp and consists of leached and ferruginized beach sands of the Yoganup Formation and Ridge Hill Sandstone. The Pinjarra Plain west of the Ridge Hill Shelf is essentially flat lying, underlain by alluvial sands and clays of the Guildford Formation. To the west of, and overlying the Pinjarra Plain, are three sand dune systems; from east to west the Bassendean Sand, the Coastal Limestone and Safety Bay Sand. The Coastal Limestone is a leached and lithified calcarenite that forms a ridge up to 60 m high.

The average rainfall is about 800 mm per annum, falling mainly in the winter months, April to September. There is no surface drainage in the sand dune systems, but a number of lakes represent the water table. The soils of the Pinjarra Plain become waterlogged and swampy in the winter. The Murray River is the only major river in the area, having its headwaters in the Wheat Belt and an average salinity in excess of 2 000 ppm TDS. Three smaller freshwater rivers, the Serpentine, North and South Dandalup Rivers have their headwaters in the Darling Ranges, but have very low flows in the summer. Several small ephemeral streams drain the Darling Scarp, and all streams reach the sea through Peel Inlet which truncates the Coastal Limestone.

GEOLOGY

The Perth Basin is an elongated sedimentary trough 1 000 km long, bounded by the Darling Fault along the western edge of the Precambrian Shield. The Mandurah-Pinjarra area lies in the southern part of the basin where the thickness of Mesozoic sediments is in excess of 10 000 m.

There are no surface outcrops of Mesozoic sediments in the Mandurah-Pinjarra area as they are generally covered by Quaternary deposits. Early

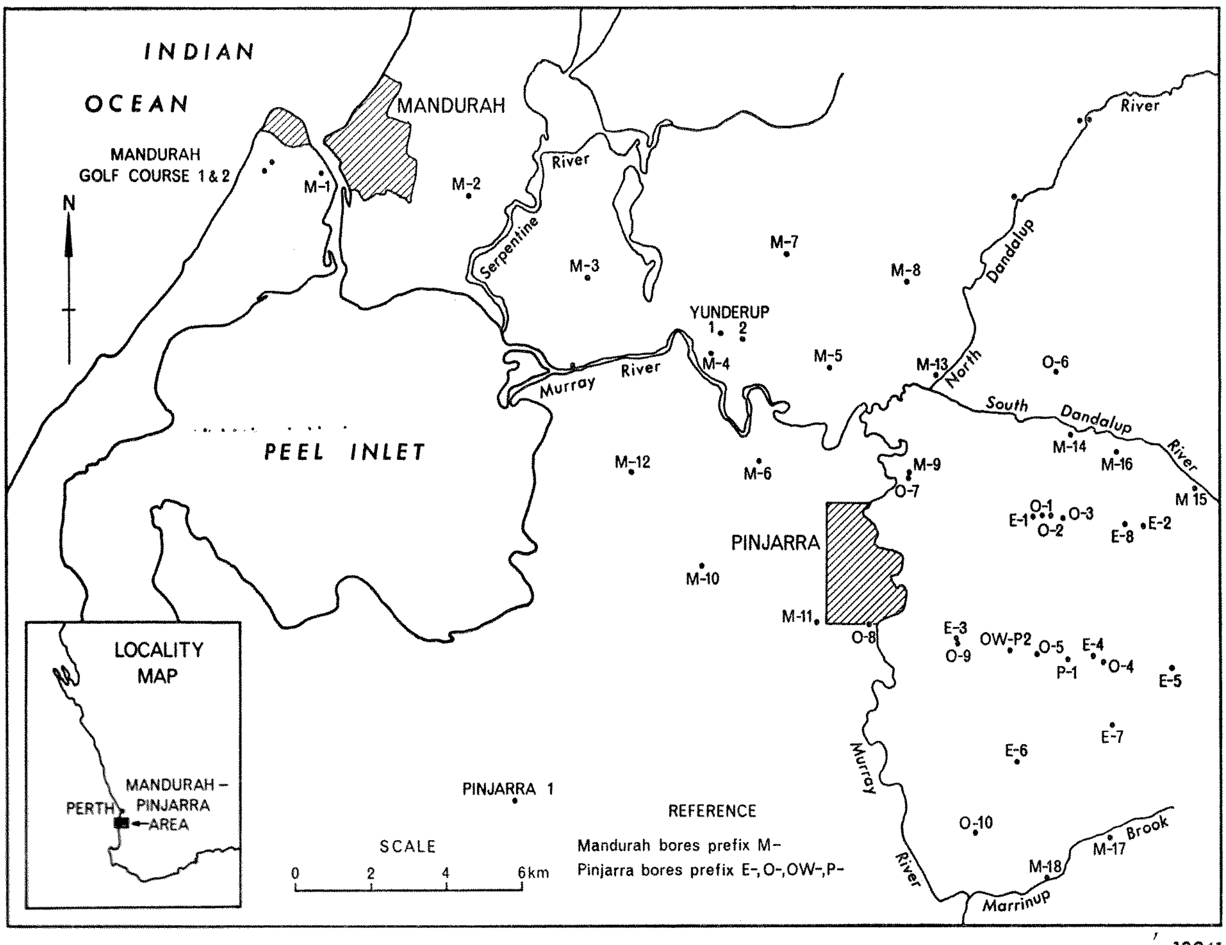

Figure 12. Mandurah–Pinjarra area—bore location map.

Cretaceous and early Jurassic sediments have been encountered in water bores, and Pinjarra No. 1 exploratory oil well bottomed in Triassic after penetrating 2 200 m of early Jurassic sediments. The intra-Neocomian unconformity cuts out the Upper Jurassic so that the Lower Cretaceous Warnbro Group lies directly on the Lower Jurassic Cockleshell Gully Formation. A simplified stratigraphic succession is given in Table 1.

TABLE 1. STRATIGRAPHY OF THE MANDURAH-PINJARRA AREA

Age	Group/Formation/Member
Quaternary	Safety Bay Sand Coastal Limestone Bassendean Sand Guildford Formation Yoganup Formation Ridge Hill Sandstone Un-named sand (deep channel filling)
UNCONFORMITY	
Lower Cretaceous	Warnbro Group: Leederville Formation South Perth Shale Gage Sandstone Member
UNCONFORMITY	
Lower Jurassic	Cockleshell Gully Formation
Middle to Upper Triassic	Lesueur Sandstone

Seismic surveys indicate substantial faulting in the Cockleshell Gully Formation and various dip directions. By contrast the Warnbro Group has a gentle westerly dip, although steeper dips occur near the Darling Fault where Lower Jurassic sediments are upfaulted.

The geology has been described by Lowry (1965), Low (1971) and Playford and others (in press).

COCKLESHELL GULLY FORMATION

Sediments of Lower Jurassic age encountered in the area are correlated with Cattamarra Coal Measures Member of the Cockleshell Gully Formation in the Northern Perth Basin.

The formation is an unconsolidated continental sand-shale succession, the sands being mostly well sorted coarse-grained quartz with minor feldspar and accessory garnet and pyrite. Thin coal seams are often present. The shale units vary from unlaminated siltstone-mudstones to fissile micaceous shales. The colour is usually dark grey, but near the unconformity there appears to be a weathered zone where mottled red-brown to yellow colours are common. The bedding is very well differentiated and the gamma-ray logs have a distinct character. The shale units do not exceed 50 m in thickness except in the upfaulted block adjacent to the Darling Fault where a shaley sequence over 150 m thick was encountered. The sand and shale units tend to be lens shaped and detailed correlations are not possible except in very closely spaced bores.

WARNBRO GROUP

The Warnbro Group can be subdivided into three distinct units on the basis of lithology, facies and age (Emmenegger, 1964). The lower unit is equivalent to the Gage Sandstone Member of the South Perth Shale, and the middle and upper units are equivalent to the rest of the South Perth Shale and the Leederville Formation respectively. The South Perth Shale equivalent has a different lithology to the type section in the metropolitan area.

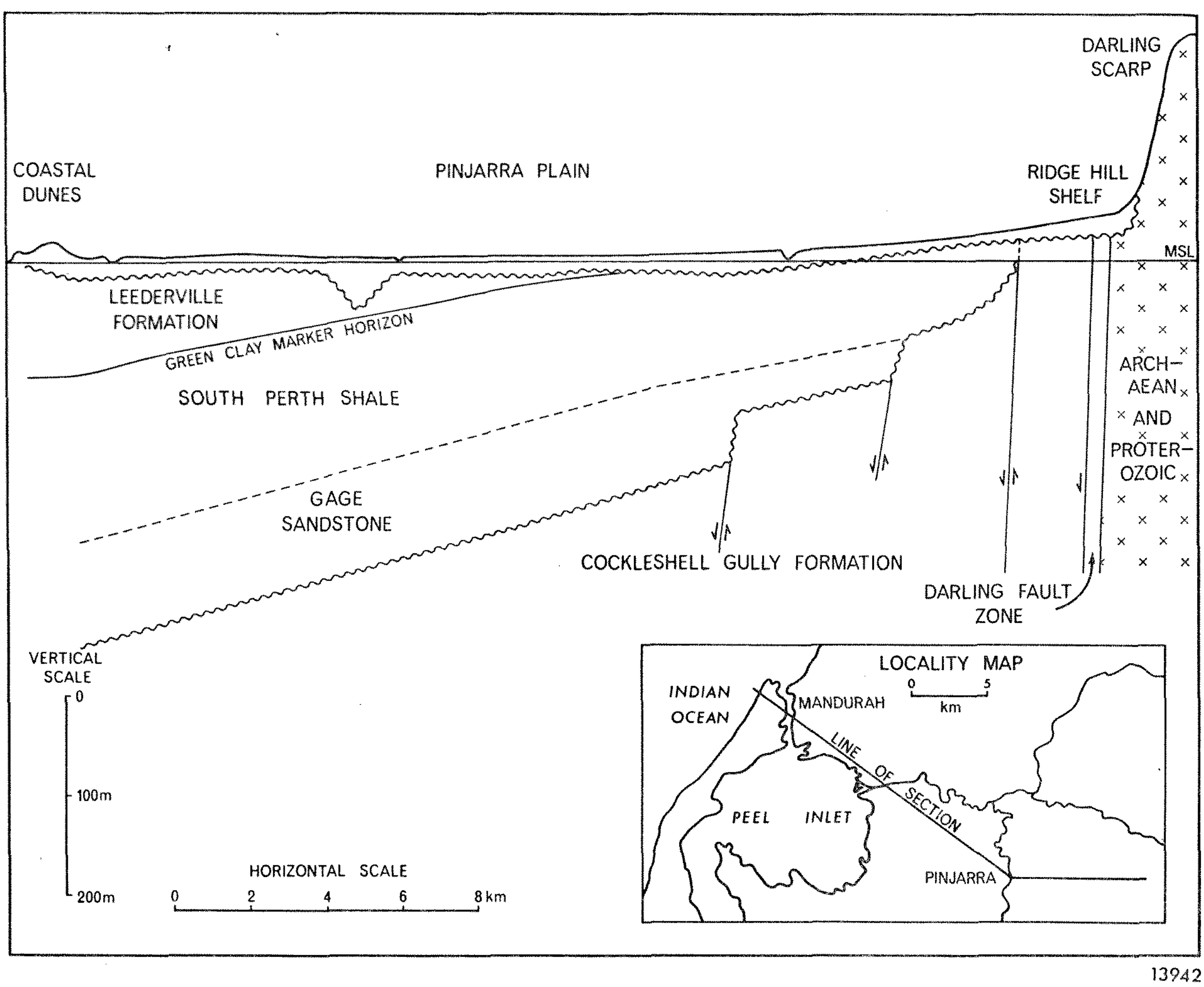

Figure 13. Mandurah–Pinjarra area—geological cross section.

Gage Sandstone

This is an alternating sand-shale succession, continental or near shore, very similar in lithology to the underlying Cockleshell Gully Formation. It is difficult to distinguish between the two on the gamma-ray logs. The age of the Gage Sandstone, however, is Neocomian, and it was deposited in depressions on an uneven surface eroded across Lower Jurassic sediments (Fig. 13). The thickness of the member varies from over 100 m at Mandurah to 40 m at Pinjarra, and it wedges out 3 km east of Pinjarra.

South Perth Shale equivalent

The South Perth Shale equivalent in the Mandurah-Pinjarra area is a succession of interbedded thin sands and silts, contrasting with the predominantly shaley type section in the metropolitan area. The thickness decreases from 170 m at the coast (M-1) to 140 m near Pinjarra. East of Pinjarra the top of the formation has been eroded and Quaternary sediments rest directly on it.

This formation can be further subdivided into a lower part, mainly siltstone, mudstone and minor sandstone, and an upper part characterised by a high concentration of calcareous material, shells, pebble beds (igneous rocks) and glauconite. The top of the formation is marked by a bright green glauconitic clay which is readily identifiable in boreholes. Individual beds are generally laterally continuous, although to the east of Pinjarra correlations are difficult.

The South Perth Shale was laid down in a predominantly marine environment with littoral intervals; beach sands were recorded at 160 m in Mandurah No. 5 bore.

Leederville Formation

The Leederville Formation occurs mainly west of Pinjarra and has been eroded to the east. The thickest section was encountered in the most westerly bore at Mandurah Golf Course, where the thickness is 117 m. The lithology is a sequence of interbedded siltstones, shales and sandstones which are grey, dark grey to brown in colour. The bedding is well differentiated in M-2 but becomes more silty in M-1; individual beds can be correlated between the two bores. In M-3 the whole section of the Leederville Formation has been eroded by a deep Quaternary channel.

QUATERNARY

Sediments of Quaternary age lie unconformably on the Warnbro Group and directly on the early Jurassic and Precambrian rocks in the extreme east. These deposits are colluvium, alluvium, littoral and eolian sands, the lithology and relationship of which have been described in Low (1971) and Morgan (1969). Mandurah No. 3 bore encountered an exceptional thickness of Quaternary sediments to a depth of 65 m below sea level (Emmenegger, 1964). These coarse well sorted sands probably represent an infilling of a river channel cut during a period of very low sea level.

HYDROGEOLOGY

EASTERN FAULT BLOCK

The narrow fault block of Lower Jurassic sediments immediately west of the Darling Fault (Fig. 13) appears to be a very shaley part of the Cockleshell Gully Formation, and no aquifers of appreciable extent were encountered in Mandurah 15 and Pinjarra E-2. The water in these bores is unconfined, and the potentiometric head declines with depth. The water level in M-15 is about 19.5 m above sea level, with a seasonal range of 1 m, and in E-2 the water level is 18 m. M-15 is slotted from 15 m above to 55 m below sea level and E-2 is screened at a depth of 100-130 m below sea level.

The western faulted boundary acts as a hydraulic barrier, and the potentiometric surface on the west side of the fault is more than 7 m higher (Fig. 14). This contrast in potentiometric levels is associated with a complementary salinity contrast as water in M-15 and E-2 has 2 400-4 000 ppm TDS while in E-8, to the west of the fault, it is only 420 ppm TDS.

Water movement within this fault block is probably very slow, the salinity is fairly high, and only small supplies are available from the limited aquifers. E-5 was drilled to a depth of 148 m and did not encounter any productive aquifers. Further details are given in Commander (in prep.)

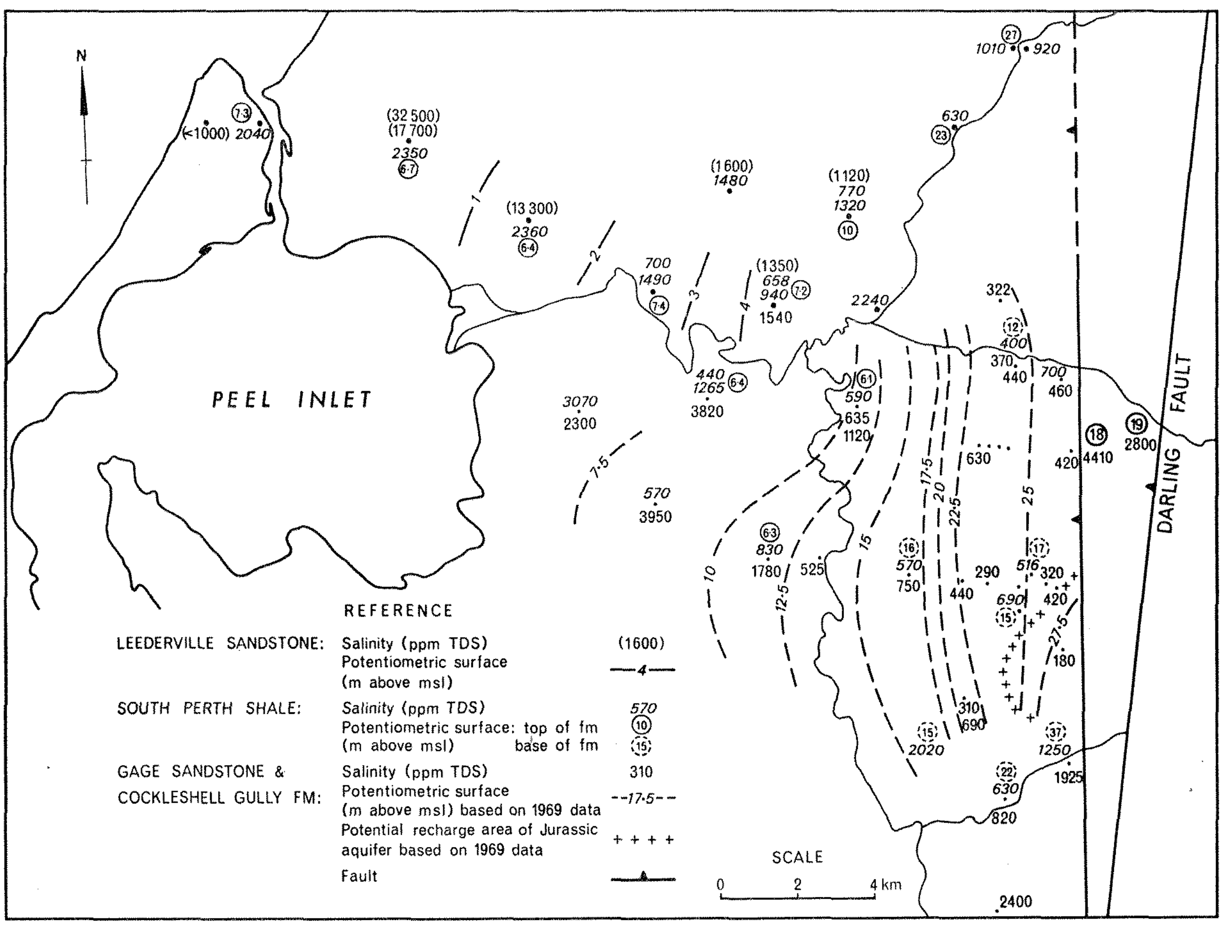

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Figure 14. Mandurah–Pinjarra—hydrogeology.

COCKLESHELL GULLY FORMATION AND GAGE SANDSTONE

The similarity of lithology in both the Cockleshell Gully Formation and the Gage Sandstone is reflected in a similarity in hydrological characteristics.

An intake area to these aquifers has been identified around Pinjarra E-7 where the potentiometric surface in the Cockleshell Gully aquifers is 27 m above sea level (Fig. 14) and 8 to 13 m lower than the water table. The salinity of less than 200 ppm TDS in E-7 is the lowest encountered in any of the Mesozoic aquifers in the Mandurah-Pinjarra area. Movement of water takes place from E-7 in a westerly direction. The salinity increases with increasing distance from the recharge area, becoming 500 ppm just east of Pinjarra and climbing steeply to 3 950 ppm in M-10 4 km west of Pinjarra. Over a large area the potentiometric surface is above ground; M-14 has an artesian head of 11 m. A region of steep groundwater gradients exists at the eastern margin of the Gage Sandstone.

In all the bores, except E-7 and E-6, the potentiometric head increases with depth and gradients of 1 m per 10 m depth are maintained across the shale units. The salinity also tends to increase with depth and in general the best quality water is encountered at the top of the formation, just below the unconformity.

The amount of fresh water, less than 500 ppm, is large in the aquifers to the east of Pinjarra, and individual bores are capable of producing 4 000 m^3 per day. However, the amount of recharge to the Mesozoic aquifers each year from rainfall is small compared with the total amount of water in storage. Forth (1974) discussed the recharge to these aquifers.

SOUTH PERTH SHALE

The sand beds in the South Perth Shale are fairly thin compared with the Cockleshell Gully and Gage Sandstone aquifers, and are interbedded with silts and shales. These thin sand beds, however, are laterally continuous and are the most important sources of underground water for domestic and farm purposes.

The potentiometric head increases with depth and a head difference of 4 m between the top and the bottom of the formation was encountered in M-9. Aquifers in the formation are confined by the green clay and other shale beds immediately below. The salinity increases westwards and is highly variable with depth. Water of less than 1 000 ppm TDS is generally available east of M-8, M-4 and M-10, and probably the cleaner the sands the better quality. In M-5 there is a sharp increase in salinity at the contact with the Gage Sandstone, the quality deteriorating from 1 200 ppm to 3 500 ppm TDS over a depth of 15 m.

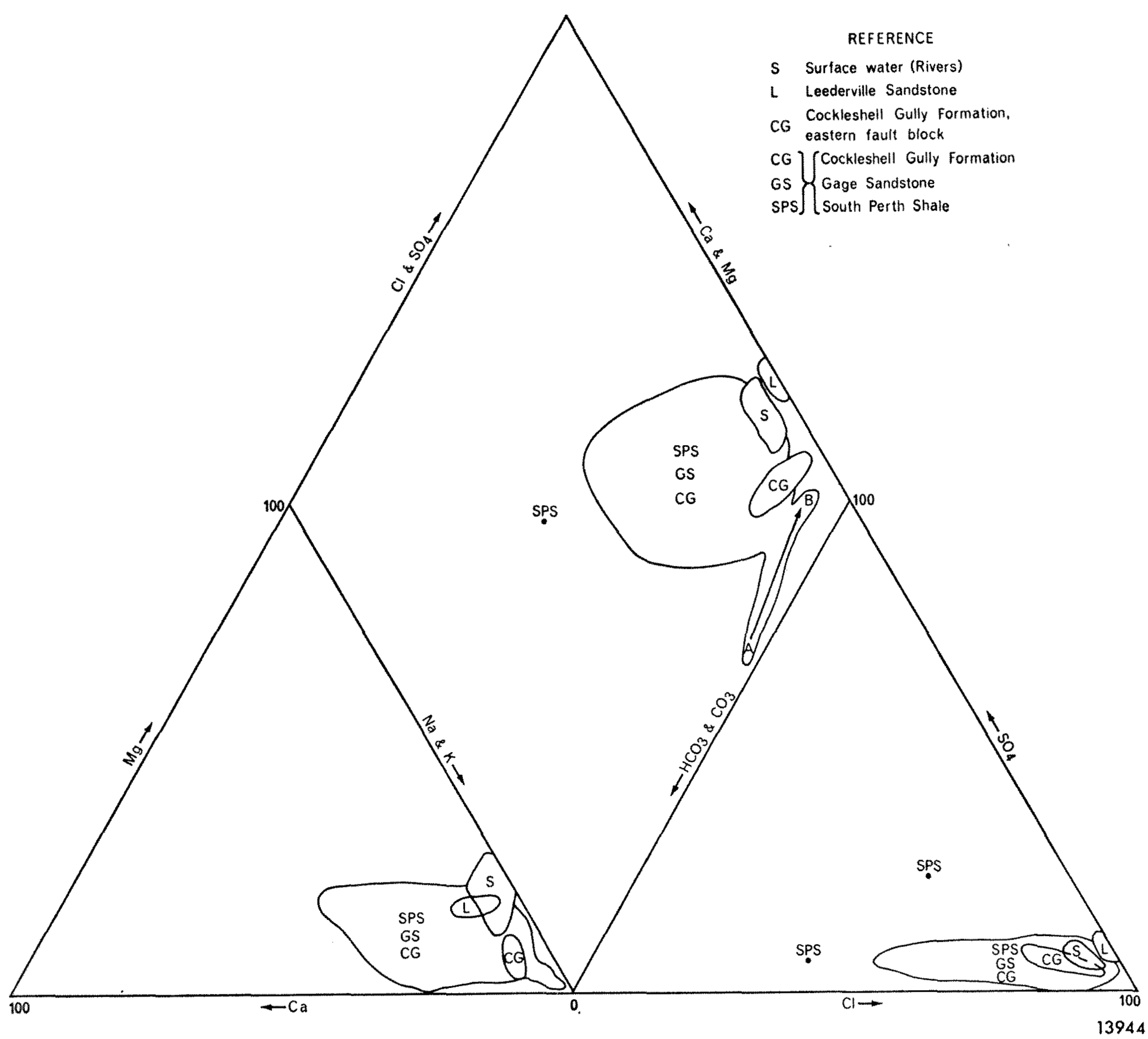

Figure 15. Trilinear plot of chemical analyses, from the Mandurah–Pinjarra area.

Recharge to these aquifers takes place in the North Dandalup district, where the potentiometric surface is over 25 m above sea level, and also by upward movement from the Cockleshell Gully Formation east of Pinjarra. Groundwater gradients in these districts are as steep as 5×10^{-3}, but west of Pinjarra the gradient is very slight, the potentiometric levels for the top of the formation in both M-5 and M-1 being just over 7 m above sea level although they are 14 km apart.

LEEDERVILLE FORMATION

The Leederville Formation has not been thoroughly explored in the Mandurah area. The thick sand units form good aquifers but the salinity is very variable. At the coast, water of 1 200 ppm TDS has been obtained from the Mandurah Golf Course borehole No. 2. Farther inland at Mandurah No. 2 the water quality obtained was 17 000-32 000 ppm; this was probably due to the Quaternary channel in M-3 which also contains saline water. The extent of this saline water intrusion is not known. The potentiometric surface falls from 4 m at M-5 to near sea level at M-2, the gradient being in the region of 5×10^{-4}. Data collected from M-2 indicate that the potentiometric head declines with depth. Recharge probably takes place directly from the water table, and inflow to the Leederville Formation aquifers can occur both from the Quaternary channel and upwards from the South Perth Shale, especially if the Quaternary channel cuts through the green clay aquiclude at any point.

QUATERNARY

Small supplies of fresh water are generally available from the dune sands and coastal limestone (Morgan, 1969). Shallow groundwater near Peel Inlet and the Serpentine River is probably brackish or saline. The Quaternary channel which contains saline water at M-3 may contain fresher water inland. Further exploration would be necessary to determine the course of this channel.

HYDROCHEMISTRY

Over ninety chemical analyses have been made on bore waters and surface waters in the area, and percentages of the main ions present are plotted on a trilinear diagram (Fig. 15). These have been grouped together in the same aquifer classes described above.

All waters are predominantly sodium chloride, with lesser amounts of calcium, magnesium, potassium, sulphate and bicarbonate ions being present. Minor amounts of nitrate were found in M-10 and O-5, but only in an analysis from M-10 was any significant quantity present (51 ppm).

The trend shown from A to B on Figure 15 represents the changes in composition from analyses lower down in E-3 and E-6 through M-11 to M-10 and M-12. This difference in composition from the aquifers higher up in E-3 and E-6 and in the other bores in the Cockleshell Gully Formation probably indicates a different flow regime and recharge area. Also water from these bores has a significantly lower hardness than water of the same TDS content in the rest of the Cockleshell Gully Formation aquifers.

Water analyses from the upper part of the South Perth Shale show higher calcium/magnesium to sodium ratios than those from the lower part; this probably reflects the more calcareous nature of the upper part of the formation.

The analyses of saline water from the Leederville Formation and the Quaternary channel have a similar composition to that of sea water indicating a connection with the sea.

CONCLUSION

Four major groups of aquifers exist in the Mandurah-Pinjarra area. The narrow fault block of Lower Jurassic rocks adjacent to the Darling Fault contains limited aquifers with a water quality in excess of 2 400 ppm TDS.

The thick sands of the Cockleshell Gully Formation, just to the west of the fault block, contain a large quantity of pressure water, less than 500 ppm TDS, with an artesian head of up to 11 m. West of Pinjarra the quality of water in the Cockleshell Gully Formation and Gage Sandstone deteriorates to over 2 000 ppm TDS.

The South Perth Shale consists of thin aquifers which contain fresh water (less than 1 000 ppm) over most of the area, and is the major supplier for domestic, farm, and town supply purposes. The top of the South Perth Shale can be recognized by the green clay bed, and bores drilled below this are often artesian.

The Leederville Formation aquifers have not yet been fully explored, and so far only water of over 1 000 ppm TDS has been located. A region of saline water intrusion into the Leederville Formation is associated with the Quaternary channel.

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WEATHERING PROFILE OF GRANITIC ROCKS IN THE BORROW AREA OF THE PROPOSED LOWER WUNGONG DAM

by G. W. Marcos

ABSTRACT

Granitic rocks at Lower Wungong are leucocratic, medium-grained gneissic tonalities and granodiorites, probably of igneous origin. Their weathering profile is more than 17 m thick, mostly represented by laterites and a completely weathered kaolin horizon. This represents an advanced stage of weathering. Local deviations which are common both in sequence and thickness, can be attributed to geomorphological history, geological structures, underground water movements and dykes acting as barriers. The weathering profile mostly represents zones I, IIa and IIb of Ruxton and Berry (1957) grades VI and V of Little (1969), zones IVa and IVb of Chandler (1969), or grades VI and V of Fookes and Horswill (1969). The weathering profile follows the normal sequence for granitic terrain, and the kaolin horizon can be subdivided into upper, middle and lower divisions.

INTRODUCTION

More than 120 hollow augerholes were drilled and sampled in the proposed borrow area at Lower Wungong (Fig. 16). Samples were taken at 3 m intervals for soil testing. Soil samples from 81 holes were examined to (1) differentiate soils derived from granitic rocks from those derived from dolerite dykes, (2) determine the general weathering sequence of each rock type present in the area, and the vertical distribution in each hole thus enabling an approximate volume distribution to be made, (3) correlate between each soil type and its engineering behaviour. The latter data are to be used for embankment soil zoning, if needed.

The results of (1) confirmed the presence of dolerite dykes previously mapped (Fig. 16), and helped in their delineation. The results of (2) showed that the granitic weathering profile is represented by an old profile where the laterite and kaolin horizons are well developed, while the highly and moderately weathered horizons are rather thin. Table 2 could be regarded as an approximate volume percentage distribution of horizons in the granitic weathering profile.

TABLE 2. PERCENTAGE DISTRIBUTION OF HORIZONS IN THE GRANITIC WEATHERING PROFILE.

(Excludes massive laterite and shear zones)

Horizon	Percentage of weathered granitic profile	Horizon subdivisions	Percentage distribution of horizons
Laterite	17·5	gravel	40·5
		massive	excluded
		pisolitic	15·5
		gibbsitic	44·0
Completely weathered	69·5	upper kaolin	50
		middle kaolin	16
		lower kaolin	34
Highly weathered	13·0		

The results of (3) demonstrated lithological and mineralogical differences in the upper and lower parts of the kaolin horizon with a middle transitional division. Many differences are reflected in the corresponding engineering properties given in Table 3.

WEATHERING PROFILE

I. *LATERITE*

The laterite horizon can be subdivided into:

(a) Gravelly
(b) Massive
(c) Pisolitic
(d) Gibbsitic

(a) *Gravelly laterite* consists of ferruginous gravels in a sand, silt and clay matrix, and when transportation has occurred, it also contains humus. It is *in situ* on high ground, from which it has been transported to the depressions. The dry material is firm and crumbles under pressure, but in the wet state it is friable. It has poor to moderate grading, high permeability and a high dry density. As the gravelly laterite is essentially a transported soil in the borrow area, it has unpredictable variable and sometime undesirable engineering properties for use as embankment borrow material.

(b) *Massive laterite* occupies high ground on both sides of the Wungong river and at the top and east side of the "island". It is composed of well cemented ferruginous nodules and concentrations, that are subangular at the base and rounded on top. The cement is mostly siliceous ferruginous gibbsitic clay. Jointing is poor and excavation normally involves the use of explosives. Its dry density is high.

(c) *Pisolitic laterite* is composed mostly of plastic gibbsitic clay and silt, with lenticular ferruginous concretions. Quartz is present only as an accessory. The *in situ* material is friable when slightly moist, but the dry material is firm and strong. Normally it has a high plasticity index although instances of moderate plasticity may occur. It is slightly permeable *in situ* but when compacted is impervious. The dry density is moderate. The main Unified Soil Classifications (Earth Manual U.S.B.R.) to be expected are CH and MH, also CI and MI to a lesser extent.

(d) *Gibbsitic laterite in situ* is granular or silty. Quartz grains are rare, and if present are mostly medum or fine grained. *In situ* it has a moderate to high void ratio and fair permeability, but when compacted is impermeable. The dry density is moderate, and the U.S.C. laboratory classifications to be expected are mostly CH, CI and MH.

II. *COMPLETELY WEATHERED GRANITIC ROCKS*

These are represented by the kaolin horizon, the three divisions being established on the basis of clay, silt and platy-micaceous mineral content. The last is of an indefinite mineralogy. It is possibly kaolinite and illite, and has been derived from the decomposition of feldspars.

(a) *Upper kaolin* is mainly clay and silt in the finer than -200 B.S. sieve fraction, but the clay size is predominant, while platy-micaceous minerals are rare. X-ray diffraction patterns show that the silt clay fraction is mainly kaolin (85 per cent); illite and montmorillonite being accessories (5 per cent). Electron micrographs show that kaolin is mostly kaolinite plates covered with halloysite in a flocculated state (Fig. 17 A, B).

In situ permeability is low and after compaction the material is impermeable. Its dry density is moderate. U.S.C. classifications to be expected are CH, MH, CI and MI.

(b) *Middle kaolin* represents a transitional stage between the upper and lower divisions. The ratio of clay to larger sized material decreases with depth, while the proportion of silt and platy-micaceous minerals increases. X-ray diffraction patterns are not yet available, but electron micrographs show that the material is mostly kaolinite and halloysite (Fig. 17C,D). Halloysite tubes are

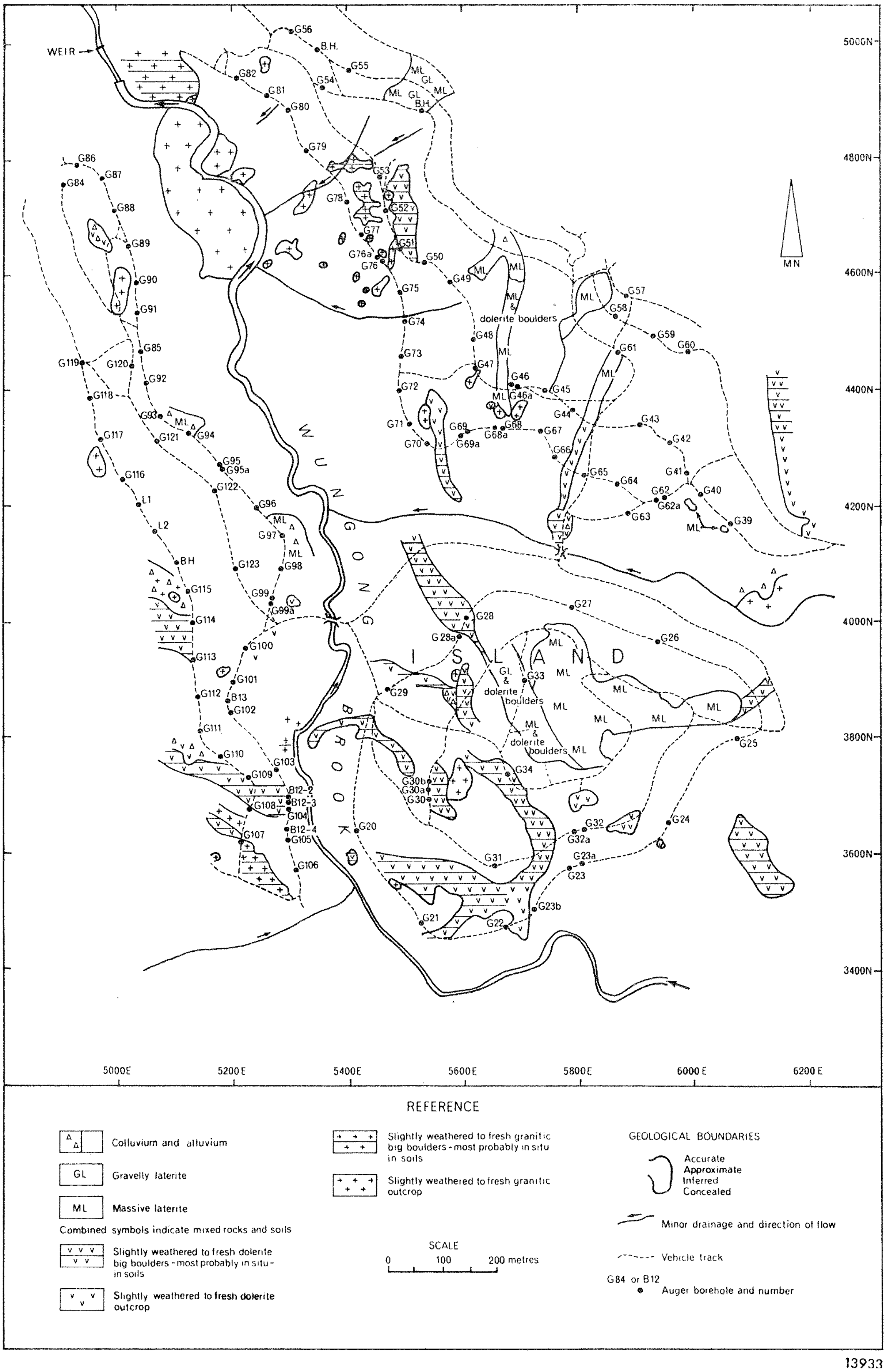

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Figure 16. Lower Wungong proposed dam site, geological map and borehole locations.

less abundant than in the upper kaolin. Kaolinite is well ordered having angular to subangular plates with occasional slight bending at the edges and a fairly open structure. Illite is present as elongated books with angular edges. U.S.C. classes to be expected are MH, CH and MI in the upper part, and MI, CI and SF_{silty} in the lower parts. *In situ* permeability is generally low except in the SF_{silty} and ML classes.

(c) *Lower kaolin* is a silty sand (of quartz and partially decomposed feldspars) with a moderate to low clay content and abundant platy-micaceous minerals. X-ray diffraction patterns show that the silt-clay fraction is predominently kaolin (85 per cent) illite (10 per cent) and montmorillonite ($\leqslant$ 5 per cent). Electron micrographs show that the kaolin is predominently kaolinite plates covered with halloysite tubes ranging from perfect to distorted cylinders (Fig. 17 E, F).

In both middle and lower kaolin divisions another unidentified mineral appears as cylinders composed of rounded plates (which could be tubes) with basal cleavage (Fig. 17D). The rounded plates are linked together on the outside by lateral elongated tube-like crystals. Electron micrographs also show that samples rich in iron oxides have a lesser percentage of halloysite than samples which are deficient in iron oxides.

The *in situ* permeability of this division is greater than in the upper or middle kaolin, but low permeability values are expected after compaction except in soils of low plasticity, e.g. SF_{silty}. The dry density is moderate.

Because of the abundance of platy-micaceous minerals in the lower kaolin, compacting methods should be carefully selected. This will avoid stratified fill of low strength. Laboratory U.S.C. classes to be expected are MI, MH and SF_{silty}.

III. *HIGHLY WEATHERED GRANITIC ROCKS*

Below the completely weathered rock is a thin highly weathered horizon of gritty clay and/or silty sands, quartz, and partially decomposed feldspar. In places it can be more than 5 m thick, but is usually one metre or less. There are partially decomposed micas in proportion to that of the parent rock.

Although it is harder than the kaolin horizon, it can be easily excavated by light equipment. *In situ* permeability is high to moderate, and varies considerably when compacted depending on the silt and clay content. Low liquid limits and plasticity are common, and high values are rare. Laboratory U.S.C. classes to be expected are MI in the upper sections and ML or SF_{silty} in the lower section.

LIQUID LIMIT VALUES

TABLE 3. PERCENTAGE DISTRIBUTION OF LIQUID LIMITS AND LINEAR SHRINKAGE IN EACH HORIZON.

Horizon	Sub-division	Percentage of total sample	L.L. Category	Percentage distribution of L.S. <5	5–9	9–10	>10
	Gravel	36	<50	20	20	20	40
		50	50–70	0	0	14	86
		14	>70	0	0	0	100
	Pisolitic	43	<50	0	33	67	0
		28·5	50–70	0	0	0	100
		28·5	>70	0	50	0	50
Laterite	Gibbsitic	44	<50	0	28	44	28
		25	50–70	0	0	25	75
		31	>70	0	0	0	100
	Upper Kaolin	32	<50	20	70	0	10
		43	50–70	0	20	36	44
		25	>70	0	8	25	67
Completely Weathered	Middle Kaolin	19	<50	20	60	0	20
		73	50–70	5	45	40	10
		8	>70	0	0	0	100
	Lower Kaolin	58	<50	8·5	80	8·5	3
		32	50–70	0	53	16	31
		10	>70	0	0	25	75
Highly Weathered		66	<50	37	49	14	0
		25	50–70	16	17	17	50
		9	>70	0	50	50	0

When liquid limits (L.L.) of the different soils of the weathered profile are grouped into three categories namely < 50, 50-70, and > 70 (Table 3), the following is apparent.

The first category (L.L. < 50), is occasionally found in soils overlying the kaolin horizon in locations where soils are believed to be transported, and in shallow laterites containing subordinate amounts of small pisolites. It is mainly found in soils (i) which are excessively silty with or without small amounts of clay, (ii) containing an appreciable to high amount of platy-micaceous minerals, (iii) of excessively high fine-grained sand content with little silt-clay size fraction.

Soils (i) and (ii) are well represented in the lower kaolin division as well as in the soils derived from sheared granitic rocks, while (iii) is well represented in the highly weathered horizon.

The second category (L.L. 50-70) is moderately represented in the laterite horizon. It is also mainly found in soils containing a high to intermediate percentage of clay and low to moderate silt and fine-grained sand with little or no platy-micaceous mineral content. The category is represented in both upper and middle kaolin divisions.

The third category (L.L. > 70) represents a moderate percentage of the soils in the laterite horizon and upper kaolin division, but a low percentage of those of middle and lower kaolin division and the highly weathered horizon.

LINEAR SHRINKAGE VALUES

Linear shrinkage (L.S.) values of more than 10 (Table 3) are well represented in soils of L.L. third category (> 70), and in the top 3 m of the weathered profile in some of the soils above the kaolin horizon which are of doubtful origin. These values are also found in weathered structurally weak zones, e.g. shear zones and in shallow permeable soils affected by leaching and precipitation.

In general the main two factors influencing L.S. values in the soils of the area are the silt-clay percentage, and the mineralogical composition of silty-clay fraction, particularly the montmorillonite percentage.

OBSERVATIONS FROM PLASTICITY CHART

The Casagrande plasticity classification chart shows that Id soils lie above the A-line, and that the IIa soils are nearly equally distributed both above and below the A-line. Further IIc soils lie below the A-line and have a lower plasticity index than the Id and IIa. Soils of II, having a negligible or very low content retained on the -200 B.S. mesh lie below the A-line (Fig. 18).

The mineralogical composition of the passing -200 B.S. mesh, particularly montmorillonite and halloysite species, influences the sample's location in the plasticity chart.

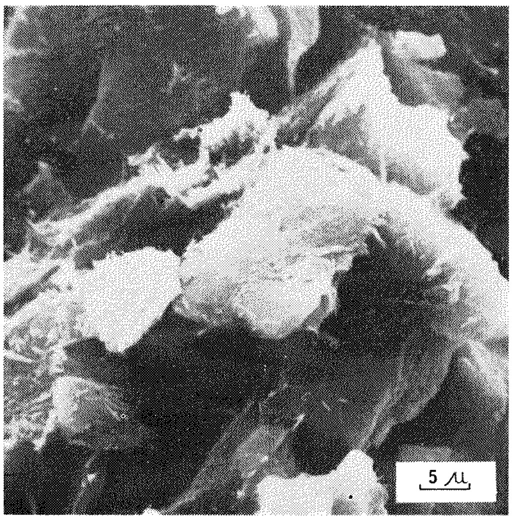
Figure 17 (opposite)

Electron micrographs of granitic soils.

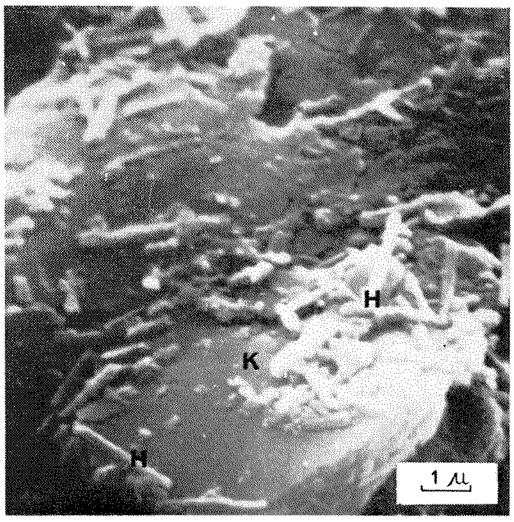
A and B Augerhole G58 at 3 m depth. Brown-yellow mottled white, damp, cleaved silty clay; upper kaolin of kaolin horizon. Kaolinite domains covered with halloysite tubes.

C and D Augerhole G58 at 6 m depth. White with brown-orange stains on cleavage planes, slightly micaceous, damp, silty clay; middle kaolin of kaolin horizon. View on cleavage, mostly kaolinite covered with halloysite tubes.

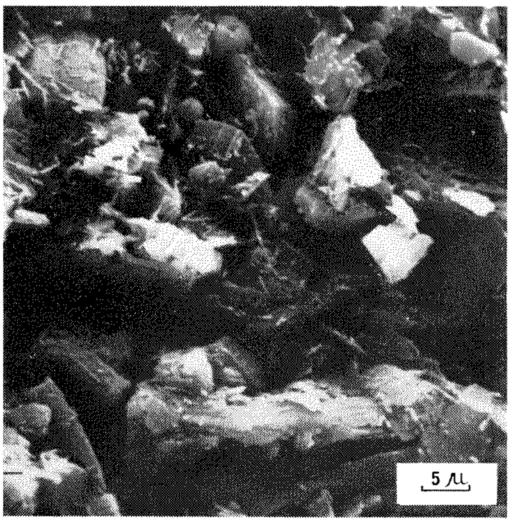
E and F Augerhole G44 at 10 m depth. Brown, wet, coarse micaceous sandy silt; lower kaolin of kaolin horizon. Kaolinite plates (K), mica laths (M), and a few halloysite tubes (H).



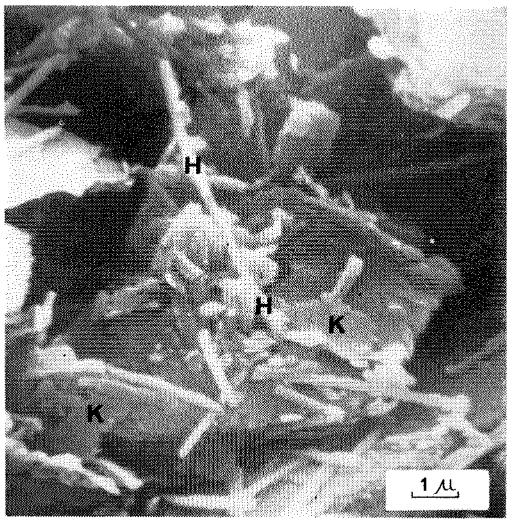
A



B

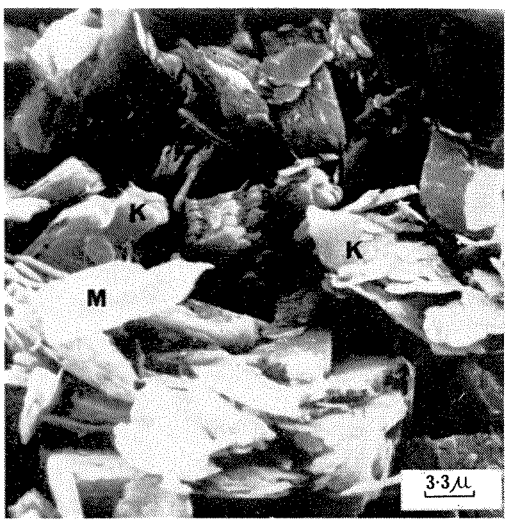


C



D

E



F

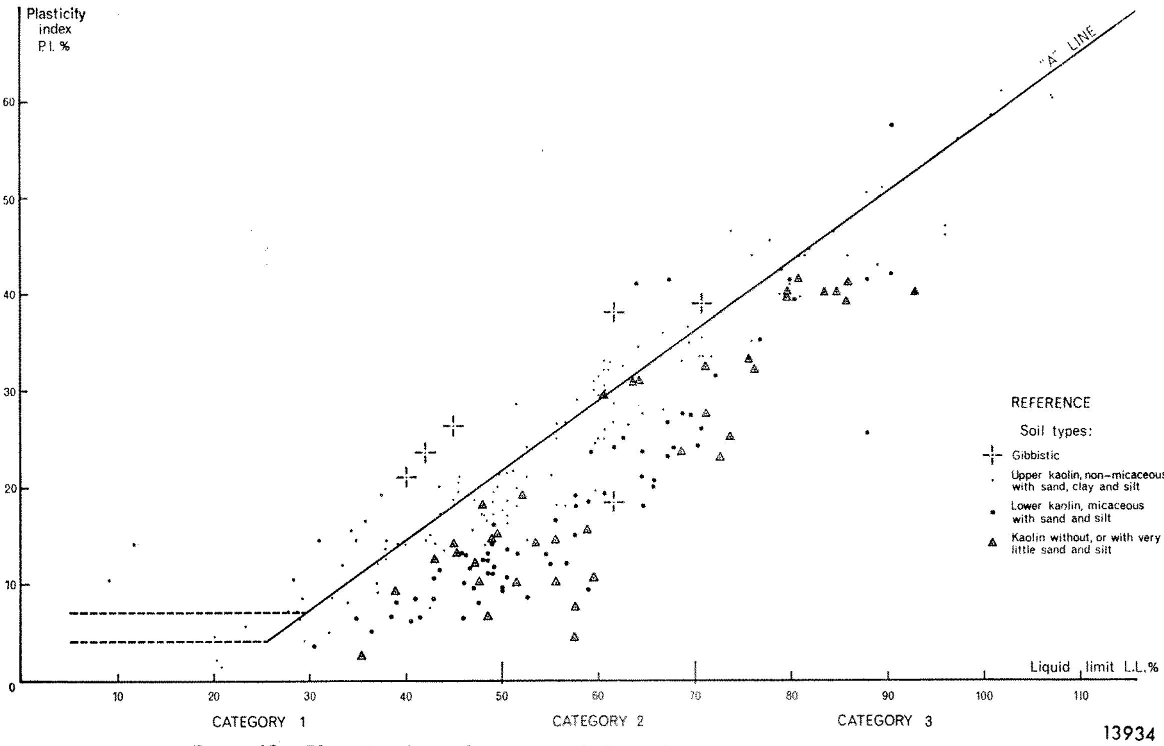


Figure 18. Plasticity chart of granitic soils from the Lower Wungong borrow area.

CONCLUSIONS

The weathering profile in the borrow area has reached an advanced stage of development.

Deviations from both sequence and thickness are common. These can be attributed to geomorphological history, geological structures, underground water movements and dykes acting as barriers to such movement.

The completely weathered granitic rocks are represented mainly by the kaolin horizon, which has been subdivided into upper, middle and lower divisions based on clay, silt and indeterminate platy-micaceous minerals.

The X-ray diffraction results for the kaolin horizon showed that: (i) kaolin is the main constituent, while illite and montmorillonite are subordinate; (ii) illite percentage increases from upper to lower kaolin divisions.

The scanning electron microscope results for the kaolin horizon showed that: (i) kaolin is mainly kaolinite plates covered with halloysite tubes (the latter is well represented in the lower kaolin division and least represented in the middle kaolin division); (ii) illite percentage increases from upper to lower kaolin divisions; (iii) the soil is characterized by a fluocculated bookhouse microstructure; (iv) there are marked variations in individual mineral sizes and shapes, as well as in the degree of packing within domains.

There is some relationship between the engineering properties of soils and their position in the weathering profile. This in turn could be related to similarities in mineralogical composition.

ACKNOWLEDGEMENTS

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1973

by G. H. Low

ABSTRACT

The tempo of oil exploration activity in Western Australia showed a marked decline during 1973 compared to the previous year. The number of test wells completed was 30 per cent less, and land seismic and marine seismic activity was 46 per cent and 65 per cent respectively less than the 1972 figure.

Drilling activity was largely confined to the northern Carnarvon, Canning and Browse Basins. The B.O.C. group successfully tested extensions to the Angel and Goodwyn fields and discovered gas, condensate, and oil in the Dockrell structure, and oil in the Egret structure. West Australian Petroleum Pty. Ltd.'s West Tryal Rocks No. 1 well found significant gas and condensate-bearing sands and has been suspended pending further tests, while the Company's Barrow Deep No. 1 is classified as a gas well.

Twenty-two wells were completed during the year and three were drilling at 31st December for a total of 63 612 m. Geophysical activity consisted of marine seismic, in some cases with associated gravity and magnetic work, in the Perth, Carnarvon, Canning, Browse and Bonaparte Gulf Basins, land seismic in the Perth, Carnarvon, Canning and Eucla Basins, and land gravity in the Perth and Eucla Basins.

During the year several onshore tenements were relinquished in the Carnarvon and Canning Basins, and offshore tenements were relinquished in the Bremer and Eucla Basins.

INTRODUCTION

Petroleum exploration activity in Western Australia showed a marked downward trend in 1973 compared with 1972. Exploratory drilling over the past two years is shown in the following tabulation:

	Wells completed		Wells drilling on 31st December	
	1972	1973	1972	1973
New field wildcat wells	22	16	4	2
Extension test wells	6	3	1	....
Deeper pool test wells	0	1	1	....
Stratigraphic wells	16	2	0	1

Total drilling : 1972—102 876m
1973—63 612m

Three of the 1973 new-field wildcat wells are regarded as successful tests and have been suspended. West Tryal Rocks No. 1 is classified as a gas/condensate discovery, Dockrell No. 1 is a gas/condensate/oil discovery, and Egret No. 1 is an oil discovery. Successful extension tests of fields discovered earlier were made in Angel No. 3, and Goodwyn No. 3 and No. 4. The deeper pool test Barrow Deep No. 1 is classified as a suspended gas well.

Test figures for gas given in the text are quoted in thousands of cubic metres per day (x 10^3 m^3/d). Oil and condensate test figures are quoted in barrels per day (b/d).

Geophysical survey and surface geological survey activity also declined compared with 1972. The totals for 1973 are as follows (with the 1972 figures in brackets):

Type of Survey	Line Km		Party months or Geologist months	
Land seismic	1 776	(3 266)	—	
Marine seismic	14 904	(43 218)	—	
Gravity (land)	—		7·0	(10·5)
Gravity (ship-board)	3	(4 362)	—	
Aeromagnetic	—	(26 445)	—	
Magnetic (ship-board)	1 117	(5 019)	—	
Geological	—		3·5	(13·0)

PETROLEUM TENEMENTS

During the year offshore tenements in the Bremer and Eucla Basins and onshore tenements in the southwestern Canning Basin and in the Carnarvon Basin were surrendered. Large areas in the sedimentary basins are currently available for application.

Petroleum tenements current on December 31st 1973 are shown in Figure 21, 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	364	14-11-74	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., B.O.C. of Australia Ltd.
WA- 2-P	381	14-11-74	West Australian Petroleum Pty. Ltd.
WA- 7-P	135	10-7-75	Continental Oil Co. of Aust. Ltd.
WA-13-P	387	29-8-74	West Australian Petroleum Pty. Ltd.
WA-14-P	396	29-8-74	„ „ „ „
WA-15-P	352	20-3-75	Arco Aust. Ltd., Australian Aquitaine Petroleum Pty. Ltd., Esso Exploration and Production Aust. Inc.
WA-16-P	354	16-4-75	„ „ „ „
WA-17-P	378	22-4-75	„ „ „ „
WA-18-P	322	16-4-75	„ „ „ „
WA-19-P	142	20-3-75	Alliance Oil Development Aust. Ltd.
WA-20-P	34	10-10-74	West Australian Petroleum Pty. Ltd.
WA-21-P	241	14-11-74	„ „ „ „
WA-23-P	398	3-10-74	„ „ „ „
WA-24-P	208	17-10-74	„ „ „ „
WA-25-P	256	16-10-74	„ „ „ „
WA-26-P	400	22-12-74	Canadian Superior Oil (Aust.) Pty. Ltd. Australian Superior Oil Co. Ltd., Phillips Australian Oil Co., Sunray Australian Oil Co. Inc., Genoa Oil N.L., Pexa Oil N.L., Hartog Oil N.L., Flinders Petroleum N.L., Crusader Oil N.L.
WA-27-P	294	18-5-75	„ „
WA-28-P	375	24-3-75	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., B.O.C. of Australia Ltd.
WA-29-P	400	18-5-75	„ „ „
WA-30-P	400	2-7-75	„ „ „
WA-31-P	400	18-5-75	„ „ „
WA-32-P	395	2-7-75	„ „ „
WA-33-P	389	18-5-75	„ „ „
WA-34-P	397	2-7-75	„ „ „
WA-35-P	400	2-7-75	„ „ „
WA-36-P	57	18-5-75	„ „ „
WA-37-P	118	2-6-75	„ „ „
WA-39-P	104	12-3-75	BP Petroleum Development Aust. Pty. Ltd. Abrolhos Oil N.L.
WA-40-P	102	12-3-75	„ „ „
WA-43-P	241	17-9-78	Planet Exploration Co. Pty. Ltd.
WA-44-P	400	17-9-78	„ „ „
WA-50-P	330	23-7-78	Esso Exploration and Production Aust. Inc.
WA-51-P	278	25-7-78	„ „ „ „

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.
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 5	132	26-7-75	West Australian Petroleum Pty. Ltd.
EP 6	199	27-8-75	„ „ „
EP 7	200	27-8-75	„ „ „
EP 8	200	8-8-77	„ „ „
EP 9	200	27-8-75	„ „ „
EP 13	200	27-8-75	„ „ „
EP 17	200	27-8-75	„ „ „
EP 18	200	27-8-75	„ „ „
EP 19	200	27-8-75	„ „ „
EP 20	200	8-8-77	Australian Aquitaine Petroleum Pty. Ltd.
EP 21	90	26-7-75	West Australian Petroleum Pty. Ltd.
EP 23	163	6-8-75	„ „ „
EP 24	167	6-8-75	„ „ „
EP 25	96	6-8-75	„ „ „
EP 26	1	27-8-75	BP Petroleum Development (Aust.) Pty. Ltd., Abrolhos Oil N.L.
EP 27	2	19-8-75	„ „ „
EP 28	4	19-8-75	„ „ „
EP 29	7	19-8-75	„ „ „
EP 31	200	6-10-75	Beach-General Exlporation Pty. Ltd., Australian Aquitaine Petroleum Pty. Ltd.
EP 32	200	15-4-76	„ „ „
EP 33	123	15-4-76	„ „ „
EP 34	1	15-4-76	Woodside Oil N.L., Shell Development (Aust.) Pty. Ltd., B.O.C. of Australia Ltd.
EP 35	1	15-4-76	„ „ „
EP 36	1	15-4-76	„ „ „
EP 37	149	22-9-75	West Australian Petroleum Pty. Ltd.
EP 38	130	22-9-75	„ „ „
EP 40	67	26-7-76	„ „ „
EP 41	180	18-7-76	„ „ „
EP 42	200	1-9-75	„ „ „
EP 43	163	1-9-75	„ „ „
EP 44	113	1-9-75	„ „ „
EP 45	197	19-11-75	Continental Oil Co. of Aust. Ltd., Australian Sun Oil Co. Ltd.
EP 46	199	1-9-75	„ „ „
EP 47	199	19-11-75	„ „ „
EP 48	199	19-11-75	„ „ „
EP 50	110	1-9-75	West Australian Petroleum Pty. Ltd.
EP 51	17	8-9-75	Lennard Oil N.L.
EP 52	18	8-9-75	„ „ „
EP 54	123	22-9-75	Alliance Oil Development Aust. N.L.
EP 58	200	20-7-76	Associated Australian Oilfields 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 59	186	18-7-76	„ „ „
EP 60	2	....	West Australian Petroleum Pty. Ltd.
EP 61	4	19-9-76	„ „ „
EP 62	8	19-9-76	„ „ „
EP 63	4	19-9-76	„ „ „
EP 64	1	....	„ „ „
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 69	82	5-4-77	Sunningdale Oils Pty. Ltd.
EP 70	71	25-9-77	Associated Australian Oilfields 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.

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
EP 71	81	6–7–77	Coastal Petroleum N.L.
EP 72	198	21–8–77	Planet Exploration Company Pty. Ltd.
EP 73	198	21–8–77	„ „ „
EP 75	198	21–8–77	„ „ „
EP 76	188	23–7–77	Genoa Oil N.L., Hartog Oil N.L., Olympus Petroleum N.L., Pexa Oil N.L., Omega Oil N.L., Kambalda Petroleum N.L.

Production Licences

Number	No. of graticular sections	Expiry date of current term	Registered holder or applicant
PL 1	5	24–10–92	West Australian Petroleum Pty. Ltd.
PL 2	4	24–10–92	„ „ „
PL 3	5	24–10–92	„ „ „

PETROLEUM TENEMENTS UNDER THE PETROLEUM PIPELINES ACT, 1969

Pipeline Licences

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

DRILLING

The positions of wells drilled for petroleum exploration in Western Australia during 1973 are shown in Figures 19 and 20. Details relating to the wells drilled during the year are given in Table 4. All the petroleum exploration wells drilled in Western Australia up to the end of 1973 are listed in Geological Survey Record 1974/2.

A summary of the principal results of the drilling in each basin during the year is as follows:

PERTH BASIN

The Lake Preston No. 1 new field wildcat was the only well drilled in the Perth Basin during 1973. It was plugged and abandoned after reaching a total depth of 4 565 m, in the Lower Permian section. No significant shows of hydrocarbons were recorded, and the shows obtained were confined to coal gas. However, the well indicated that the Sue Coal Measures is a good generative unit.

CARNARVON BASIN

Seven wells were completed by the B.O.C. group in the Carnarvon Basin during 1973, and Lambert No. 1 was drilling at the end of the year. Four of the completed wells were new field wildcat tests and of these Dockrell No. 1 was a successful gas/condensate/oil discovery and Egret No. 1 was a successful oil discovery. Extensions to the Angel and Goodwyn fields were successfully tested in Angel No. 3 and Goodwyn No. 3 and 4. All the successful tests were on the Nelson Rocks and Rosemary structures.

West Australian Petroleum Pty. Ltd. completed two wells in the Carnarvon Basin, West Tryal Rocks No. 1 and Barrow Deep No. 1, both of which were spudded in 1972.

West Tryal Rocks No. 1, a new field wildcat well, was a successful gas/condensate discovery. It has been suspended until a new rig is available for further testing. Barrow Deep No. 1 was a deeper-pool test on Barrow Island. The well yielded significant quantities of gas but serious drilling difficulties were experienced with supernormal formation pressures.

The only onshore wells in the Carnarvon Basin were Tamala No. 1 and Kalbarri No. 1 drilled for stratigraphic information by Oceania Petroleum Pty. Ltd.

The results obtained in the extension test wells in the Angel and Goodwyn fields are discussed in a separate report on petroleum development and production in 1973 (p. 37). Some details of the discovery wells are as follows:

Dockrell No. 1

The testing programme indicated a main hydrocarbon reservoir of approximately 105 m of gross pay with an oil leg approximately 12 m thick. Two separate thin gas/condensate zones were also located below the main reservoir. The following is a summary of the results of two drill-stem tests run in the hole:

D.S.T. No.	Interval (metres)	Surface choke	Oil b/d	Gas x 10^3 m^3/d	Condensate b/d
1.	2 987–2 995	$\frac{3}{4}$ inch	....	371·4	755
2.	3 004–3 008	$\frac{3}{8}$ inch	1 869	53·8	....

The gas and condensate in D.S.T. No. 1 was accompanied by water at the rate of 7.4 barrels per day.

Egret No. 1

The Egret No. 1 well is located approximately 8 km southeast of the Eaglehawk oil discovery well. The results of a drill-stem test are summarized as follows:

D.S.T. No.	Interval (metres)	Surface choke	Oil b/d	Gas x 10^3 m^3/d	Water b/d
1.	3 119–3 128	$\frac{3}{4}$ inch	2 729	81·2	20–30

The oil was 39° A.P.I. gravity and it was recovered from the top sand of the Tithonian section.

West Tryal Rocks No. 1

This well is currently suspended until a new drill rig is available for testing a significant hydrocarbon accumulation identified in Late Triassic to Early Jurassic sands of the Mungaroo Formation. Wireline log evaluation indicates the presence of 90 m of possible hydrocarbon pay in a column which extends over a gross interval of 265 m with a transitional hydrocarbon water contact from 3 489-3 501 m.

Barrow Deep No. 1

This well was drilled as a deep exploratory test on Barrow Island and is currently classified as a gas well after the discovery and testing of significant hydrocarbon accumulations in Middle Jurassic sands. The well did not reach the planned total depth of 4 877 m because of supernormal formation pressures and the primary objective of testing possible Late Triassic sands of the Mungaroo Formation was not achieved. Six drill stem tests were conducted to evaluate three sands between 3 242-3 254 m, 3 329-3 363 m, and 3 424-3 500 m. Because of the necessity to maintain pressure control these tests were of limited duration and none of the zones was flowed to the surface. The lowermost zone, with a proven net gas pay of 9.4 m between 3 424 and 3 500 m, gave the best results during later production tests and it has a calculated open-flow potential of 5 660 x 10^3 m^3 gas per day.

CANNING BASIN

Three offshore new field wildcat wells, East Mermaid No. 1 drilled in 389 m of water for Shell Development (Australia) Pty. Ltd., Wamac No. 1 drilled for Amax Petroleum (Australia) Inc., and Ronsard No. 1 drilled for the B.O.C. group, were completed during 1973. The B.O.C. Poissonnier No. 1 wildcat was drilling at the end of the year. Onshore West Australian Petroleum Pty. Ltd. completed three new field wildcats in the northern Canning Basin and one of them, Mimosa No. 1, encountered a minor gas and oil show, the remainder of the completed wells were dry, and all were abandoned. Contention Heights No. 1 new field wildcat well, drilled for Australian Aquitaine Petroleum Pty. Ltd. in the southeastern Canning Basin, was also dry and was abandoned after reaching a total depth of 1 791 m in Early Ordovician sediments.

BROWSE BASIN

The B.O.C. group drilled two new field wildcat wells, Londonderry No. 1 and Yampi No. 1, in the Browse Basin during 1973. In Yampi No. 1 log analysis indicates that several thin hydrocarbon-bearing sands are present but reservoir characteristics are poor. Both wells were abandoned.

BREMER BASIN

An onshore stratigraphic well, Kendenup No. 1, was being drilled for Silfar Pty. Ltd. at the end of the year.

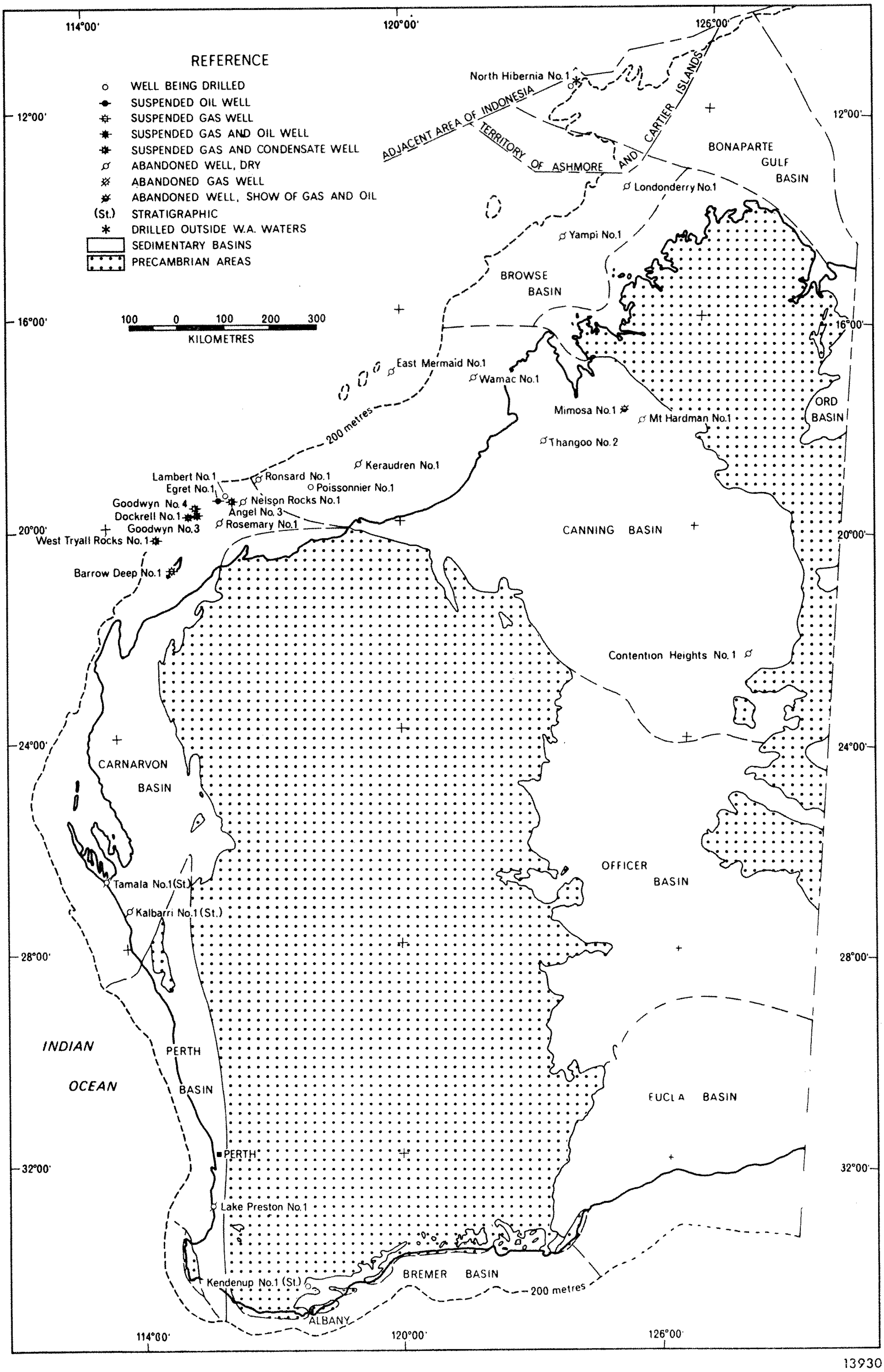

Figure 19. Wells drilled for petroleum exploration in W.A. during 1973.

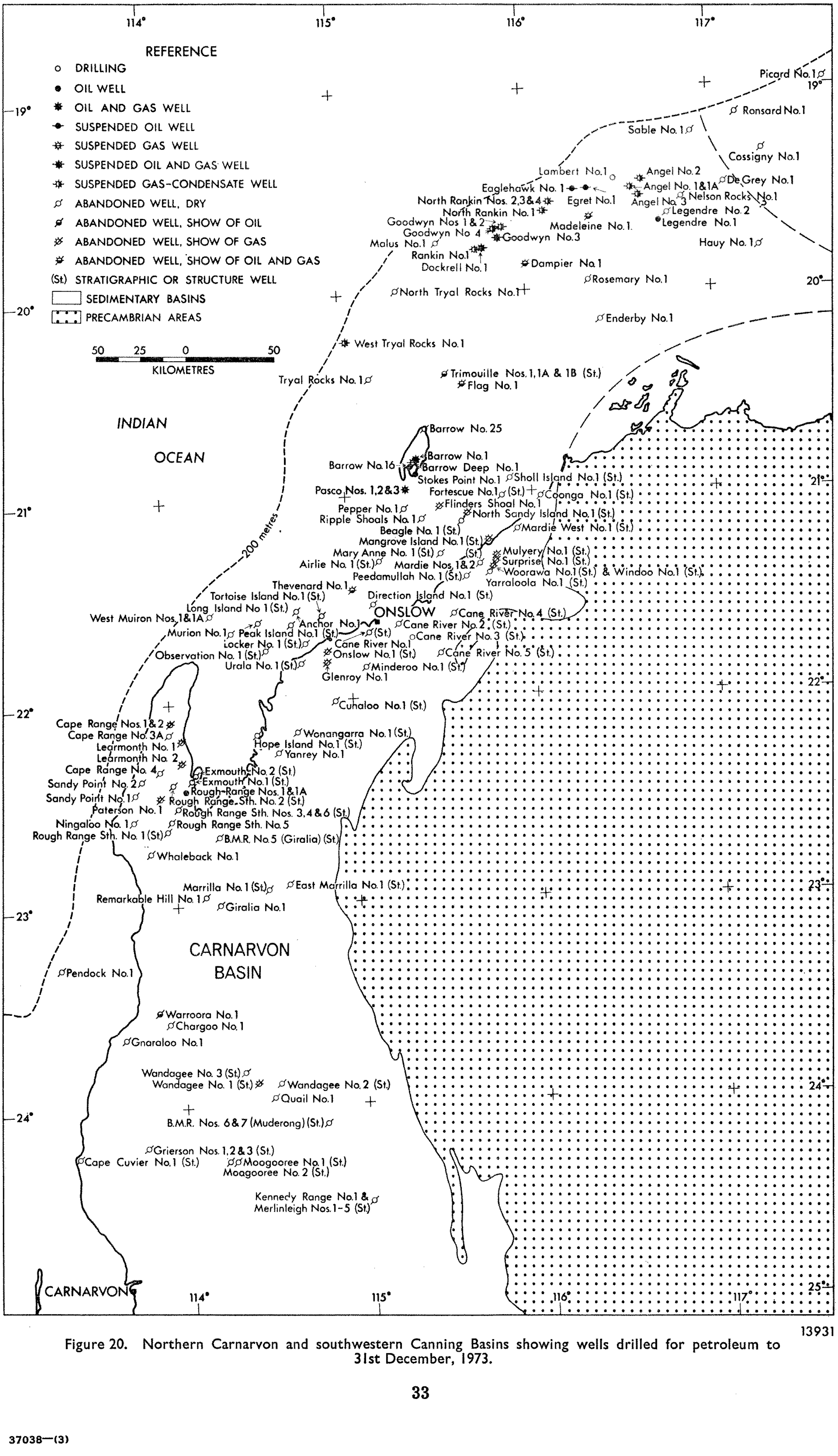

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Figure 20. Northern Carnarvon and southwestern Canning Basins showing wells drilled for petroleum to 31st December, 1973.

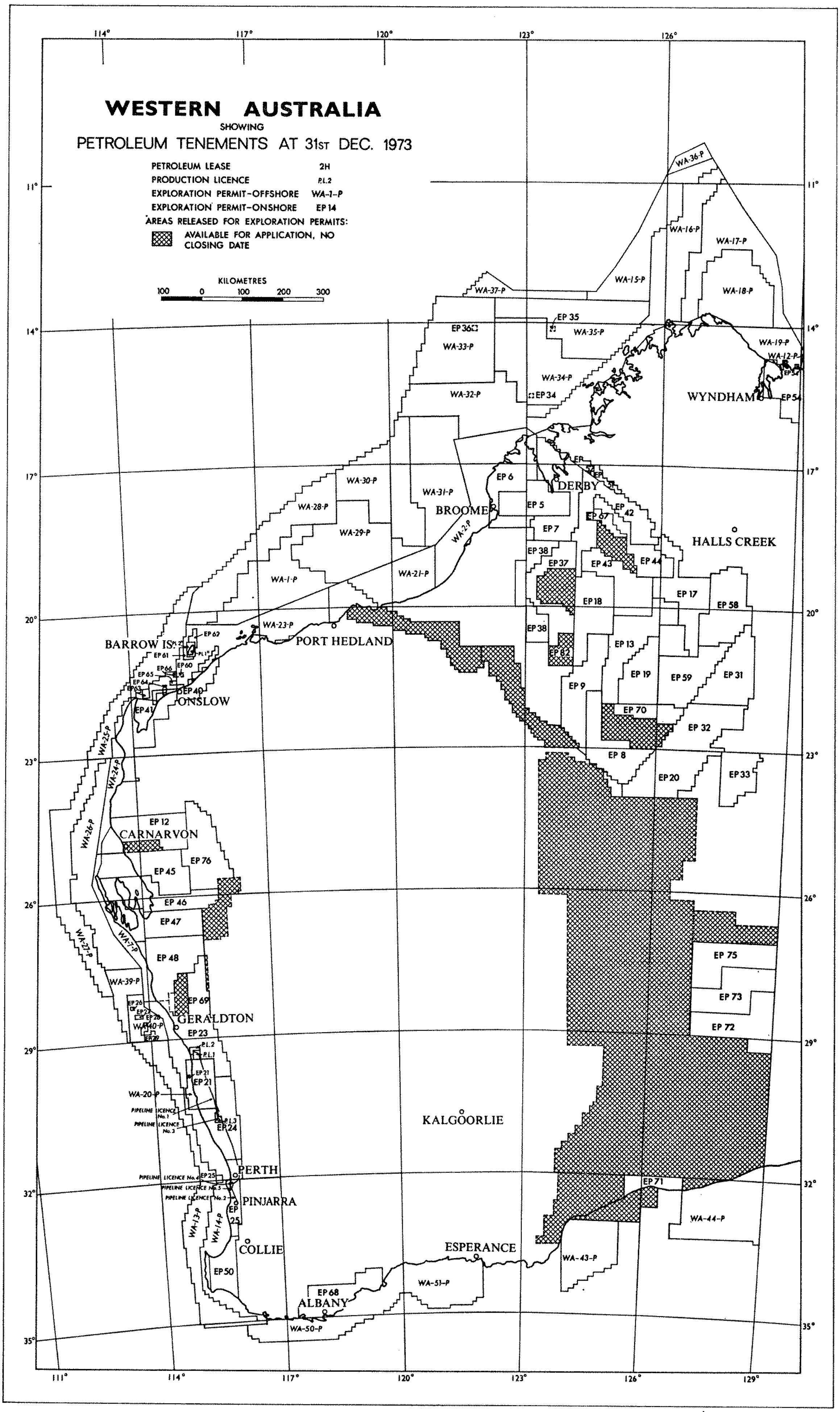

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Figure 21. Petroleum tenements at 31st December, 1973.

TABLE 4. WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1973

Basin	Well	* = subsidized	Concession	Operating Company	Type	Position						Elevation and water depth (metres)			Dates			Total depth (or depth reached) in metres	Bottomed in	Status on 31 Dec., 1973
						Latitude South			Longitude East			G.L.	R.T.	W.D.	Commenced	Reached T.D.	Rig released			
						°	′	″	°	′	″									
Perth	Lake Preston No. 1	*	EP–25	Wapet	NFW	32	55	13	115	39	39	10·1	14·6	....	20/12/72	7/3/73	9/3/73	4 565	L. Permian	Dry, P. & A.
Carnarvon	Angel No. 3	....	WA–1–P	B.O.C.	EXT	19	32	30	116	37	46	....	9·4	66·4	27/4/73	15/6/73	28/6/73	3 780	....	G & C well suspended
	Barrow Deep No. 1	*	PL–1H	Wapet	DPT	20	50	07	115	22	57	38·7	46·6	....	16/9/72	20/6/73	21/7/73	4 650	M. Jurassic	Gas well suspended
	Dockrell No. 1	....	WA–28–P	B.O.C.	NFW	19	47	16	115	46	49	....	30·0	110·0	30/6/73	17/8/73	28/8/73	3 895	....	G, C & O well suspended
	Egret No. 1	*	WA–28–P	B.O.C.	NFW	19	30	24	116	20	52	....	12·5	118·2	24/12/72	12/5/73	28/5/73	3 658	Triassic	Oil well suspended
	Goodwyn No. 3	....	WA–28–P	B.O.C.	EXT	19	44	09	115	52	43	....	30·2	118·8	14/12/72	9/2/73	22/2/73	3 657	....	G & O well suspended
	Goodwyn No. 4	....	WA–28–P	B.O.C.	EXT	19	41	38	115	50	54	....	30·2	128·0	24/2/73	6/6/73	28/6/73	3 633	....	G & C well suspended
	Kalbarri No. 1	*	EP–47	O.P.P.L.	STR	87	16	00	114	06	26	129·2	132·8	....	11/9/73	3/10/73	4/10/73	1 539	Silurian	Dry, P & A
	Lambert No. 1	....	WA–28–P	B.O.C.	NFW	19	27	24	116	29	23	....	10·0	125·0	13/11/73	....	....	3 476	....	Drilling
	Nelson Rocks No. 1	....	WA–1–P	B.O.C.	NFW	19	33	37	116	51	19	....	10·0	75·0	30/6/73	30/7/73	1/8/73	2 190	....	Dry, P & A
	Rosemary No. 1	*	WA–1–P	B.O.C.	NFW	19	57	14	116	20	40	....	9·5	64·9	13/11/72	26/3/73	26/4/73	3 909	L. Jurassic	Dry, P & A
	Tamala No. 1	*	EP–47	O.P.P.L.	STR	26	38	42	113	38	04	2·7	7·0	....	4/4/73	7/5/73	8/5/73	1 225	Silurian	Dry, P & A
	West Tryal Rocks No. 1	*	WA–25–P	Wapet	NFW	20	13	45	115	02	04	....	12·2	137·8	23/10/73	4/3/73	31/3/73	3 866	M-U. Triassic	G & C well suspended
Canning	Contention Heights No. 1	*	EP–32	A.A.P.	NFW	22	25	36	127	13	31	418·4	4·6	....	16/8/73	24/9/73	6/10/73	1 791	L. Ordovician	Dry, P & A
	East Mermaid No. 1 RDR 2	....	WA–30–P	Shell	NFW	17	10	01	119	49	21	....	9·7	389·2	30/6/73	9/10/73	15/10/73	4 067	....	Dry, P & A
	Keraudren No. 1	....	WA–29–P	Hemat	NFW	18	54	28	119	09	15	....	30·0	95·0	31/8/73	13/12/73	19/12/73	3 844	....	Dry, P & A
	Mimosa No. 1	*	EP–44	Wapet	NFW	17	51	00	124	35	00	57·0	61·6	....	17/6/73	17/8/73	23/8/73	4 117	M-U. Devonian	Gas & oil show
	Mt. Hardman No. 1	*	EP–67	Wapet	NFW	18	00	38	124	54	48	57·0	61·6	....	6/9/73	6/11/73	10/11/73	3 360	U. Devonian	Dry, P & A
	Poissonnier No. 1	....	WA–1–P	B.O.C.	NFW	19	18	31	118	09	20	....	28·9	82·0	20/12/73	....	....	1 042	....	Drilling
	Ronsard No. 1	*	WA–1–P	B.O.C.	NFW	19	08	32	117	09	34	....	9·7	154·0	12/10/73	9/11/73	12/11/73	2 843	....	Dry, P & A
	Thangoo No. 2	*	EP–14	Wapet	NFW	18	26	33	122	54	35	118·0	192·8	....	9/5/73	31/5/73	2/6/73	4 830	Precambrian	Dry, P & A
	Wamac No. 1	*	WA–31–P	Amax	NFW	17	14	26	121	29	28	....	19·5	76·0	6/8/73	22/9/73	11/10/73	2 764	....	Dry, P &A
Browse	Londonderry 1	....	WA–35–P	B.O.C.	NFW	13	36	53	124	30	40	....	12·5	90·8	28/9/73	7/10/73	8/10/73	1 145	....	Dry, P & A
	Yampi No. 1	*	WA–34–P	B.O.C.	NFW	14	33	21	123	16	21	....	13·4	97·8	3/6/73	17/9/73	27/9/73	4 176	....	Dry, P & A
Bremer	Kendenup No. 1	....	EP–68	Silfar	STR	34	29	36	117	45	22	159·0	....	....	19/12/73	....	....	31	....	Drilling

Total	78 053
Less drilling done in 1972	14 441
Total drilling done in 1973	63 612

A.A.P. = Australian Aquitaine Petroleum Pty. Ltd.
Amax = Amax Petroleum (Australia) Inc.
B.O.C. = B.O.C. of Australia Ltd.
Hemat = Hematite Petroleum Pty. Ltd.
O.P.P.L. = Oceania Petroleum Pty. Ltd.
Shell = Shell Development (Australia) Pty. Ltd.

Silfar = Silfar Pty. Ltd.
Wapet = West Australian Petroleum Pty. Ltd.
DPT = Deeper pool test well
EXT = Extension test well
G & C = Gas and Condensate
G, C & O = Gas, condensate and oil

G & O = Gas and oil
NFW = New field wildcat well
P & A = Plugged and abandoned
STR = Stratigraphic well

GEOPHYSICAL SURVEYS

SEISMIC

During 1973 seismic surveys were conducted in the Perth, Carnarvon, Canning, Browse, Bonaparte Gulf and Eucla Basins. Details are as follows:

SEISMIC SURVEYS

Basin	Permit No.	Company	Line kilometres	
			Marine	Land
Perth	EP–21	West Australian Petroleum Pty. Ltd.	....	55
,,	EP–23	,, ,, ,,	....	27
,,	EP–24	,, ,, ,,	....	194
,,	EP–25	,, ,, ,,	....	123
,,	WA–20–P	,, ,, ,,	2 000	....
Carnarvon	PL–1H	West Australian Petroleum Pty. Ltd.	....	15
,,	WA–23–P	,, ,, ,,	126	....
,,	WA–24–P	,, ,, ,,	360	....
,,	WA–25–P	,, ,, ,,	2 753	....
,,	WA–41–P	,, ,, ,,	....	48
,,	WA–27–P	Canadian Superior Oil (Aust.) Pty. Ltd.	981	....
Carnarvon/ Canning	WA–1–P	B.O.C. of Australia Ltd	1 125	....
	WA–28–P	,, ,, ,,	975	....
Canning	EP–5	West Australian Petroleum Pty. Ltd.	....	31
,,	EP–7	,, ,, ,,	....	75
,,	EP–13	,, ,, ,,	....	75
,,	EP–15	,, ,, ,,	....	64
,,	EP–18	,, ,, ,,	....	109
,,	EP–19	,, ,, ,,	....	77
,,	EP–37	,, ,, ,,	....	56
,,	EP–43	,, ,, ,,	....	139
,,	EP–44	,, ,, ,,	....	15
,,	WA–2–P	,, ,, ,,	1 508	....
,,	WA–21–P	,, ,, ,,	376	....
,,	EP–58	Associated Australian Resources N.L.	....	257
,,	EP–59	,, ,, ,,	....	398
,,	WA–29–P	B.O.C. of Australia Ltd.	127	....
,,	WA–30–P	,, ,, ,,	571	....
,,	WA–31–P	,, ,, ,,	584	....
,,	WA–31–P	Amax Petroleum (Aust) Inc.	98	....
,,	WA–29–P	Hematite Petroleum Pty. Ltd.	191	....
Browse	WA–32–P	B.O.C. of Australia	314	....
,,	WA–33–P	,, ,, ,,	893	....
,,	WA–34–P	,, ,, ,,	581	....
,,	WA–35–P	,, ,, ,,	531	....
,,	WA–37–P	,, ,, ,,	402	....
Bonaparte Gulf	WA–15–P	Arco Australia Ltd.	428	....
,,	WA–16–P	,, ,,	942	....
,,	WA–17–P	,, ,,	229	....
,,	WA–18–P	,, ,,	361	....
,,	WA–19–P	,, ,,	105	....
,,	WA–36–P	B.O.C. of Australia Ltd.	143	....
Eucla	EP–71	Coastal Petroleum N.L.	....	18
		Totals	14 904	1 776

GRAVITY

Gravity surveys were carried out during the year in the Perth and Eucla Basins. Details are as follows:

GRAVITY SURVEYS

Basin	Permit No.	Company	Party	Ship-board line kilometres
Perth	EP–69	Sunningdale Oils Pty. Ltd.	5·0	....
Eucla	EP 71	Coastal Petroleum N.L.	0·4	....
		Totals	5·4	....

In addition West Australian Petroleum Pty. Ltd. carried out a total of 47 work days of gravity survey in association with land seismic, and 2-5 km of gravity survey associated with marine seismic, in the Perth, Carnarvon and Canning Basins.

MAGNETOMETER

Ship-board magnetic surveys were conducted in the Carnarvon and Canning Basins. Details are as follows:

MAGNETIC SURVEYS.

Basin	Permit No.	Company	Line kilometres	
			Aero-magnetic	Ship-board
Canning	WA–31–P	Amax Petroleum (Aust.) Inc.	....	98
,,	WA–29–P	Hematite Petroleum Pty. Ltd.	....	191
Carnarvon	WA–27–P	Canadian Superior Oil (Aust.) Pty. Ltd.	....	825
		Totals		1 114

GEOLOGICAL SURVEYS

A surface geological survey amounting to 3.5 geologist months was carried out by Associated Australian Resources N.L. in EP 59 and EP 70 in the Canning Basin.

OTHER SURVEYS

West Australian Petroleum Pty. Ltd. carried out 576 square kilometres of hydrographic survey, 148 km of bathymetric sparker, and 39 km of bathymetric sonar in the Perth and Carnarvon Basins.

PETROLEUM DEVELOPMENT AND PRODUCTION IN WESTERN AUSTRALIA IN 1973

by R .N. Cope

ABSTRACT

During 1973 the Barrow Island Field produced 2 295 467 m^3 of crude oil. Sales totalled 2 314 043 m^3 on which royalty of A$1 362 522 was paid. Remaining oil reserves are estimated to be about 27 x 10^6 m^3. Production testing of Pasco Island No. 1 (near Barrow Island) showed that the Pasco Field is sub-economic.

In the Rankin area, three additional appraisal wells were drilled in 1973; Goodwyn No. 3, No. 4 and Angel No. 3. The combined proved plus probable gas reserves of the North Rankin, Goodwyn and Angel Fields have been estimated at 380 x 10^9 m^3. Additional possible gas reserves are put at 130 x 10^9 m^3. The North Rankin Field alone is estimated to hold about 223 x 10^9 m^3 of recoverable gas in the proved plus probable categories.

Gas production from the Dongara and Mondarra Fields in the northern Perth Basin during 1973 totalled 815 487 000 m^3; sales were 809 629 000 m^3 and royalty paid was A$320 741. Remaining gas reserves are about 11 090 000 000 m^3. Wapet's options to apply for the secondary entitlement blocks in Locations 1 and 2 (Dongara-Mondarra) and 3 (Walyering) were not exercised. Seven blocks were therefore excised from EP-23 and four blocks from EP-24. An application was received from Wapet to surrender Production Licence No. 3 (Walyering).

INTRODUCTION

There are three petroleum fields in the course of long-term planned production in Western Australia; the Barrow Island Field, in the northern Carnarvon Basin, and the Dongara and Mondarra Fields in the northern Perth Basin.

The Barrow Island Field, sited about 60 km off the northwest coast near Onslow, produces oil with some liquid petroleum gas and condensate. The solution gas is nearly all flared as its utilization is non-commercial, apart from about 9.4 per cent of the gas produced which is currently used as field fuel.

The Dongara Field, south of Geraldton, and the nearby small Mondarra Field, produce gas, which is piped south to Perth, Kwinana, and Pinjarra. A small quantity of condensate is separated from the gas and sold. The small Yardarino Field, also near Dongara, has not so far been developed to the production stage.

Implementation of the national policy of metrication is proceeding fairly smoothly with respect to petroleum development and production. "Soft" metrication (conversion to metric units after recording in imperial units) is being adopted by both West Australian Petroleum Pty. Ltd. (referred to here as Wapet) and B.O.C. of Australia Ltd. "Hard" metrication (recording in metric units) presents special instrumentation problems. These problems hinge largely on the fact that the regulatory bodies of the petroleum industry in the United States of America (the home, and supply base, of much of the industry) have no plans for metrication, as they consider that it would be prohibitively expensive.

In this report volumes of both liquids and gas are expressed in cubic metres at Australian metric standard conditions; these conditions were decided in 1973 as 15 degrees Celsius (°C) and 101.325 kilopascals (kPa). Liquid volumes are also stated (between parentheses after the metric quantities) in barrels at imperial standard conditions (60 degrees Fahrenheit and 14.73 pounds per square inch in air), as the barrel (34.972 6 imperial gallons) is an internationally accepted unit in crude oil production.

The conversion factors used to prepare the tables of this report are: 1 cubic metre at metric standard conditions = 35.42 cubic feet at imperial standard conditions; 1 barrel at imperial standard conditions = 0.158 91 cubic metres at metric standard conditions; 1 volume unit at imperial standard conditions = 1.005 0 volume units at metric standard conditions.

NORTHERN CARNARVON BASIN

GENERAL

The northern Carnarvon Basin is the most petroleum-productive area of the State to date, and it is also the most prospective. In addition to the producing Barrow Island Field, three offshore fields are thought to contain commercial reserves of gas, namely, North Rankin, Goodwyn and Angel (Fig. 22). For detailed information on the petroleum geology of this area see Martison and others (1973).

The 1973 half-yearly report of Woodside-Burmah Oil N.L. gave the estimated proved plus probable natural gas reserves of the "Rankin Trend" as 380 x 10^9 m^3 (13.5 x 10^{12} CF). Additional possible reserves were put at 130 x 10^9 m^3 (4.5 x 10^{12} CF). These figures cover the North Rankin, Goodwyn and Angel Fields, although the Angel Field is not on the "Rankin Trend" (the southern margin of the Rankin Platform).

BARROW ISLAND FIELD

Petroleum is produced from the Barrow Island Field under Petroleum Lease 1H.

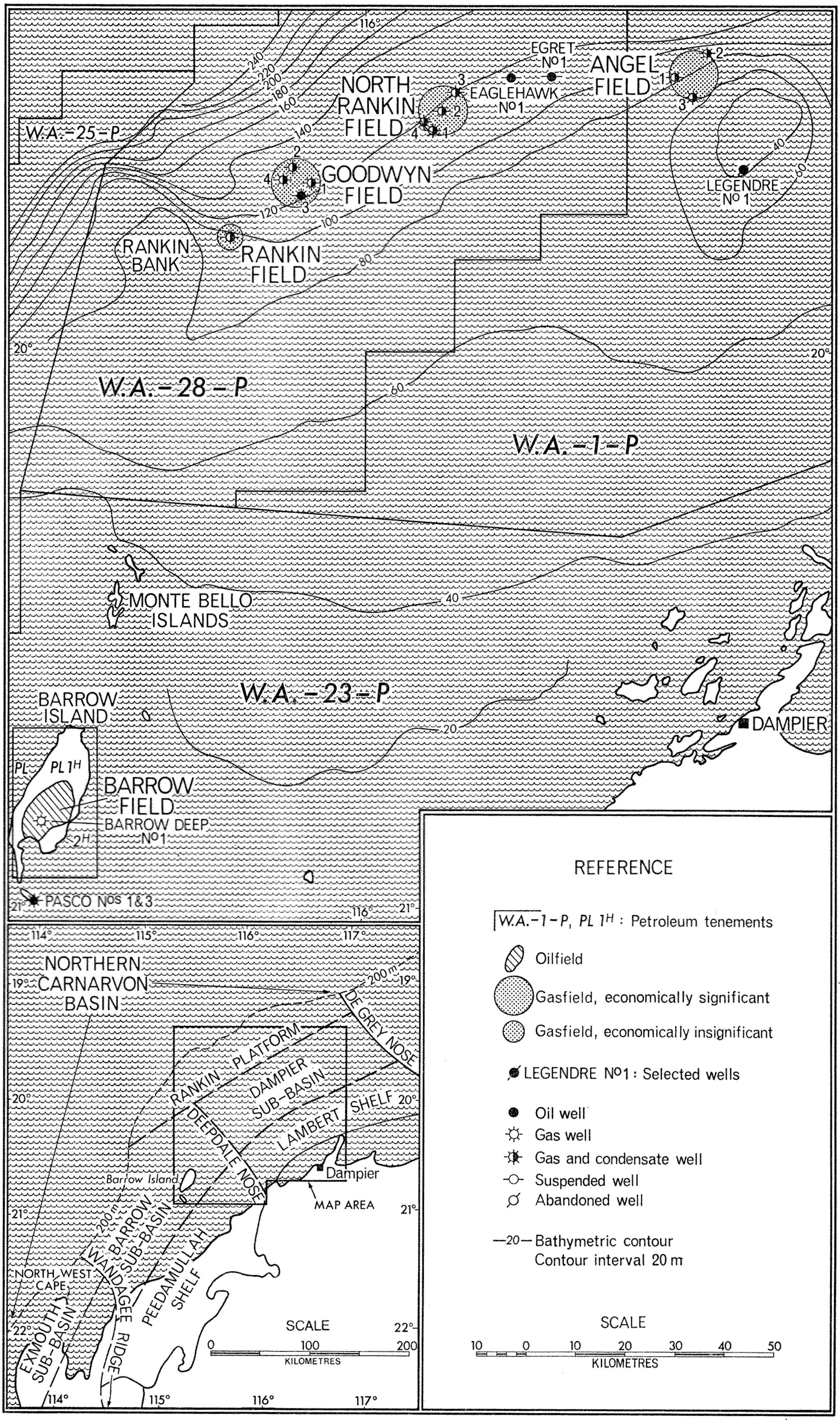

Figure 22. Northern Carnarvon Basin. Bathymetry and petroleum development. Inset map shows area of main map in relation to structural sub-divisions.

TABLE 5. BARROW ISLAND FIELD. PRODUCTION DURING 1973

Reservoir	Average daily prod. oil in m³ (bbls) during December, 1973	Production for year 1973					Cumulative production				
		Oil in m³ (bbls)	L.P.G. in m³ (bbls)	N.G. in m³ (bbls)	Water in m³ (bbls)	Gas 10³ m³	Oil in m³ (bbls)	L.P.G. in m³ (bbls)	N.G. in m³ (bbls)	Water in m³ (bbls)	Gas 10³ m³
Windalia	5 681 (35 754)	2 252 980 (14 177 711)	4,794 (30 169)	5 082 (31 978)	958 631 (6 032 540)	163 829	14 213 722 (89 445 107)	4 794 (30 169)	5 082 (31 978)	2 757 753 (17 354 182)	1 494 014
Muderong	51 (318)	20 237 (127 350)	....	....	9 210 (57 958)	3 423	154 597 (972 862)	....	....	34 942 (219 884)	23 392
Jurassic, 5 500′	....	....	....	....	....	....	2 476 (15 580)	....	....	16 150 (101 628)	14 577
Jurassic, 6 200′	....	....	....	....	....	....	9 136 (57 489)	....	....	19 697 (123 952)	80 563
Jurassic, 6 600′	36 (224)	10 911 (68 664)	....	....	28 311 (178 160)	2 587	47 522 (299 053)	....	....	84 846 (533 923)	20 606
Jurassic, 6 700′	30 (187)	11 339 (71 357)	....	....	7 673 (48 284)	11 023	177 682 (1 118 128)	....	....	50 341 (316 792)	94 636
Total Field	5 798 (36 483)	2 295 467 (14 445 082)	4,794 (30 169)	5 082 (31 978)	1 003 825 (6 316 942)	180 862	14 605 135 (91 908 218)	4 794 (30 169)	5,082 (31 978)	2 963 729 (18 650 361)	1 727 878

Water injected during 1973 : 5 895 243 m³ (37 098 000 bbls). Cumulative water injected : 28 081 914 m³ (176 715 839 bbls).

Table 5 gives the statistics of production by reservoir and product during 1973 and the cumulative production including that of 1973. Figure 23 shows the status of wells with respect to the main ("Windalia Sand") reservoir at the end of 1973. The various categories are shown in Table 6. Stripping of the solution gas was initiated in January 1973 and the products sold. Apart from limited demand for field-fuel and gas-lift in production operations, no commercially viable outlet for the unused gas can be found and 90.6 per cent was flared.

TABLE 6. BARROW ISLAND FIELD. WELL STATUS BY RESERVOIRS AT 31st DECEMBER, 1973.

Reservoir	Flowing	Pumping	Gas lift	Closed in	Water injection	Water source	Water disposal	Total
Windalia	16	177	110	15	158	9*	7†	492
Muderong..	2	3	3	....	....	....	....	8
Jurassic, 5 500′	....	....	....	·1	....	....	....	1
Jurassic, 6 200′	....	....	....	2	....	....	....	2
Jurassic, 6 600′	1	....	....	....	....	....	....	1
Jurassic, 6 700′	2	1	....	2	....	....	....	5
Total	21	181	113	20	158	9	7	509

*Completed in Barrow Formation.
† Completed in Cape Range Group.

The statistics relating to field-fuel gas, crude-oil disposal and royalty paid are shown in Table 7. Details of the development of the Barrow Island Field have been given in previous Annual Reports (e.g. Cope, 1972, 1973).

TABLE 7. BARROW ISLAND FIELD. OIL AND GAS DISPOSAL DURING 1973

	Oil m^3 (bbls)	Gas $m^3 \times 10^3$
Total Production	2 295 467 (14 445 082)	180 862
Field fuel	....	17 013
Oil shipments	2 314 043 (14 561 971)	....

Royalty paid : $1 362 522.

The subsurface geology of Barrow Island has recently been made public (Crank, 1973). Geochemical studies have revealed that in the Barrow Island Field, and in the Barrow Basin generally, the crude oils fall into two families. "Those occurring in Cretaceous reservoirs are naphthenic to aromatic in composition, while those in the Jurassic are paraffinic-naphthenic and have a high wax content" (Powell and McKirdy, 1973, p. 84).

Remaining reserves of crude oil in the Barrow Island Field in the proved and probable categories at the end of 1973 were 27.4 million m^3 (172 million barrels).

PASCO ISLAND FIELD

In 1967 three wells, Pasco Nos. 1, 2 and 3, were drilled on a then unnamed island (subsequently named Boodie Island), southwest of Pasco Island (Fig. 23). Wells 1 and 3 encountered oil and gas in Upper Jurassic sands of the Barrow Formation, but due to problems of logistics and product disposal they could not be tested adequately at the time of discovery. However, after suitable arragements had been made in 1973, Pasco No. 1 was production-tested between 26th January and 12th May. The results demonstrated that the field is sub-economic.

NORTH RANKIN FIELD

No further appraisal wells were drilled during 1973 in the North Rankin Field (No. 22). For the development of this important field to date, previous reports should be consulted (e.g. Cope, 1973).

On 29th March 1973, Woodside-Burmah Oil N.L. announced that it had received the independent assessment of reserves of the North Rankin Field which it had commissioned in the latter part of 1972. The press release added that the report of the consulting geologists (DeGolyer and MacNaughton) estimates proved and probable recoverable gas reserves was 223×10^9 m^3 (7.9×10^{12} CF). This represents a substantial reduction from the company's own preliminary estimate (in the combined proved plus probable categories) of 287×10^9 m^3 (10.17×10^{12} CF), released on 14th December, 1972. The 20th March, 1973 release attributed this reduction to further reservoir studies and seismic reinterpretation.

GOODWYN FIELD

At the start of 1973 Goodwyn No. 3 was being drilled. A further extension test well, Goodwyn No. 4, was drilled directly after No. 3 was finished (Low, 1974, Table 4). Test results were as follows:

Well No.	DST No.	Perforated interval m	Choke sizes (inches) bottom	Choke sizes (inches) surface	Gas flow 10^3 m^3/d	Liquid recovery type	Liquid recovery rate m^3/d	Liquid recovery gravity API
3	1	3 017–3 028	3/4	1/2	76	oil	434	41·7
....	2	2 988–2 996	3/4	3/4	....	water	394	....
....	3	2 881–2 893	3/4	3/4	487	condensate	187	50·9
4	1	2 900–2 901	3/4	5/8	306	,,	89	not released
....	2	2 858–2 905	3/4	3/4	483	,,	131	,,

The water depth over the Goodwyn Field is about 120 m. Substantial reserves will therefore be necessary for viable development. No reserves figure has so far been released for his field. However, subtraction of North Rankin reserves from those of the total for the three main fields results in a proved plus probable gas reserves estimate for the Goodwyn and Angel Fields of 158×10^3 m^3 (5.6×10^{12} CF).

ANGEL FIELD

The area around the Angel Field is one of poor seismic resolution, presumably owing to the absence of acoustic reflectors in the critical interval of the stratigraphic column.

Angel No. 3 was drilled during 1973 (see Low, 1974, Table 4). A drill-stem test over the interval 2 741-2 750 m yielded 220 000 m^3 per day of gas accompanied by 45 m^3 per day of condensate, using a ⅝ inch bottom choke and a ½ inch surface choke.

NORTHERN PERTH BASIN

GENERAL

Petroleum tenements in the northern Perth Basin are illustrated in Figures 24 and 25, and also in Low, 1974, Figure 21. Important developments affecting the tenements over the past 10 years may be summarized as follows.

The discovery of oil and gas in Yardarino during 1964 was followed by gas discoveries in Gingin No. 1 (1965), Dongara No. 1 (1966), Mondarra No. 1 (1968), and Walyering No. 1 (1971). Locations 1 and 2 were declared on 29th January 1971 and 26th March 1971 respectively, to cover the Yardarino, Dongara and Mondarra Fields. Location 3 was declared on 17th September 1971 to cover the Walyering Field.

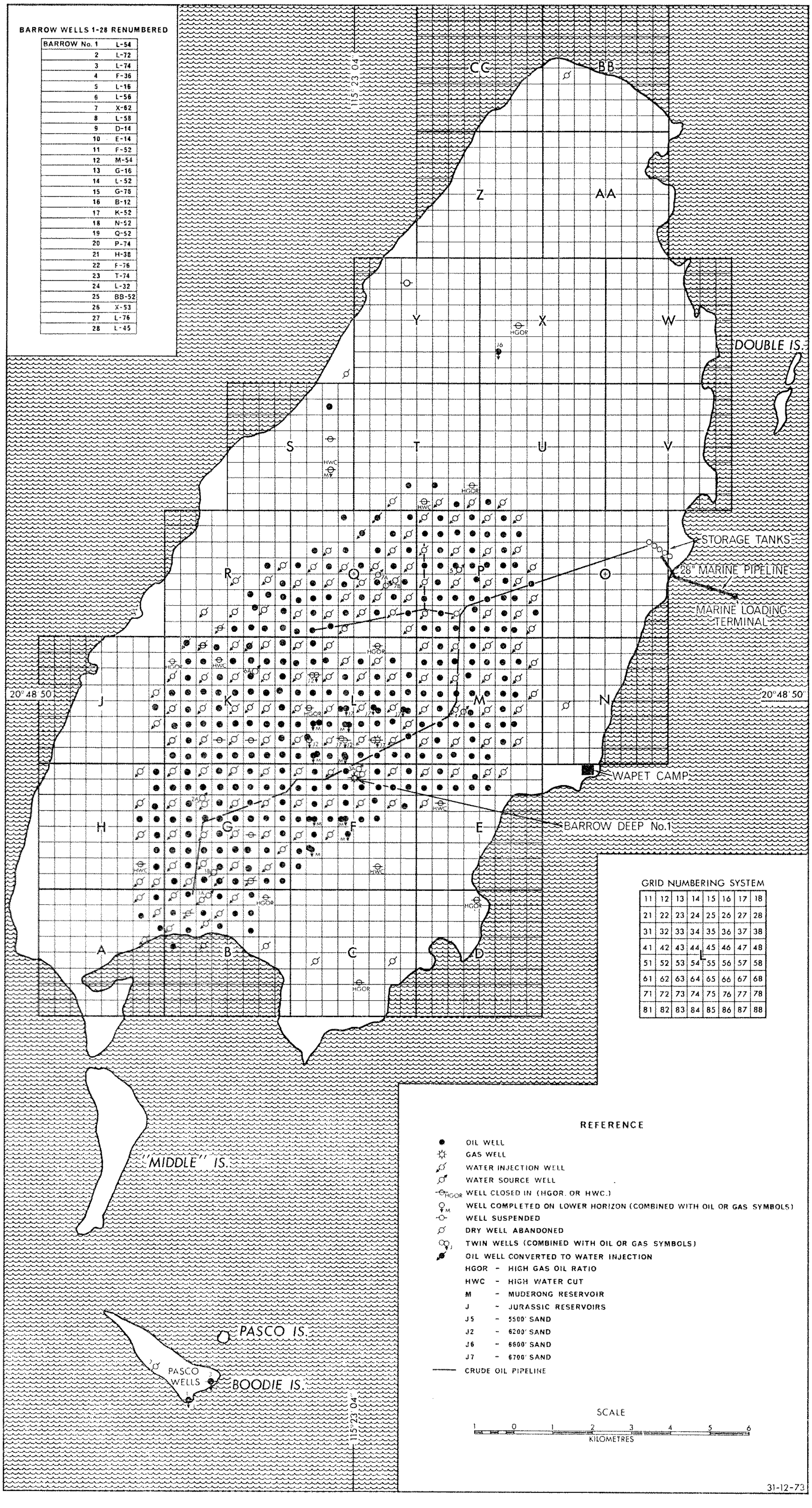

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Figure 23. Barrow Island Field, northern Carnarvon Basin. Status of wells with respect to the "Windalia Sand" reservoir.

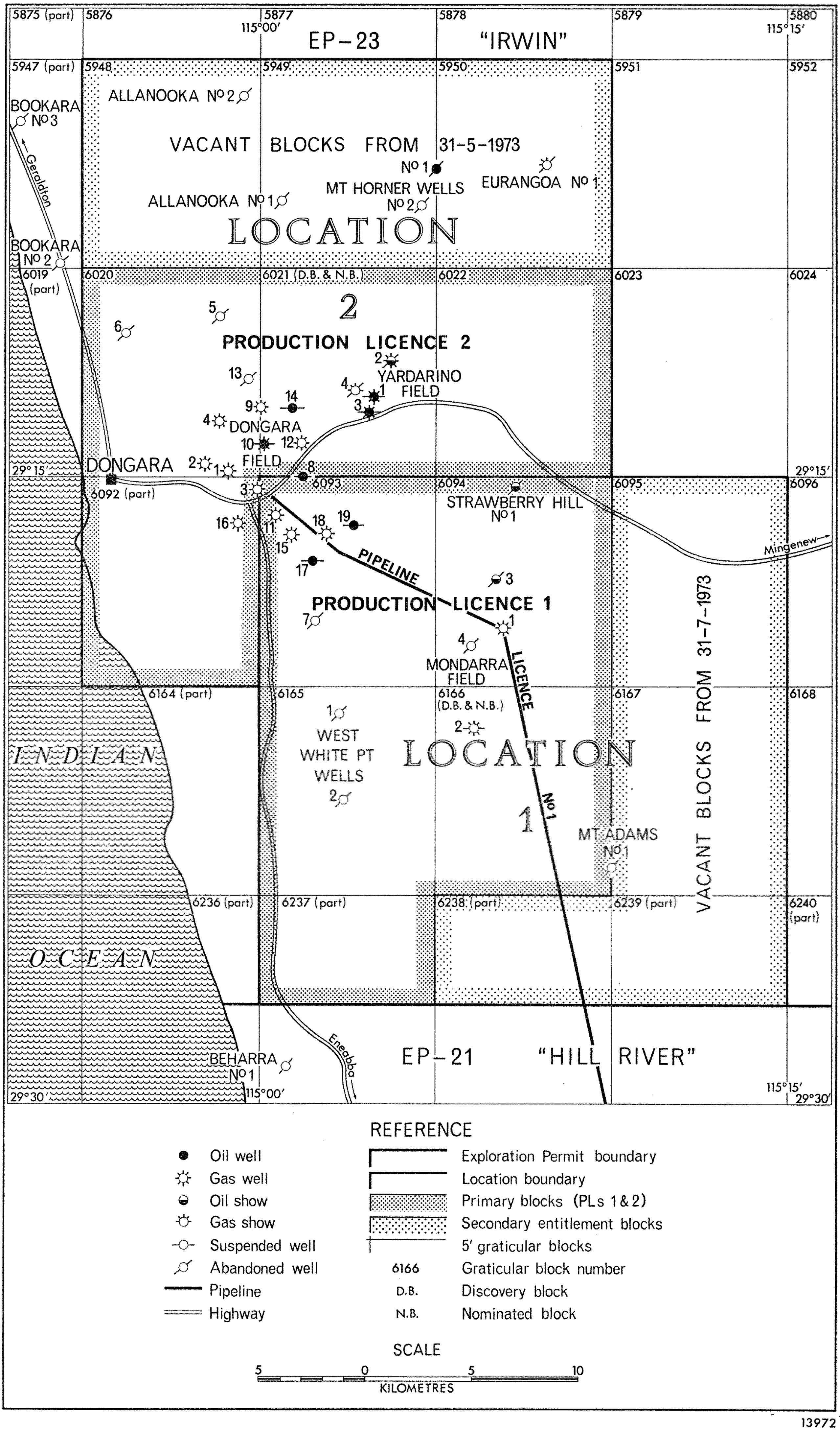

Figure 24. Dongara area, northern Perth Basin. Status of petroleum tenements and wells (Perth Sheet; 1 : 1 000 000 Map Series).

Appraisal drilling of the Dongara and Mondarra Fields was carried out between 1966 and 1970. Gas reserves have been put at about $12\,600 \times 10^6$ m^3 (450×10^9 CF). After market studies in the Perth area a 415 km long 36 cm pipeline was laid (see Cope, 1972, Fig. 16). Production was started on the same day that the Wapet applications for Production Licences 1 and 2 were approved, i.e. 25th October, 1971. Monthly gas production from the Mondarra and Dongara Felds to the end of 1973 is illustrated in Figure 26.

The originally planned pipeline route was diverted to take in the Walyering No. 1 well and Production Licence 3 was approved, also on 25th October, 1971, covering the Walyering Field (Fig. 25). For the details of production testing of Walyering No. 1 and Gingin No. 1 during 1972 see Cope (1973), p. 42 and 43 and Figure 17.

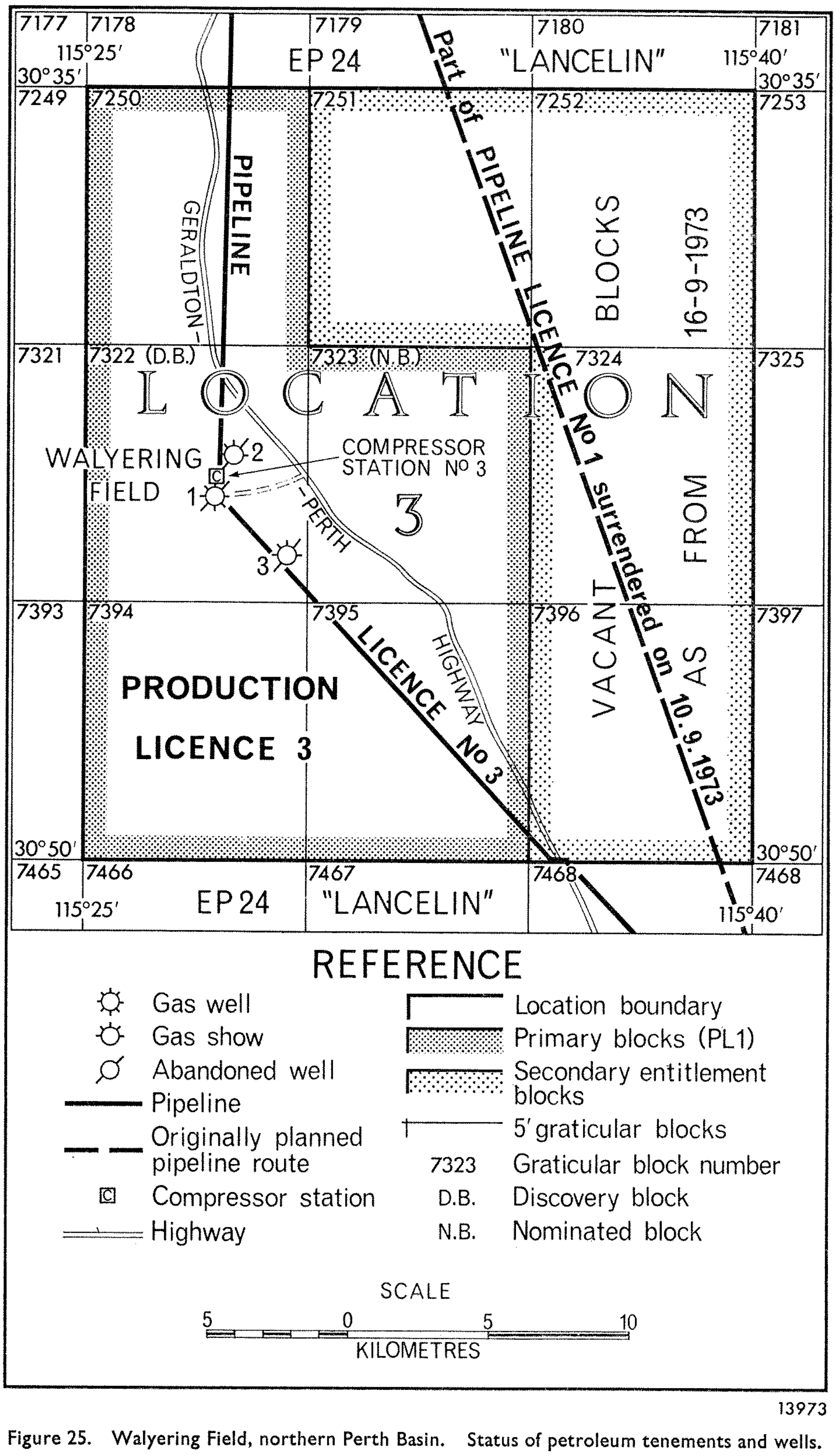

Figure 25. Walyering Field, northern Perth Basin. Status of petroleum tenements and wells.

TABLE 8. DONGARA AND MONDARRA FIELDS. PRODUCTION DURING 1973

Field	Number of producing wells at 31–12–73	Average daily production during December, 1973		Production for year 1973			Cumulative production		
		Gas 10^3 m^3	Condensate m^3 (bbls)	Gas 10^3 m^3	Condensate m^3 (bbls)	water m^3 (bbls)	Gas 10^3 m^3	Condensate m^3 (bbls)	Water m^3 (bbls)
Dongara	10	1 920·7	9·0 (56·7)	756 206	3 731 (23 481)	3 031 (19 074)	1 360 734	7 601 (47 834)	5 640 (35 491)
Mondarra	1	125·8	2·6 (16·4)	59 281	1 195 (7 517)	247 (1 553)	102 475	2 152 (13 541)	482 (3 034)
Total	11	2 046·5	11·6 (73·1)	815 487	4 926 (30 998)	3 278 (20 627)	1 463 209	9 753 (61 375)	6 122 (38 525)

Total gas sold in 1973 = 809 629 x 10^3 m^3. Total royalties paid = $A320 741.

DONGARA, MONDARRA AND YARDARINO FIELDS

Production from the Dongara and Mondarra Fields during 1973 is given in Table 8. The status of the petroleum tenements and the wells at the end of the year is shown in Figure 24. Using the approximate initial gas reserves figure of 12 600 x 10^6 m^3 the remaining reserves at the end of 1973 were 11 090 x 10^6 m^3 (about 400 x 10^9 CF).

Upon declaration of Production Licences 1 and 2 the balance of the total number of blocks in Locations 1 and 2 were available for application by Wapet within the prescribed time limit. In neither case was the option exercised. The three-block secondary entitlement of Location 2 was excised from EP-23 on 31st May and the four-block secondary entitlement of Location 1 also from EP-23 on 31st July, 1973 (W.A. *Government Gazette* of 25th January, 1974). At the end of 1973 all the excised blocks were vacant.

WALYERING FIELD

As with Locations 1 and 2 Wapet did not exercise its option to apply for the four secondary entitlement blocks in Location 3 (Fig. 25). On 16th September, 1973, the four blocks were excised from EP-24 and at the end of 1973 they remained vacant. In the fourth quarter, an application from Wapet to surrender Production Licence 3 was registered. The application was dated 26th October, 1973.

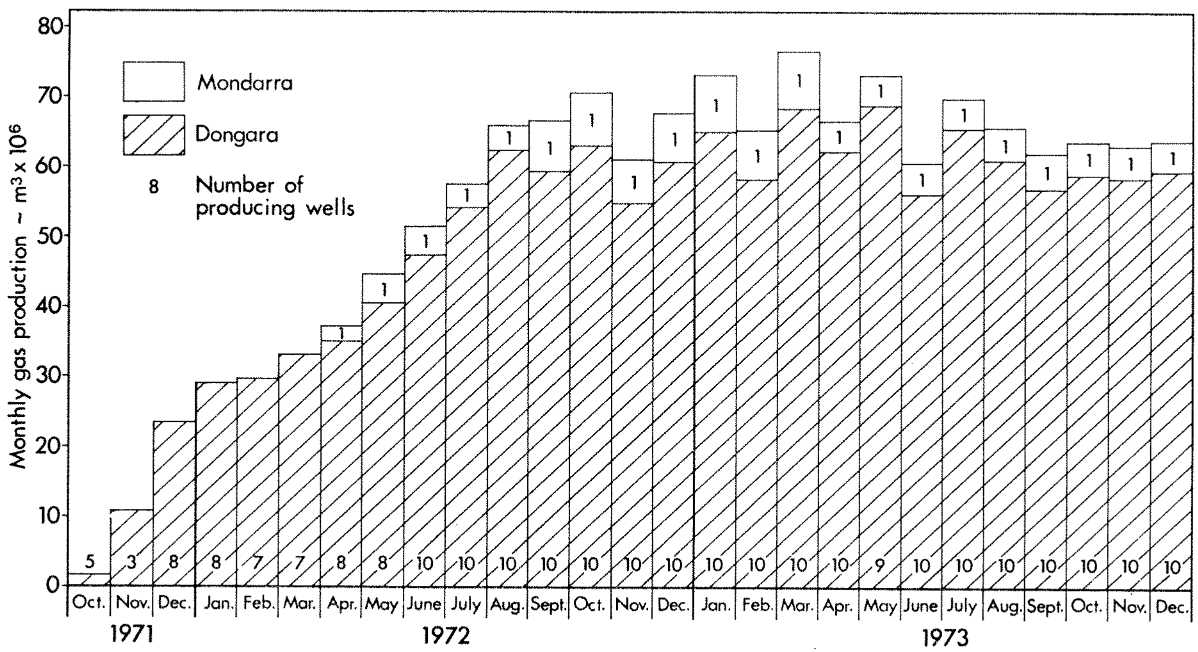

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Figure 26. Mondarra and Dongara Fields (Production Licences 1 and 2), northern Perth Basin. Monthly gas production between 25th October, 1971 and 31st December, 1973.

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PALAEODRAINAGES AND CAINOZOIC PALAEOGEOGRAPHY OF THE EASTERN GOLDFIELDS, GIBSON DESERT AND GREAT VICTORIA DESERT

by J. A. Bunting, W. J. E. van de Graaff and M. J. Jackson*

ABSTRACT

The salt-lake chains of the arid interior of Western Australia are the remnants of ancient river courses. Based on topographic contour maps a reconstruction of these palaeodrainages has been made. The river systems formed between the Early Cretaceous and the Late Eocene, and have been inactive since the Middle Miocene.

The rivers in the southern part of the area studied once flowed to the Southern Ocean via the Eucla Basin, while those in the north flowed to the Indian Ocean via the Canning Basin. Extensive river capture of some southerly flowing streams has taken place by rivers that flowed to the north.

The uplift of Western Australia since the Eocene has been very uniform, and only minor tilting has occurred.

INTRODUCTION

As part of the geological mapping projects of the Officer Basin and the Eastern Goldfields topographic contour maps of the area, shown in Figure 27, were produced. These maps are of great importance for the reconstruction of palaeodrainages as marked by the present day salt-lake systems, and generally for the unravelling of the Cainozoic history of the area. The contour maps were drawn using spot-height data obtained by the Bureau of Mineral Resources during regional gravity surveys of Western Australia. Most of the State has now been covered by these surveys and the results are available as maps on 1 : 250 000 scale. The elevations of the gravity stations, which are spaced at intervals of approximately 11 km, have been determined barometrically. As a result, altimetric information for large areas of the State is available for the first time.

The aim of this paper is to present some ideas generated by the new topographic maps and information gained during the current regional mapping programme.

Gibson (1909, 1912) and Gregory (1914, 1916) were the first to interpret the numerous salt lakes in the arid interior of Western Australia as remnants of ancient river courses. Jutson (1934), on the other hand, argued that the present-day salt lakes cannot be considered as damned portions of dismembered rivers.

However, the new evidence shows that the lakes occur in broad interconnected valley systems. Some continue into relatively deep valleys with strings of small, partly interconnected lakes and are very clearly old river courses, for example those of Ponton Creek and Salt Creek (which occasionally flow today) and Serpentine Lakes. The evidence, therefore, favours the interpretation that the salt-lake systems mark old drainage lines developed during a period of considerably higher precipitation than that of today.

Since Gregory (1916) made a first attempt, a number of writers (Jackson, 1966; Morgan, 1966; Lowry, 1970; Mulcahy and Bettenay, 1972; Beard, 1973; Sullivan, 1973 among others) have presented reconstructions of parts or all of the palaeodrainage systems in Australia. These reconstructions were based on the general distribution of the salt lakes, soil mapping (Mulcahy and Bettenay, 1972), vegetation mapping (Beard, 1973), information on flows of water, and scant altimetric information. In the areas underlain by Precambrian rocks the old drainage lines are relatively well defined and easy to recognise. In the Gibson and Great Victoria Deserts, however, a thick sand dune cover in many areas makes it difficult or impossible to trace the old drainage lines directly between clay pans and salt lakes. Nevertheless, it is locally feasible to reconstruct large parts of the ancient drainage systems by tracing soil and vegetation patterns on aerial photographs. Because of the very gentle relief in most of the desert areas it is, however, difficult to take topography into account when tracing the old drainages. This has unavoidably led to serious errors in earlier reconstuctions. In the lower reaches of the major trunk valleys, where topographic relief is often nearly imperceptible, it is essential to have reliable altimetric information in order to trace the older river courses. The upper reaches of a drainage system are fairly easy to reconstruct. For example Figure 28, which was produced before the spot-height data were available, shows the palaeodrainages on the Warri Sheet area (SG/51-4).

METHOD OF CONTOURING

The barometric spot-height data are sufficiently accurate and reliable to permit topographic contouring on a regional scale, although some heights and/or positions can be shown to be inaccurate. An attempt was made to prepare computer-drawn contour maps, but this was not satisfactory, owing to the wide spacing of the data. In order to draw realistic contours all topographic information visible on air-photographs must be taken into account. This means that much of the contouring is necessarily subjective. Moreover, the data have been contoured on the assumption that the palaeodrainages form an integrated valley system, and it has been further assumed that the infilling of the valleys, which dismembered the ancient rivers, did not produce topographic irregularities of sufficient magnitude to completely obscure the valley forms. That the drainage systems were indeed integrated can be easily observed in parts of the Gibson Desert, where a dendritic dry valley system is present over Cretaceous claystones and siltstones (Fig. 28). Because of the absence of sand-dune cover even very small valleys can be recognized on air-photographs. The variations in the density of the drainage system in this area are mainly due to subsequent erosion which has obliterated some parts of the valley system.

Apart from the gravity-survey data there is also altimetric information in the form of accurately levelled benchmark traverses (only the heights shown on the maps are accurate, the plotting of the benchmark positions is often inaccurate) and other spot-height data. However, these various sets of data show systematic differences. Therefore, only the gravity-survey data have been used to determine the course and location of the contours whereas the other data have only been used to differentiate low and high areas. At a few locations a single inconsistent spot-height elevation has been disregarded but the discrepancy rarely exceeds a few metres.

Although the contours are partly interpretative, the fact that they can be drawn in the shape of integrated valley systems is very significant.

* Bureau of Mineral Resources.

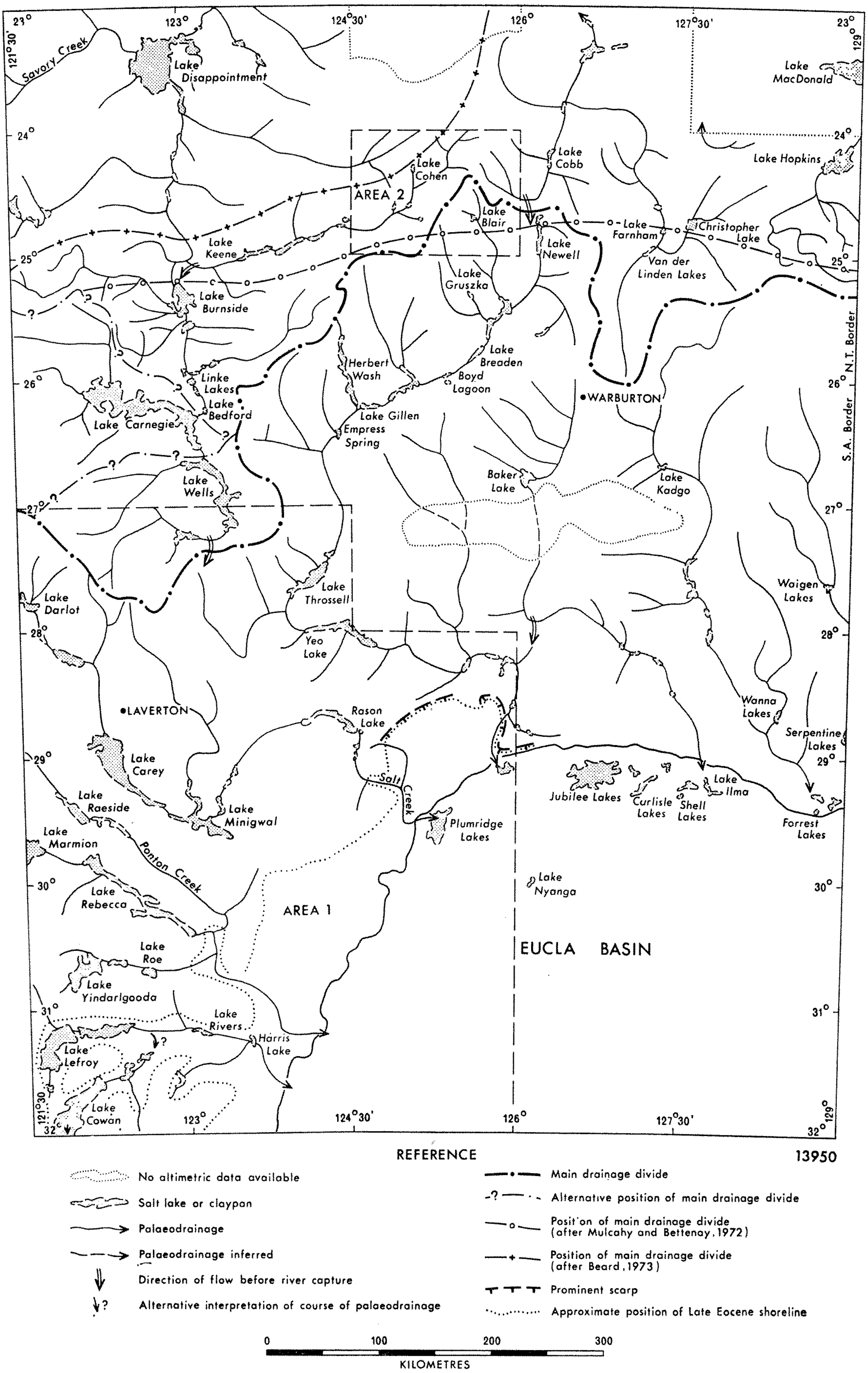

Figure 27. Palaeodrainage of part of the arid interior of Western Australia. (Inset 1, see Fig. 29; inset 2, see Fig. 28).

Figure 28. Palaeodrainage on the Warri Sheet (SG/51-4).

GENERAL ASPECTS OF PALAEODRAINAGE SYSTEMS

One important conclusion is that the major drainage divide between ancient drainage systems which once flowed to the Indian Ocean via the Canning Basin, and those systems which flowed to the Southern Ocean, generally has a more southerly position than that suggested by previous authors (Fig. 27). Another important conclusion is that the configuration of some of the drainage systems is strongly suggestive of large-scale river capture. The capture was mainly by the rivers that drained towards the northwest. The first example of river capture is the Lake Cobb system, which has captured the southeast-flowing headwaters of the Lake Throssell system (to the north of the mapped area the Lake Cobb-Lake Farnham system enters an enclosed depression which may be of relatively recent tectonic origin). The Lake Disappointment system has captured a very substantial number of streams. The northernmost of these is probably the Lake Keene system. The west-southwest orientation of the Lake Keene system strongly suggests that it originally formed part of a southwardly discharging system. As far south as Lake Bedford all originally south-flowing palaeodrainages have been captured by the north-flowing Lake Disappointment system. Though the data are not conclusive it seems very likely that Lake Carnegie and Lake Wells were also captured by the Lake Disappointment system. A third example of probable river capture is present in the Baker Lake system. From the map configuration it is inferred that the Baker Lake system was originally a tributary of the lower reaches of the Lake Throssell system. Other cases of river capture probably occur in the southwestern part of the study area, and are discussed below.

The orientation and texture of the various parts of the drainage system is determined to a large extent by bedrock geology. The finely-textured drainage pattern (Fig. 28) is characteristic of the relatively impermeable claystones and siltstones, which are mostly Cretaceous. On the predominantly sandy bedrock in the remainder of the Gibson and Great Victoria Deserts a much more coarsely textured drainage pattern is present. On the sedimentary rocks the drainage pattern is dendritic at an areal scale (Fig. 28), but at a regional scale it has a somewhat parallel aspect. The pronounced parallelism of the tributaries of the upper parts of the Lake Throssell and Baker Lake systems, that have their tributaries occurring to the northwest of the main valley, is suggestive of an extremely gentle cuesta-type topography.

Another instance where bedrock geology obviously determines the course of the palaeodrainage is that of the Lake Disappointment system, which runs almost due north-south along the contact between the Proterozoic and Phanerozoic sediments.

In the Precambrian basement areas, bedrock geology only locally affects the orientation of the palaeodrainages. In part of Lake Raeside, where it follows the eastern flank of the Edjudina Range, and parts of Lake Rebecca, there is an obvious relationship between lake orientation and basement strike.

EASTERN GOLDFIELDS, EUCLA BASIN, AND WESTERN GREAT VICTORIA DESERT

The area depicted in Figure 29 exemplifies most of the important aspects of the palaeodrainage systems in the study area.

Age of the palaeodrainages

No precise age of the palaeodrainages can be established, and it is likely that the age varies from district to district. There is, however, a concensus of opinion that since the Miocene little flow of water occurred in the rivers draining towards the Eucla Basin (Jackson, 1966; Morgan, 1966; Lowry, 1970; Beard, 1973). This contention is based on the observation that none of the major valleys which are recognizable in the Eastern Goldfields or in the Great Victoria Desert continue across the Eucla Basin, which is surfaced by

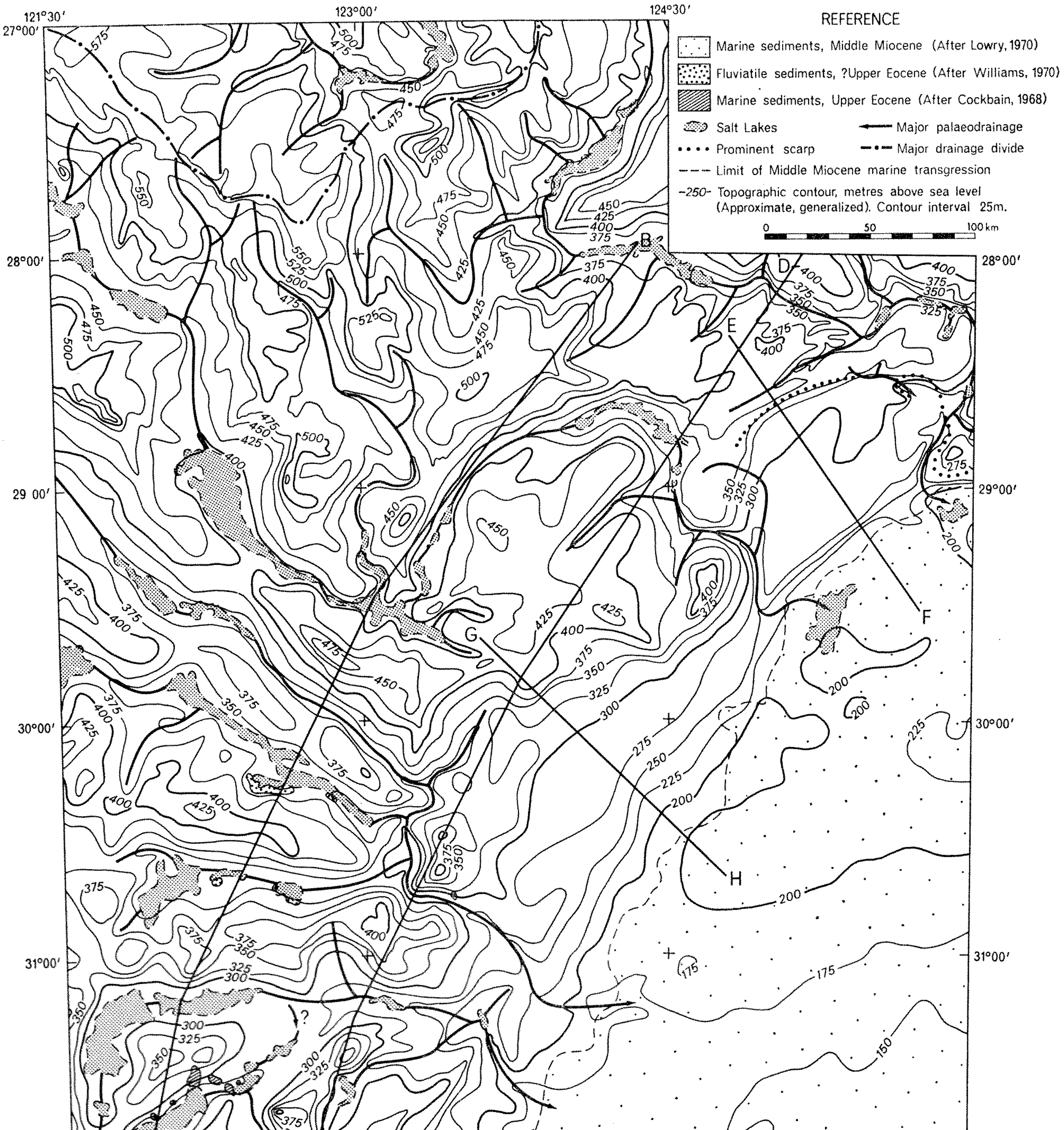

Figure 29. Topographic contour map of parts of the Eastern Goldfields, Great Victoria Desert and Eucla Basin.

Miocene limestone. At the discharge points of some of the valleys along the basin margin, groups of salt lakes have formed, e.g. Forrest Lakes, Plumridge Lakes. Other palaeodrainages have not given rise to any major salt lake at the discharge point, e.g. Ponton Creek. Also there are some salt lakes on the northern part of the Eucla Basin area which have no obvious relationship with a palaeodrainage discharge point (Jubilee Lakes). Though Lowry (1970) has mapped a number of ancient drainage lines in the Eucla Basin area, these do not appear to be related to the integrated systems farther north. The inference is that although some rivers which flowed across part or all of the Eucla Basin did exist in Late Miocene or more recent times, they were of relatively minor importance. The valley systems in the adjoining areas must have formed before the sea finally retreated from the Eucla Basin. As the youngest sediments in the Eucla Basin are of Middle Miocene age, the palaeodrainages are of pre-Middle Miocene age.

The distribution of laterite also points to a pre-Middle Miocene age for the palaeodrainages. A laterite duricrust is widespread in the area, except in the Eucla Basin where it is conspicuously absent. The lateritic crust follows the shape of the valley (cf. Mulcahy and Bettenay, 1972, p. 353) and therefore must have formed while valley formation was still taking place. Under the present arid to semi-arid climate laterite cannot form; substantially higher precipitation is necessary for the formation of a lateritic profile. It is obvious that for the formation of a well-developed river system, such as depicted in the accompanying illustrations, a high humidity climate is required. Jennings (1967 a, b) and Lowry (1970) argue, mainly on the basis of geomorphological evidence, that for long periods, since the Miocene, the climate of the Eucla Basin has never been much more humid than at present.

Geomorphological evidence on the Neale Sheet area permits palaeodrainages in the Great Victoria Desert to be more accurately dated. Across the Neale Sheet area runs a scarp (Fig. 29, also Lowry, 1970, Fig. 52), which separates a plain of very gentle relief in the south from the undulating laterite surface in the north (N.B. only the approximate position of the crest of the scarp is shown on the maps). The maximum height of the scarp is of the same order as the contour interval, and therefore it does not stand out very clearly on the contour map (Fig. 29). In the field, however, it is quite conspicuous and it is expressed very clearly on aerial photographs.

The scarp and the plain to the south have been modified only slightly by the palaeodrainages. Even where the Lake Throssell river system crossed the scarp there is no incised valley. Some palaeodrainages can be traced across the plain, but topographic relief is much more gentle and subdued than the adjoining parts of the Great Victoria Desert. Thus it is probable that the palaeodrainages system formed before the development of the scarp and plain, but that some flow continued afterwards.

The scarp and the rather featureless plain to the south are interpreted as a marine erosion scarp and platform. They occur at considerably higher elevations than the northernmost marine sediments of Middle Miocene age (29°S, 126°E). The scarp has been lateritized and is therefore older than the unlateritized Miocene sediments. It seems most likely that the scarp and plain formed during the Late Eocene transgression, represented in the Eucla Basin by the Wilson Bluff and Toolinna Limestones and in the Eastern Goldfields by the Eundynie Group. In the Gibson Desert the palaeodrainage systems developed on Lower Cretaceous strata and therefore the main period of major valley formation in the Gibson and Great Victoria Deserts was between the Early Cretaceous and Late Eocene. On those areas of the Precambrian shield not covered by the Early Cretaceous transgression the palaeodrainage features may, in part, be much older.

The Late Eocene Marine Transgression

Marine sediments consisting of spongolite, dolomite and limestone, collectively called the Eundynie Group outcrop along the shores of Lake Cowan. These have been dated on fossil evidence as Late Eocene (Cockbain, 1968). Similar spongolite crops out on the northern side of Ponton Creek 3 km south of Cundeelee Mission. The Lake Cowan sediments range in elevation from 270 to 300 m and the Ponton Creek outcrop is at 300 m. The range in elevation of the base of the possible Late Eocene scarp mentioned above is about 270 to 320 m. This range may be due to minor tilting, but erosion and sand migration subsequent to its formation are equally likely interpretations. It has to be stressed however, that only the crest of the scarp has been mapped. The position and elevation of its base are unknown as it is covered by recent sediments. The approximate limit of the Late Eocene transgression can therefore be drawn at about the 320 m contour in the Neale-Plumridge area, gradually falling to 280 m at Lake Cowan. The change in elevation is similar in magnitude to that shown by the Middle Miocene shoreline (see Fig. 29) and is probably due to slight warping of the shield. The position of the Late Eocene shoreline is also illustrated by profiles E-F and G-H (Fig. 30). Profile E-F shows two distinct steps, a lower one with the western limit of Miocene sediments at its base, and an upper one, between 325 and 375 m marking the prominent scarp. Two similar, if more subdued steps occur along line G-H.

Lowry (1970, p. 156-157) suggests that the 1 000 ft (305 m) contour is the limit of the Late Eocene transgression and shows an arm of sea extending inland to include the whole of Lake Rebecca. It is probable that this arm extended no farther than the lowermost reaches of Lake Rebecca. Pre-laterite fluviatile sediments of possible Late Eocene age (Williams, 1970) occur along the shores of Lake Rebecca and Lake Roe indicating that these areas may have been continental at that time.

Topographic Profiles

Two profiles, A-B and C-D are shown in Figure 30. These are approximately 180 and 100 km respectively from the line marking the western limit of Miocene marine sediments. Profile A-B shows a steady rise in elevation from SW to NE. This is best illustrated by the successive steps of the salt lake floors from Lake Cowan (265 m) to Lake Minigwal (395 m). The trend continues south of Lake Cowan with a further fall of 20 m to Lake Dundas. The magnitude of the steps is generally greater than the gradual falls along the lengths of the individual lakes (e.g., the Lake Carey-Minigwal system drops only 10 m in 200 km). It is suggested that these features could be due to a gentle upwarp of the shield after the development of the river system but before the Late Eocene marine transgression. The same warping could account for the capture of Lake Minigwal by the Lake Rason system.

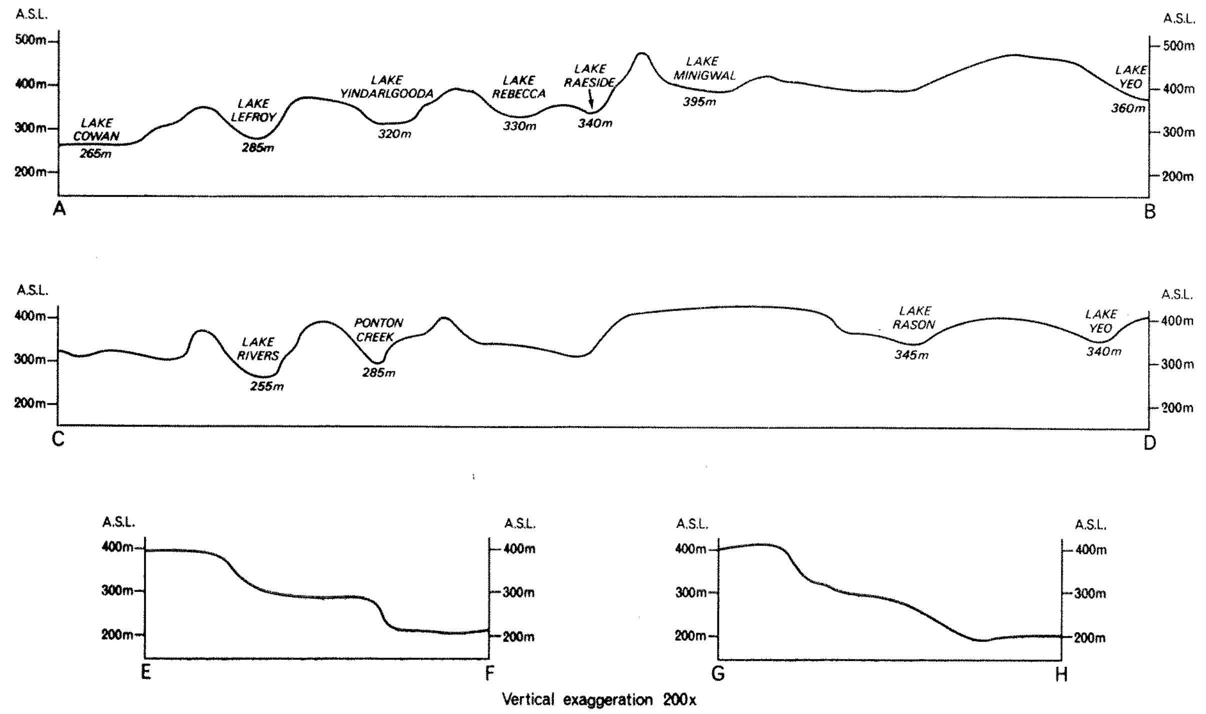

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Figure 30. Topographic profiles (for location of section lines see Fig. 29).

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INDIVIDUAL DRAINAGE SYSTEMS

Some of the features of the area shown on Figure 29 will now be discussed from the viewpoint of the individual drainage systems.

Lake Throssell System

One of the most conspicuous features of the Lake Throssell system is the sharp change in direction between Lake Throssell and Lake Yeo. The southwest flowing Lake Throssell drainage turns abruptly on approaching the Archaean Yilgarn Block, and continues east-southeast, roughly parallel with the edge of the shield, through Lake Yeo. Minor uplift and tilting of the shield margin early in the development of the drainage system may have contributed to the sharp change in direction.

Lake Carey—Minigwal system

Most major lake systems draining the eastern Yilgarn Block discharge southeastward into relatively narrow, deep valleys (e.g., Ponton Creek, Salt Creek). These disappear at the westernmost limit of the Miocene marine sediments. The Lake Carey-Minigwal system is unusual in having no such valley. It appears not to have reached even the Eocene coastline, although it may at some stage have flowed into the northern reaches of Ponton Creek. It is suggested that at some time before the Late Eocene, the Lake Carey-Minigwal system was captured by the Lake Rason system possibly due to crustal uplift, and subsequently flowed to the Eucla Basin via the Salt Creek system.

Lake Raeside system

The Lake Raeside system and its tributaries, the Lake Rebecca and Lake Yindarlgooda systems, discharged through the deeply incised Ponton Creek. The distinctly parallel Lakes Raeside and Rebecca make an angle of about 30 degrees with the general strike direction of the Archaean basement rocks.

Lake Lefroy system

The Lake Lefroy system probably discharged through Harris Lake into the Eucla Basin. The topographic data, however, are inconclusive and it is possible that Lake Lefroy drained through Lake Cowan. It is more likely that when the palaeodrainages ceased regular flow the Lake Cowan system was on the point of capturing the upper reaches of the Lake Lefroy system. That the Lake Cowan system was actively capturing streams at that time is indicated by the presence of a northwestward-trending tributary which logically would have formed part of the Lake Lefroy system.

CONCLUSIONS

The uplift of the central parts of Western Australia since the Miocene has been remarkably uniform with only minor warping. This is clearly demonstrated by the fact that palaeodrainages which formed before the Late Eocene and which stopped flowing during or soon after the Middle Miocene, can be reconstructed by drawing topographic contours of the present land surface. The same very gentle uplift is demonstrated by the gentle slope to the south of the Middle Miocene shoreline. The position of this shoreline corresponds approximately with the present extent of the Eucla Basin. The general evidence of the Late Eocene transgression around the 300 m contour also indicates uplift with very little tilting (Johnstone and others, 1973), although there was probably some upwarping in pre-Late Eocene times centred on Lake Minigwal.

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RECENT PROGRESS ON THE PRECAMBRIAN STRATIGRAPHY OF WESTERN AUSTRALIA

by R.D. Gee

INTRODUCTION

The accompanying chart summarizes recent progress on the Precambrian stratigraphy of Western Australia (Fig. 31). It updates the summary of Horwitz (1968), and is presented within the framework of the Precambrian tectonic units after Daniels and Horwitz (1969). The subdivision of the Yilgarn Block is after "The Geology of Western Australia" (G.S.W.A., in press).

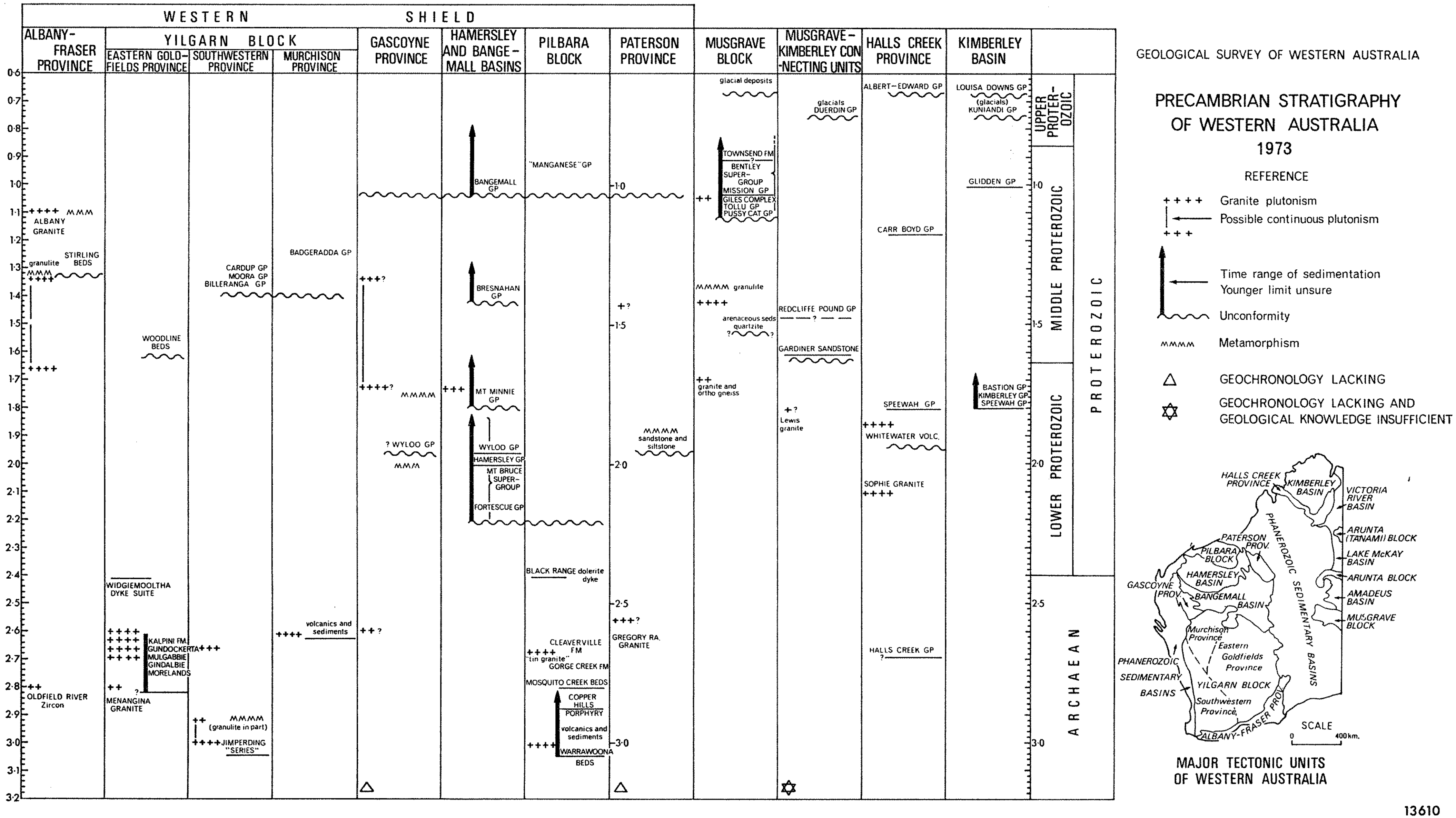

Figure 31. Precambrian stratigraphy of Western Australia.

RECENT GEOCHRONOLOGY

A joint geochronology programme between the Geological Survey of Western Australia and the Western Australian Institute of Technology has been operating since 1968. The more notable results include a younger limit of 2 200 m.y. for the base of the Mount Bruce Supergroup (de Laeter and Trendall, 1971), and the confirmation of two episodes of granite intrusion of 3 120 m.y. and 2 670 m.y. in the Pilbara Block (de Laeter and Blockley 1972). Geochronology studies at the Australian National University have documented a period of widespread granitic activity in the Yilgarn Block at 2 600-2 700 m.y., and an earlier period of plutonism and high-grade metamorphism at 2 900-3 100 m.y. that was confined to the Southwestern Province (Arriens, 1971). Finally, there is an age of 1 630 m.y. on the glauconitic Gardiner Sandstone that unconformably overlies the basement rocks of the Tanami Block (Blake, Hodgson and Muhling, 1973).

SUBDIVISION OF THE PRECAMBRIAN

The Geological Survey of Western Australia uses a two-fold subdivision of the Precambrian. The Western Shield contains two roughly equant cratonic blocks of mostly granitic and volcanogenic rocks that record ages (whole-rock Rb/Sr) older than 2 600 m.y. These blocks are surrounded by either thick basins of continental-type sediments, or wide belts of metamorphism and plutonism that record ages younger than 2 200 m.y. This forms the basis of two divisions which are conveniently called Archaean and Proterozoic. On geological grounds the natural position of the boundary in Western Australia lies somewhere between 2 600 m.y. and 2 200 m.y. although it should be noted that the base of the Mount Bruce Supergroup may be older than that shown on the chart. The boundary at present is set at 2 400 m.y. by a date on the Widgiemooltha Dyke Suite. This allocation is justified on the premise that the mafic dykes, that cut both the Yilgarn and Pilbara Blocks, indicate stabilization of the Archaean terrains. The current application of this figure (2 400 m.y.) does not preclude the possibility that the boundary may be diachronous. It will be noted that there is a tendency here to use the term Archaean in a tectonic sense rather in a strict time sense.

For descriptive regional geology, the Survey does not use a time-stratigraphic subdivision of the Proterozoic. Such studies are fitted to a framework of rock-term stratigraphy, magmatism, metamorphism and isotopic ages. However, for convenience in communication, especially with the limited number of isotopic dates available at present, the terms Lower, Middle and Upper Proterozoic are used. The boundaries (1 640 m.y. and 880 m.y.) although taken from the Canadian Shield (Stockwell, 1964), are arbitrary, and bear no implied relationship to major tectonic and magmatic cycles in the Western Shield of Australia. There are no present intentions to vary these figures to follow the changes in the boundaries in Canada (for example, Stockwell, 1970, p. 51; Stockwell, 1972), or to bend the boundaries to fit major geological events in the Western Shield. The status of the terms Lower, Middle and Upper may well decline and become informal adjectives.

The outline of a single sedimentary-magmatic cycle is emerging for the entire Western Shield. This involves long and continued sedimentation commencing no later than 2 200 m.y., followed by widespread metamorphism and plutonism peaking at about 1 400 m.y., and terminating at about 1 100 m.y. The resultant terrains are unconformably overlain by gently folded and unmetamorphosed sedimentary rocks of an age about 800-1 000 m.y. It is considered premature to erect a time-stratigraphic sub-division punctuated by major events of the above nature. In view of the possibility of diachronous tectonic events on a continental or global scale, it is questionable whether such an approach is even desirable. As an example of the possible difficulties that this approach may encounter, it is notable that the base of the Carpentarian (Dunn, Plumb and Roberts, 1966) in the Kimberley area, has no counterpart in the Western Shield.

ARCHAEAN STRATIGRAPHY

Recent geological mapping has concentrated on the Archaean terrains of the Yilgarn Block, of which 40 per cent are now mapped. Data are presented on lithological maps, but stratigraphic analyses have employed the concept of the association (Williams, 1973). The Archaean succession is composed of consanguineous lithological groups, for example mafic volcanic, felsic volcanogenic, arenaceous groups. The individual lithologies may be complex, but are related by a consistent spatial association, and a common volcanic or sedimentary regime. The associations are formalized and generally given formational status. The association is related to the formal term "group" (Australian Code of Stratigraphic Nomenclature, 1964), although this latter term has not been used because the constituent units of the association are generally not established.

Superposition of associations has been demonstrated in several places, especially in the Eastern Goldfields Province, where the multicycling of several mafic and felsic associations is recognized. Within the Archaean succession consistent stratigraphical relationships between associations can be deduced from facing evidence and established regional fold structures. A regional, composite stratigraphic succession can then be postulated. However, where discrete volcanic centres or piles are identified and lateral variation occurs between volcanic rocks and volcanoclastic sedimentary rocks, the correlations can be tenuous.

The search for a sialic basement to the Archaean granite-volcanogenic terrains has not been successful. Current concepts of mantle-derived granite and "primitive" oceanic basaltic crust, which derive support from geochemical, petrological and isotopic studies, are not inconsistent with the data of regional mapping. However, there is evidence of a protonucleus of highly metamorphosed pelitic, psammitic and calcareous sedimentary rocks in the Southwestern Province of the Yilgarn Block.

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STRUCTURAL SUBDIVISION OF THE EASTERN GOLDFIELDS PROVINCE, YILGARN BLOCK

by I. R. Williams

ABSTRACT

The Eastern Goldfields Province of the Archaean Yilgarn Block is divided into three units, called from west to east, the Southern Cross, Kalgoorlie and Laverton Subprovinces. The subprovinces have distinctive structural, lithological and geochemical characteristics. However, the Southern Cross and Laverton Subprovinces show petrogenetic and structural similarities which can be interpreted in terms of a broadly analogous origin. In contrast the central Kalgoorlie Subprovince contains many unique structural and lithological elements. Structural and stratigraphic discontinuities occur at the junctions between the subprovinces.

The Kalgoorlie Subprovince has been the locus of long-term instability. It is postulated that instability is related to incipient development of a trough, graben or rift-like structure within earlier-formed Archaean crustal material. The uniqueness of the Kalgoorlie Subprovince is further expressed by its economic wealth. The subprovince has produced 75 per cent of the gold and contains over 96 per cent of known nickel reserves in Western Australia.

INTRODUCTION

The subdivision of the Eastern Goldfields Province is largely based on 1 : 250 000 scale regional mapping by the Geological Survey over the last ten years. More than fifty per cent of the province has now been mapped and the results published in an Explanatory Note Series. Photogeological interpretation has now been used in the unmapped adjoining areas of the province. Geophysical data, particularly total magnetic intensity maps, issued by the Bureau of Mineral Resources, Canberra, and geochemical and petrological information from publications and theses of the C.S.I.R.O. and University of Western Australia, have also been taken into account. All sources of information are gratefully acknowledged.

The subdivision of the Eastern Goldfields Province is provisional and stems from an attempt to explain the regional distribution of the major lithologies. This distribution supports the concept of structural, petrological and probable geochemical domains within the province. All three aspects are in some way related to puzzling north to north-northwest trending major tectonic lineaments, recently found in the Archaean terrain (Williams and others, 1971; Gower and Bunting, 1972).

This subdivision also attempts to place in perspective the mineralized zone that extends from Norseman to Wiluna, a zone colloquially called the "nickel belt".

REGIONAL SETTING

The Eastern Goldfields Province (G.S.W.A., The Geology of Western Australia, in press) occupies an area of about 325 000 km^2 and roughly constitutes the eastern half of the Archaean Yilgarn Block (Daniels and Horwitz, 1969). The boundaries of the province are loosely defined, pending the completion of regional mapping, and in many cases mark the erosional rather than the real extent of the Archaean rocks. The northern and eastern boundaries and south-western corner of the province are irregular erosional boundaries. In these areas the Archaean terrain is unconformably overlain by the Proterozoic Bangemall Basin sediments (c. 1 000 m.y.), Permian Officer Basin sediments and the Proterozoic Barren Beds (more than 1 150 m.y.), respectively. The southeastern and southern extension of the Eastern Goldfields Province is terminated by a linear tectonic, high-grade, polymetamorphic and magmatic belt (mobile zone) called the Albany-Fraser Province (less than 1 660 m.y.) The western boundary is an arbitrary line which separates structural disparities within the Yilgarn Block. It is gently arcuate, with convexity westwards. The boundary occurs over granitic rocks and it does not cross linear or arcuate greenstone belts (metamorphosed volcanic and sedimentary assemblages). However, the boundary passes over an immense layered mafic body, the Windimurra Complex (de la Hunty, 1970), which is situated 50 km east of Mount Magnet.

The western boundary separates the north-northwesterly trends of the Eastern Goldfields greenstone belts from the northeasterly trending belts of the Murchison Province and from the high-grade metamorphic terrain (granulite) and greenstone-deficient region of the older (about 3 000 m.y.) Southwestern Province (Fig. 32 A).

STRUCTURAL AND STRATIGRAPHIC ELEMENTS OF THE EASTERN GOLDFIELDS PROVINCE

The Archaean terrain of the province can be divided into two major components; the intrusive granite-migmatite-gneiss areas and the greenstone belts. Although the former occupies about 70 per cent of the area, it is petrologically, chemically and structurally the lesser known entity. The contents of the greenstone belts, on the other hand, have been studied in detail for at least 60 years, particularly in the southeastern portion of the province (MacLaren and Thompson, 1913; Woodall, 1965; Prider, 1965; Horwitz and Sofoulis, 1965; Williams, 1969; Glikson, 1971; Hallberg, 1972). Although most lithologies are now well documented, proposed stratigraphic, structural and genetic models remain controversial.

STRUCTURAL ELEMENTS OF THE GREENSTONE BELTS

The regional shape of the greenstone belts (the present visual extent and not the presumed original extent) is attributed to a complex interplay of tectonic, igneous and erosional events (see Fig. 32 B). The shapes vary from narrow arcuate belts, sometimes linked by "bow-tie" structures (see Barlee Sheet, total magnetic intensity map, Bureau of Mineral Resources) in the Southern Cross-Sandstone region to large irregular (vermiform) regions with linear appendages in the Norseman-Kalgoorlie-Wiluna region. Smaller isolated linear metamorphic belts occur along the eastern margin of the province.

The internal structure of the narrow (less than 50 km in width) greenstone belts is mostly synclinal, the thickest accumulation of volcanic and sedimentary rocks occurs towards the central axis. In some cases homoclinal sequences and major anticlinal structures may dominate individual greenstone belts of this type, e.g. Bremer Range area, Lake Johnston Sheet area (Gower and Bunting, 1972). Such structures suggest a wider distribution of volcanic and sedimentary assemblages than is now preserved. The linkages have been disrupted and removed by later granitic intrusion. The major fold axes are roughly parallel to the elongation of the greenstone belt. The arcuate greenstone belts are draped around concordant domal granite-migmatite complexes. In detail the complexes are intrusive, have contact metamorphic aureoles and xenolith-rich margins. Shearing and normal faulting at the margins suggests diapiric emplacement. The configuration of the greenstone belts in the Southern Cross-Sandstone region, and to a lesser extent in the eastern margin of the province, is attributed to the emplacement of granitic bodies. There appears to be a close connection between rising granitic domes and concomitant downsagging of the greenstone belts.

Various structural relationships are present in the large complex greenstone belt of the central part of the province. The Archaean layered succession can be traced continuously (allowing for superficial cover) for over 800 km from south of Norseman to the Wiluna area. The greenstone terrain reaches a maximum width of about 200 km. Thick stratigraphic sequences are common, and the maximum known thickness of about 27 km occurs in the Kalgoorlie-Norseman region (McCall, 1969; Doepel, in press; Williams, 1970).

Major fold axes, trending north-northwest, dominate the central region. They are linear rather than arcuate, and are commonly truncated by discordant composite granitic bodies. North-northwest-trending anticlinal structures are commonly intruded by small granitic plutons, e.g. Edjudina Anticline (Williams and others, 1971). This structural-magmatic relationship is different from that in the Southern Cross-Sandstone region where the granitic rocks are coeval rather than subsequent to major structures.

The differing styles of greenstone belts can be emphasized by simplifying their gross shape (Fig. 32C). The narrow linear and arcuate belts can be represented by a single line which is the elongation direction of the belt (this trend direction is also roughly parallel to the major fold axes). In complex belts the regional foliation, magnetic trends, fold axes and gross outline of the granite-greenstone contact have all been taken into account. This simplification may require several representative trend lines.

The arcuate style and northerly pre-granite trend of the greenstone belts in the western third (Southern Cross-Sandstone region) contrasts with the style of other areas which are more linear and have a dominant north-northwest trend. This latter style is evident in the central Norseman-Wiluna region of the province. Remnants of the arcuate style are possibly present in the northeast corner of the province.

LINEAR DISRUPTION ZONES

The pattern of the simplified trends suggests that there are a number of major, linear disruption zones along which lithological and structural trends terminate or change direction (Fig. 32D). The zones diverge south-southeasterly across the province from Wiluna region towards the southern boundary. The more westerly zones extend from west of Wiluna to the vicinity of Ravensthorpe. They lie between the arcuate greenstone belts of the Southern Cross-Sandstone region and the extensive linear belts of the Norseman-Wiluna region. Sections of the western zones correspond to established faults, shear zones and air-photograph and aeromagnetic lineaments. However, the continuity of these zones has been disrupted by granitic intrusions. The plutons form part of a continuous north-trending zone of coelesced bodies, commonly porphyritic, which are roughly coincident with the western zone. Consequently there is no physical connection between the greenstone belts on either side of this zone. Geological mapping of the Lake Johnston 1 : 250 000 Sheet area has shown that these granitic bodies may be dilational (Gower and Bunting, 1972). The movement along the western zone is not conclusive but an east-block-down movement is present along some sections.

The easterly disruption zones occur mainly within the greenstone belts and are rarely intruded by later granitic bodies. A prominent lineament in this zone extends from the Mount Keith area southeast past Leonora, to the Mulgabbie area. It corresponds with the Mount Kilkenny Fault (Williams and others, 1971), and is here called the Keith-Kilkenny Lineament. A parallel lineament that extends through Mount Celia has been called the Mount Celia Fault (Williams and others, 1971). In places the easterly zones appear to be intruded by dykes of ultramafic material, for example in the Mount Keith area. Truncation of regional magnetic trends and splay "faults" are characteristic features of the eastern zones. In contrast to the western zone, the stratigraphy can be correlated across the eastern zones and a consistent west-block-down movement can be deduced. The regional setting for the zones is given in Figure 32D.

Regional mapping has revealed numerous less continuous strike faults and lineaments in the layered succession. (The term "strike-fault" is used for a fault whose strike is parallel with the regional strike of the surrounding rocks, and does not necessarily imply strike slip movement.) These faults are concentrated in the central part of the province between the major western and eastern linear disruption zones. The Boulder Fault (Woodall, 1965), Hampton, Mount Monger and Claypans Faults (Williams, 1970) and Yilmia dislocation (McCall, 1969) belong to this category. The faults appear to decrease in frequency away from this region and although parallel faults and lineaments persist in the Laverton region they are not common in the Southern Cross-Sandstone region (see Fig. 33A).

STRATIGRAPHIC STRUCTURAL RELATIONSHIPS

The stratigraphy of the southwestern portion of the province is reasonably well documented (McCall, 1969; Doepel, in press; Williams, 1970; Glikson, 1971; Williams and others, 1971; Gower and Bunting, 1972). Although a wide variety of lithologies is present, a natural two-fold subdivision, formulated on the dominant volcanic rock type can be established. These groupings were called by Williams (1969) basic volcanic and acid volcanic-clastic associations. More recently, the terms mafic-ultramafic and felsic-clastic associations have been favoured (Williams and others, 1971). Williams (1969) noted the cyclical repetition of the associations and suggested that volcanic cycles may principally be responsible. Formalized stratigraphy and numbered volcanic cycles were adopted for the Kurnalpi and Edjudina Sheet areas (Williams, 1970; Williams and others, 1971).

Stratigraphic review has shown that the youngest Archaean rocks (2 600 m.y.), belonging to cycles 2 and 3, predominate in the Norseman-Wiluna region that lies between the eastern and western disruption zones. Outside this region the equivalent stratigraphic levels are confined to major synclinal structures. In contrast, stratigraphically older rocks are confined to the cores of large anticlinal structures within the Norseman-Wiluna region (e.g. Bulong Anticline, Williams, 1970). However, they constitute the major part of the succession in the Laverton region which lies northeast of the eastern zone (Keith-Kilkenny Lineament). It is not possible, at this stage, to define the relative stratigraphic position of the rocks in the Southern Cross-Sandstone region. Lithological associations suggest that the rocks are probably slightly older than the cycles 2 and 3 of the Norseman-Wiluna region. The Bremer Range belt, lying midway between the Norseman area and the southern extension of the Southern Cross belt, consists mainly of cycle 1 rocks (Gower and Bunting, 1972).

The distribution of cycle 2 and 3 in the Kurnalpi Sheet area is controlled by north-northwest fold axes (Williams, 1970). Cycle 1 rocks are confined to cores of the larger north-northwest-trending anticlinal structures and are independently folded about north-trending, variably plunging, axes. Hence the older fold generation is oblique to the younger north-northwest-trending fold period and the cycle 2 rest unconformably on cycle 1 rocks. Local unconformities are also present within individual cycles. Many of the large granitic bodies in this region are concordant with the younger fold trends but truncate the older fold trend.

Regional mapping has indicated that cycle 1 rocks predominate in the Laverton region and both north and north-northwest fold trends occur in this region. Cycle 2 rocks are preserved only in long, sinuous north-northwest-trending synclines which are in most cases closely connected to regional strike faults (Williams and others, 1971). These faults have a consistent west-block-down movement and are thought to be genetically related to the eastern linear disruption zone (see Fig.

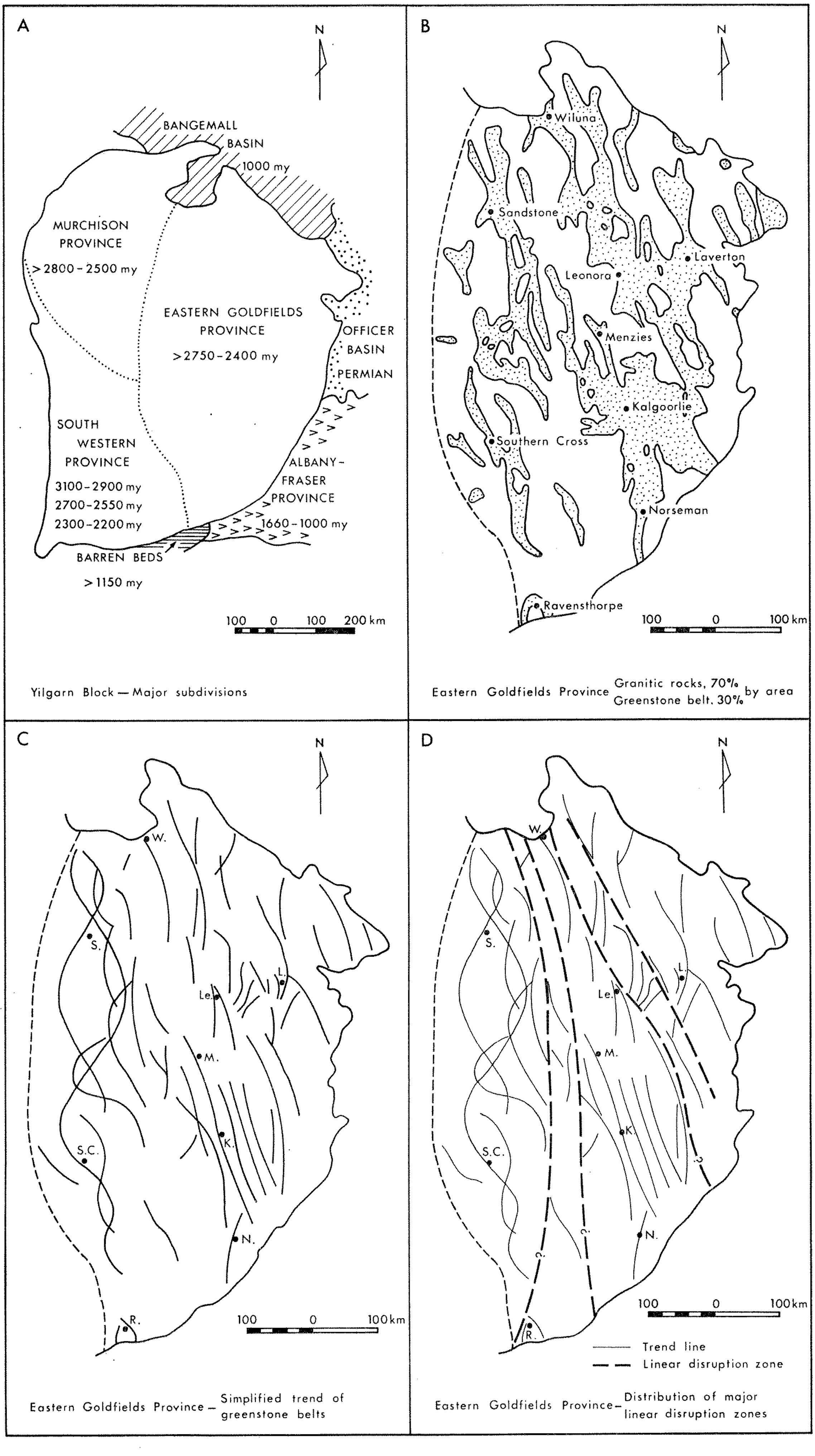

Figure 32. Structural subdivisions of the Eastern Goldfields Province, Yilgarn Block.

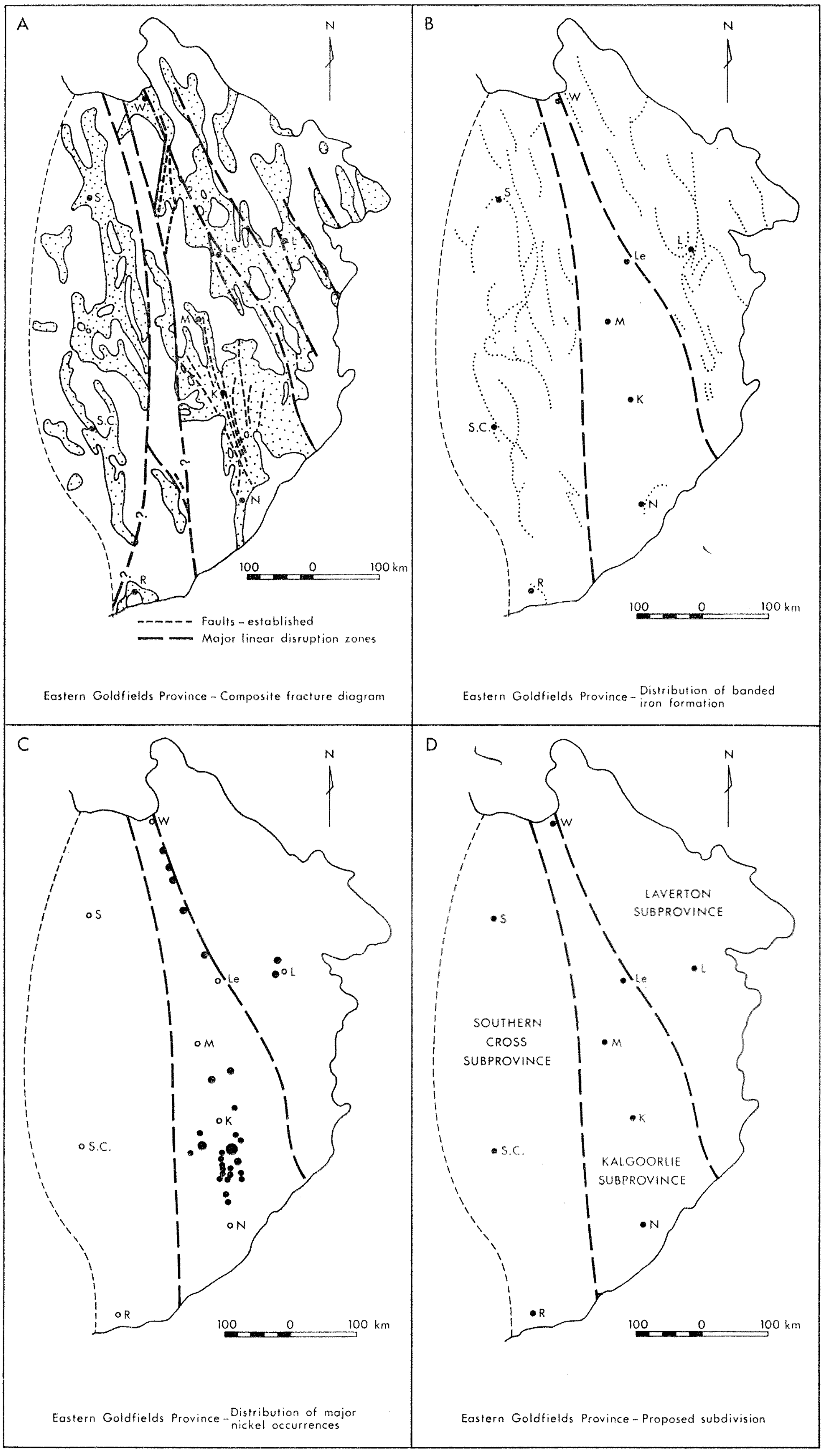

Figure 33. Structural subdivisions of the Eastern Goldfields Province, Yilgarn Block.

33A). Grantic rocks show affiliations with both structural episodes.

Detailed stratigraphic data are not yet available for the Southern Cross-Sandstone region. However, the distinctive regional configuration of the greenstone belts and the resolved northerly trend (the older trend of the Norseman-Wiluna region?) distinguishes the region from the remainder of the province.

LITHOLOGY DISTRIBUTION IN THE EASTERN GOLDFIELDS PROVINCE

The spatial distribution of the individual lithologies within the greenstone belts is well documented for the southeastern quarter but is incompletely known in the remainder of the province. However, collation of available data has revealed distribution patterns which are believed to reflect significant palaeogeographical conditions.

BANDED IRON FORMATION

The distribution of banded iron formation (BIF) is perhaps the most significant. BIF, in this case, refers to rocks (mainly chemical sediments) which have distinct colour and compositional banding and which exhibit varying degrees of magnetism that can be detected on regional total magnetic intensity maps. They are closely associated with, but not as widespread as, the non-magnetic cherts. The magnetic BIF occurs in the Southern Cross-Sandstone and Laverton regions but is almost entirely absent from the central Norseman-Wiluna region (see Fig. 33B). The chert occurs throughout the province and in some areas appears to be a facies equivalent of the magnetic BIF (Williams, 1970; Williams and others 1971). Major BIF and chert horizons occupy particular levels in the Archaean succession. The main horizons in the Laverton and Norseman-Wiluna regions lie between successive volcanic cycles. Regionally they overlie felsic volcanic rocks and associated clastic rocks and underlie mafic and ultramafic rocks. They may be interbedded with tuffaceous, sedimentary or mafic rocks.

BIF and chert horizons are particularly prominent between cycles 1 and 2 in the Kurnalpi and Edjudina Sheet areas. They are well exposed in the Edjudina Range (Williams and others, 1971). This same stratigraphic level can be traced westwards from the Laverton region to the Norseman-Wiluna region. However, a progressive change has been documented from BIF and chert in the Laverton region, to chert on the eastern margin of the Norseman-Wiluna region. This horizon is expressed by an angular unconformity in the Kalgoorlie area (central part of the Norseman-Wiluna region, Williams, 1970).

The stratigraphic position of the prominent BIF and chert horizons in the Southern Cross-Sandstone region has not yet been determined. However, structural correlation across the Norseman-Wiluna region suggests that the BIF of the Mount Ida-Davyhurst belt, on the eastern margin of the Southern Cross-Sandstone region, may also lie between cycles 1 and 2.

Banded iron formation and chert horizons may have been deposited during periods of quiescence between successive volcanic cycles. The paucity of these rocks in the Norseman-Wiluna region may then be attributed to continuous tectonic activity which inhibited BIF formation. The boundaries of the BIF-free central zone coincide with the inner margins of the major western and eastern linear disruption zones.

ULTRAMAFIC ROCKS

Broadly the ultramafic rocks show a reverse distribution pattern to that of the BIF in the province. They are concentrated within the Norseman-Wiluna region and are less frequent and more isolated in the Laverton and the Southern Cross-Sandstone regions.

The ultramafic rock group comprises discrete, podiform extrusive and intrusive, serpentinized bodies after peridotite and dunite (D. A. C. Williams, 1972), layered mafic-ultramafic bodies (Williams and Hallberg, 1973), and high-magnesian basalts. The discrete podiform and layered mafic-ultramafic bodies and to a lesser extent the high-Mg basalts are concentrated in the Norseman-Wiluna region. The discrete peridotitic and dunitic bodies may carry segregated nickel-sulphide deposits (Hudson, 1972). The distribution of existing nickel mines and potential deposits clearly indicates a concentration of this nickel mineralization in the Norseman-Wiluna region (see Fig. 33C). The mineralization in turn is largely restricted to the mafic-ultramafic association of cycle 2 (Mulgabbie Formation, Williams, 1970) within this region.

The disposition of nickel-bearing and other ultramafic rocks in the Norseman-Wiluna region also corresponds to the greatest concentration of the strike faults in the province (see Fig. 33A). The major linear disruption zones and associated faults control the emplacement of ultramafic dykes in the Mount Keith, Kathleen Valley and Agnew districts and pass near or truncate thick ultramafic complexes such as those at Mount Clifford, Murrin, Yundamindra and Linden. Several ages of ultramafic emplacement are evident although the present fracture pattern is, in most cases, not the obvious feeder system for the bulk of the ultramafic material. However, it is still tempting to postulate that these lines of weakness reflect fundamental fractures or mantle-tapping structures in the Archaean crust which, at an earlier stage, acted as conduits for the rapid transfer of ultramafic material from depth to a surface or near-surface environment. There appears little doubt that a direct relationship exists between the intensity of fracturing and the distribution of the ultramafic rocks. The paucity of nickel-bearing ultramafic rocks in the Southern Cross-Sandstone region could possibly be attributed to the apparent lack of north-trending fracture zones.

MAFIC ROCKS

Mafic rocks are widespread in the province. Tholeiitic basaltic rocks are the most common, but their associated lithologies suggest a varied environment. Hallberg (1972) studied pillowed tholeiitic basalts in the Kalgoorlie-Norseman areas and found them to be a uniform sequence of quartz-normative tholeiites which showed little differentiation throughout a pile greater than 8 000 m in thickness. Major and minor element chemistry resembles that of present day abyssal tholeiites. The tholeiitic basalts are associated with ultramafic rocks but are chemically and texturally separate (D.A.C. Williams, 1972). The mafic-ultramafic assemblage is abruptly overlain by a felsic-clastic sequence. Andesitic rocks are absent and there is no evidence of calc-alkaline differentiation. The tholeiitic basalts described by Hallberg (1972) belong to cycles 2 and 3.

In contrast, tholeiitic rocks in the Laverton region and those found in cycle 1 within the Norseman-Wiluna region are associated with mafic to felsic cyclicity. The mafic assemblages pass gradually upwards to predominantly felsic assemblages. Andesitic rocks have been recorded from these piles (Williams and others, 1971). Internal small-scale cyclicity, represented by the mafic rock, felsic rock, BIF triplet, is common (these may also be tuffaceous rocks). The tholeiites are generally massive and pillow lavas are not common. The ultramafic rocks in cycle 1 tend to form separate complexes and are spatially separate from the mafic to felsic cycles.

Andesitic rocks have also been found in the Southern Cross-Sandstone region at Marda (Bye, 1970) and Diemals. They occur in small calc-alkaline complexes. Basaltic rocks are common in areas away from the calc-alkaline centres and are closely associated with BIF, gabbro, mafic tuff and high-Mg basalt. This assemblage differs from the mafic-ultramafic association of the Norseman-Wiluna region in respect of high BIF and low peridotitic ultramafic content.

A characteristic lithology of the Southern Cross-Sandstone region is a layered gabbro with poorly developed ultramafic layers and thick gabbroic and anorthositic layers. The bodies contain segregated, titaniferous, vanadiferous, magnetite deposits. The Windimurra Gabbro and layered intrusions at Barrambie, Montague Range, Youanmi and near Lake Medcalf belong to this category. The magma stem is believed to be tholeiitic.

FELSIC ROCKS

Felsic rocks have several modes of occurrence in the province. They may form thick extremely restricted piles of mixed flows, breccias, intrusive and pyroclastic rocks, bordered by extensive coarse to fine-grained volcanoclastic deposits. The composition varies from dacite to potash rhyolite with occasional andesitic types. The felsic complexes show no genetic or chemical affinities with underlying or overlying mafic volcanic rocks (Larking, 1969; Hallberg, 1970). This type of felsic complex is common in cycles 2 and 3. It also occurs in cycle 1 which crops out in the Norseman-Wiluna region.

Other felsic complexes are related to mafic rocks. The association constitutes a mafic to felsic cycle, where lithologies progress from basalt upwards through andesite to dacite and rhyodacite. The upward progression is accompanied by increased pyroclastic content. BIF and chert cap the mafic to felsic cycles. The ratio of basic, intermediate and acid components in the mafic to felsic piles varies considerably. Some centres have a large basalt and andesitic component and only minor felsic material; others resemble calc-alkaline sequences and are dominated by andesitic rocks ($\leqslant$ 60 per cent). Mafic to felsic volcanic piles are confined to cycle 1 and are typically found in the Southern Cross-Sandstone and Laverton regions.

CLASTIC SEDIMENTARY ROCKS

Clastic sedimentary rocks that exhibit a mixed provenance are generally deposited in areas devoid of coeval volcanism. These sedimentary rocks are characteristic of higher levels of the Archaean succession in the province and constitute the clastic part of the felsic-clastic associations of cycles 2 and 3. Although sequences of clastic rocks are found in older felsic-clastic associations they are not the major lithology. They tend to be oligomictic and the major components are volcanoclastic and chemical sedimentary rocks.

Polymictic conglomerate is a major component of the younger clastic sequences. The Kurrawang Beds, situated between Kalgoorlie and Coolgardie, contain a high proportion of conglomerate horizons (Glikson, 1971). Similar conglomerate horizons occur in the Merougil Creek area west of Kambalda, the Penny, White Gate and Gundockerta districts of the Kurnalpi Sheet area, the Yilgangi area near Edjudina and the Butcher Bore area northeast of Malcolm. The conglomerates occur in the upper horizons of felsic-clastic associations at or near the top of the Archaean succession.

The Kurrawang Beds, which lie near the western margin of the Norseman-Wiluna region, contain a high proportion of BIF, jaspilite and chert clasts. Likewise, but to a lesser degree, the conglomerate horizons at Yilgangi and Butcher Bore on the eastern margin of the Norseman-Wiluna region contain chert and jaspilite clasts. The remaining conglomerate horizons, situated centrally within the Norseman-Wiluna region contain no BIF and only very small percentages of chert clasts. The provenance of the BIF and probably the greater portion of the chert and jaspilite clasts lies outside the Norseman-Wiluna region. The nearest BIF occurrence to the Kurrawang Beds lies 70 km to the southwest near Queen Victoria Rocks.

The general immaturity and poor sorting of the conglomeratic assemblages would suggest the fairly rapid filling of a basin or trough structure. Significantly, the majority of thick polymictic conglomerate beds lie within or adjacent to the Norseman-Wiluna region. This region is bordered by the major linear disruption zones that appear to define a trough or graben-like structure.

TABLE 9. CHARACTERISTICS OF THE MAJOR REGIONAL SUBDIVISIONS OF THE EASTERN GOLDFIELDS PROVINCE

Southern Cross-Sandstone region	Norseman-Wiluna region	Laverton region
1. *Individual or single greenstone belts* ; arcuate trends.	Compound greenstone belts, irregular shape with linear appendages, linear trends.	Compound and individual greenstone belts, linear and gently arcuate trends.
2. Resolved northerly regional trend.	Dominant younger north-northwesterly fold trend, older northerly trend unconformably beneath.	Dominant older northerly trend, younger north-northwesterly trend.
3. Domal granites and arcuate greenstone belts genetically related.	Large granitic bodies related to north-northwest fold ; trend truncates north fold trend. Granitic rocks intrude pre-existing structures.	Granitic rocks are probably related to both the north and north-northwest fold trends.
4. Bordered by gently arcuate linear disruption *zone on eastern side. Relative movement east*-block-down. Strike faults in layered succession uncommon.	Bordered by eastern and western linear disruption zones. Numerous strike faults in layered succession. Concentrated in centre of region (Kalgoorlie), decrease east and west from central region.	Bordered by linear disruption zone on western side. Relative movement west-block-down Strike faults in layered succession occur throughout but decrease eastwards.
5. Archaean stratigraphy not well known. At*tempted correlation suggests rocks may* be equivalent to cycle 1 and older.	Youngest Archaean rocks in province, 2 600 m.y. Predominantly cycle 2 and 3 rocks, cycle 1 rocks in cores of regional anticlines.	Predominantly cycle 1 rocks, some older cycle 2 rocks occur in keels or regional synclines.
6. BIF and chert prominent, local disconformities and unconformities between cycles.	Chert, very minor BIF between cycle 1 and 2, major unconformity between cycles 1 and 2 ; and cycles 2 and 3.	BIF and chert prominent, disconformities and unconformities between cycles.
7. Intermittent tectonic activity, periods of quiescence denoted by BIF.	Continuous tectonic activity, interval of time lasting from cycle 1 to 3.	Intermittent tectonic activity, periods of quiescence between succeeding volcanic cycles, as denoted by BIF.
8. Ultramafic rocks not common, mainly high-*Mg basalts, periodotitic ultramafic concentrated* in southern half of region, traces of nickel mineralization.	Ultramafic rocks very common, form ultramafic-*mafic assemblages* ; region contains 80 per cent known ultramafic rocks of province. Contains 96 per cent proven nickel reserves in W.A.	Ultramafic rock content variable, decreases eastwards across the region, concentrated in ultramafic complexes separate from cyclic mafic to felsic assemblages. Scattered nickel mineralization.
9. Rare occurrences of ultramafic-mafic bodies *derived from high-Mg basalt magma.*	Contains numerous layered ultramafic-mafic *bodies derived from high-Mg basalt magma.*	Not found.
10. Contains large layered gabbros, characterized by anorthosites, poor ultramafic development, segregated titaniferous vanadiferous magnetite bands.	Not found.	Not found.
11. Gabbro-basalt, high-Mg basalt, mafic tuff-BIF assemblages, minor calc-alkaline sequences, andesites. Pillow lavas not common.	Mafic-ultramafic assemblages. Tholeiitic basalts resemble recent abyssal tholeiites, calc-alkaline sequences absent, andesites very rare or absent. Pillow lavas common.	Cyclic volcanic mafic to felsic assemblages, BIF, minor calc-alkaline sequences ? andesites. Pillow lavas not common, ultramafic complexes.
12. *?Cyclic felsic rocks associated with mafic rocks,* felsic complexes rare.	*Felsic complexes common* ; felsic rocks unrelated to underlying mafic rocks.	Cyclic mafic to felsic assemblages. Felsic complexes rare.
13. Polymictic and oligomictic conglomerates are present but not common. Stratigraphic relationship not known.	Polymictic conglomerates form thick sequences near and at the top of Archaean succession. Source of clasts commonly from adjoining *regions. Oligomictic conglomerates common* with felsic complexes.	Polymictic and oligomictic conglomerates are present but occur at base of sequences, possibly related to unconformities.
14. Relatively stable area may be shelf or platform environment.	Unstable region, indications suggest a trough, rift or graben-like environment within older Archaean crustal material.	Relative stable area, may be shelf/platform with possible terrestrial environments.

CONCLUSIONS

The significant structural and lithological variations of the Eastern Goldfields Province are listed in Table 9.

The data reveal three natural divisions of the Eastern Goldfields Province which are separated by linear disruption zones. The divisions have been designated subprovinces and are called, from west to east, the Southern Cross, Kalgoorlie and Laverton Subprovinces (Table 10).

TABLE 10. SUBDIVISIONS OF THE EASTERN GOLDFIELDS PROVINCE, YILGARN BLOCK

Region	Subprovince
Southern Cross-Sandstone	Southern Cross
Norseman-Wiluna	Kalgoorlie
Laverton	Laverton

A structural-palaeogeographic reconstruction of the Archaean environment, before the closing tectonic magmatic events, would possibly reveal a tensional pattern represented by an incipient graben or rift-like structure corresponding to the Kalgoorlie Subprovince. By far the greater proportion of Younger Archaean rocks, namely cycles 2 and 3, occur within this region together with the bulk of the nickel-bearing ultramafic rocks. In consequence the Kalgoorlie Subprovince forms a unique and economically important component of the Eastern Goldfields Province.

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ARCHAEAN ULTRAMAFIC LAVAS FROM MOUNT CLIFFORD

by R. G. Barnes, J. D. Lewis, and R. D. Gee

ABSTRACT

A thick pile of Archaean ultramafic volcanic rocks at Mount Clifford, 260 km north of Kalgoorlie has accumulated on a platform of tholeiitic pillow basalts adjacent to a major tectonic feature, the Keith-Kilkenny lineament. The complex consists of a multitude of thin serpentinized peridotite flows, together with other highly magnesian rock types.

The lavas display distinctive features of morphology and petrology indicating an extrusive origin. These include thin chilled margins, an upper spinifex-textured zone of pyroxene peridotite and a lower porphyritic zone of olivine peridotite. This textural asymmetry provides a primary facing indicator.

Eleven chemical analyses from a core sample of a flow 1.24 m thick are presented. Chemical and modal variations within the flow indicate that the chilled margins are undifferentiated. The olivine peridotite was formed by crystal settling from a highly fluid magma containing about 12 per cent phenocrysts.

INTRODUCTION

The existence of magmatic ultramafic rocks as a characteristic component of Archaean volcanogenic belts is now widely accepted. Such rocks have been described from Canada by Naldrett and Mason (1968) and Pyke and others (1973), from South Africa by Viljoen and Viljoen (1969a), and from Western Australia by Nesbitt (1971), McCall and Leishman (1971), D.A.C. Williams (1971) and Lewis and I. R. Williams (1973).

The occurrence of peculiar quench or "spinifex" textures in these rocks has been fully described by Nesbitt (1971) who, with Lewis (1971), interprets the texture as indicating the rapid cooling of a crystal-free ultramafic liquid.

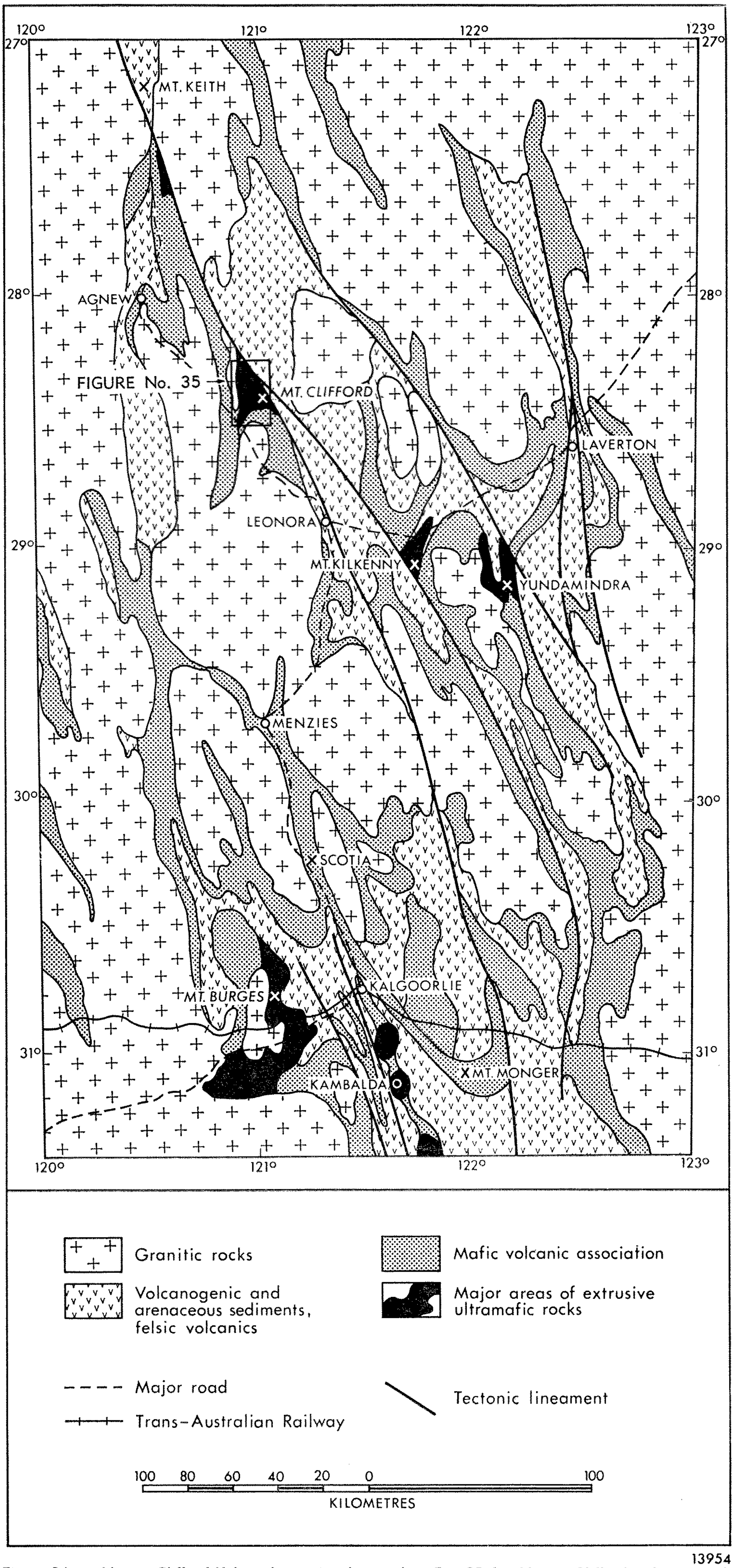

Figure 34. Mount Clifford-Kalgoorlie regional map (see Fig. 35 for Mount Clifford enlargement).

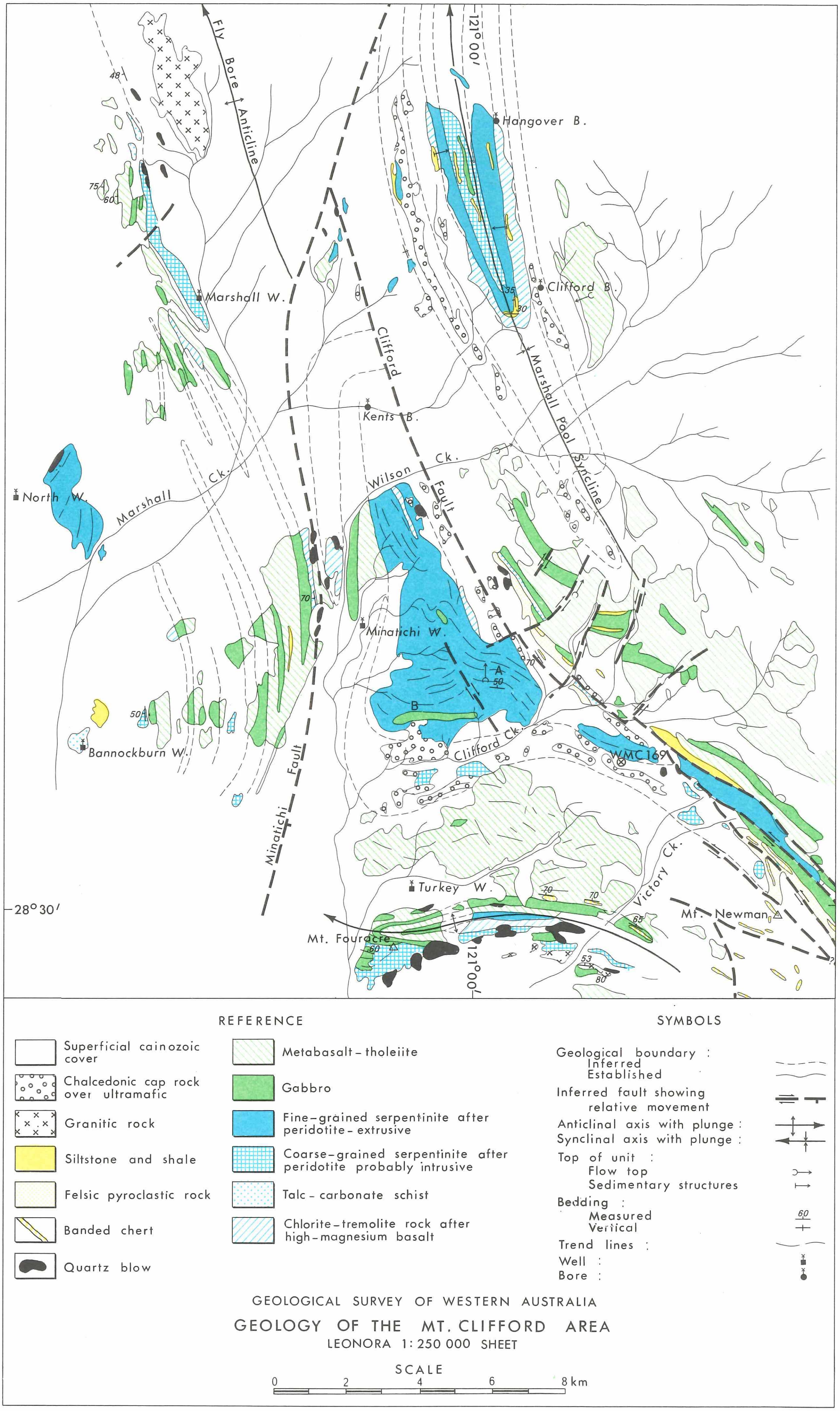

Figure 35.

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However, the presence of spinifex texture alone does not provide unequivocal evidence for an ultramafic lava, as such textures are often developed at the margins of obviously intrusive bodies. At present three localities of undoubted peridotite lavas have been described (Viljoen and Viljoen, 1969a; Pyke and others, 1973; Lewis and I. R. Williams, 1973). In each case there are distinctive features of morphology and petrography indicative of extrusion of a mobile peridotitic magma. These include pillow forms, from the South African examples, and a marked textural asymmetry and slaggy vesicular flow top from Canadian and Western Australian examples.

The purpose of this paper is to describe the field occurrence, flow morphology, petrography and chemistry of Archaean ultramafic lava flows at Mount Clifford, 53 km north-northwest of Leonora township in the Mount Malcolm Goldfield. This area contains one of the best exposed outcrops of extrusive, serpentinized peridotite in Western Australia. The recognition of extrusive morphological features is of value to the field geologist in interpreting facing and environment. Further, the chemistry of the serpentinized periodotite closely reflects that of the original rock.

The authors believe the lavas of the Mount Clifford area are broadly similar to the ultramafic lavas of Munro Township, Ontario (Pyke and others, 1973) with which they are compared.

REGIONAL SETTING

The Mount Clifford area lies in the northern part of the Norseman-Wiluna greenstone belt, which is characterized by elongate, domal, granitic plutons and batholiths. The latter intrude and deform an Archaean volcanogenic succession which consists of tholeiitic basalts, intrusive and extrusive rocks of the high magnesia (ultramafic) rock suite, felsic volcanics, volcanogenic sediments, arenaceous and conglomeratic sediments and banded iron formations. The belt is further characterized by north-northwest trending tectonic lineaments that have been active throughout the deposition of the volcanogenic succession.

Mount Clifford lies on the western side of the most conspicuous and perhaps most important of these lineaments, named informally the Keith-Kilkenny lineament (Williams, 1974, p. 54). This lineament forms a major boundary in the subdivision of the Eastern Goldfields Province. Williams has further postulated that this structure is the expression of a fundamental mantle-tapping fracture that initiated and controlled the subsequent development of the Archaean crust.

Regionally the Keith-Kilkenny lineament marks a thick accumulation of volcanogenic rocks, including extrusive peridotite. It is also the regional locus of a high level conglomerate and intrusive ultramafic lenses, and appears to have controlled the intrusion of adjacent granite plutons. There is evidence that splay faults and folds are related to the lineament, thus demonstrating progressive deformation related to plutonic activity.

Periodotite lavas also occur in association with thick mafic sequences in other parts of the Eastern Goldfields (Fig. 34). Those at Sir Samuel, Mount Kilkenny and Yundamindra bear a regional spatial relationship to tectonic lineaments but this relationship is more tenuous in the Mount Burges and Kambalda areas. The regional stratigraphic position of the peridotite lavas at these localities is uncertain, however, it appears to be variable and is by no means confined to the lowest part of the Archaean succession. This contrasts with occurrences in the Kaapvaal Shield, South Africa, where peridotite lavas occur only in the lower half of the Onverwacht Group (Anhaeusser, 1971, a,b).

LOCAL GEOLOGICAL SETTING

An interpretive geological map of the area after Thom and Barnes (in press) is presented in Figure 35. The Keith-Kilkenny lineament passes along the eastern edge of the geological map but is not marked as it is ill-defined on the ground in the Mount Clifford area. Faulting in the area is defined by prominent quartz ridges and zones of sheared rock. These, together with aeromagnetic data delineate two major faults in the Mount Clifford area called the Clifford and Minatichi faults.

East of the Keith-Kilkenny lineament, in the Mount Clifford area, is a thick sequence of felsic volcanic and related sedimentary rocks, whereas to the west there is a mafic suite that includes the ultramafic rocks in question. The mafic rocks are exposed in a series of north-northeast plunging folds, therefore the more southerly outcrops are stratigraphically lower, the youngest rocks in the area being preserved in the core of the Marshall Pool syncline.

Two major structural zones are present in the area:

Western area. This contains a mafic association consisting predominantly of tholeiitic basalt and intrusive gabbros. Ultramafic rocks, including both intrusive and extrusive types are also found. The sequence is presumed to face west and is confined to the area west of the Minatichi fault.

Central and Eastern area. These areas contain a mafic-ultramafic association exposed in the trough of the Marshall Pool syncline and on the western side of the Clifford fault.

The Marshall Pool syncline contains a sequence of high-Mg basalts and serpentinized peridotite, interbedded with thin sedimentary horizons and rare intrusive rodingite (Ca-metasomatized gabbro), The syncline is nearly isoclinal, plunges gently north, and is bounded by the Keith-Kilkenny lineament to the east and the Clifford fault to the west. To the south, within this fault slice and underlying the ultramafic rocks, is a lower sequence of strongly carbonated and pillowed tholeiitic basalt.

West of the Clifford fault, in the central area, the mafic-ultramafic association is again exposed in an elbow shaped, north-east facing pile of intrusive and extrusive serpentinized peridotite with minor high-Mg basalt and thin sedimentary horizons. A minimum thickness of 1 200 m is exposed. The elbow shape outlines a rather angular asymmetrical syncline, that plunges 45° northeast. The peridotite mass is underlain to the south by tholeiitic basalt. The western boundary of this succession is formed by either the Minatichi fault, or a thin elongate dome of granitic rock extending southwards from the core of the Fly Bore anticline. Alternatively the granite may have been intruded along the Minatichi fault. Farther south the tholeiitic basalt is underlain by a chert, sediment, layered gabbro sequence which is exposed in the Mount Fouracre anticline. This anticline is isoclinal and has an arcuate trace around a lobe of granite on its southern side. Several strike faults or dislocations can be identified immediately south of Mount Fouracre between the gabbro and the granite, and also at Mount Newman where a series of faults slice a chert horizon. These faults are parallel or slightly acute to the strike of the surrounding rocks and swing to the west in sympathy with the regional structure. They appear to be folded splay faults related to the Clifford fault.

The favoured structural interpretation for the Mount Clifford area is that a single succession, consisting of a basal chert, sediment, gabbro sequence passing up through tholeiitic basalt into a mafic-ultramafic sequence, was folded and dislocated by a splay fault system related to the Keith-Kilkenny lineament. A lobe of granite, that stems from the main batholith to the south, appears to have ruptured the isoclinally folded sequence causing strike-slip movement along the Clifford and related faults. Thus the succession on the western side of the Clifford fault is repeated on the eastern side.

THE ULTRAMAFIC SUITE

The ultramafic suite comprises four rock types:

Extrusive serpentinized peridotite

This peridotite displays a primary flow zonation that includes glassy peridotite, fine and coarse-grained bladed spinifex peridotite, fine and medium-grained granular to porphyritic peridotite, with skeletal olivine and acicular clinopyroxene. The variety of textures and structures are shown in Figures 37A, B, C, D and E.

High-Mg basalt

This is characteristically a fine-grained grey-green, tremolite-chlorite, or carbonate-tremolite serpentine rock and may contain pseudomorphs after olivine phenocrysts. Acicular pyroxene gives the rock a distinctive texture (Fig. 37E) and in places a characteristic hackly fracture. Chemically (Table 12, Column 10; and McCall and Leishman, 1972) they are of pyroxenitic composition and contain about 10 or 12 per cent MgO. They compare favourably with the average high-Mg basalt of Hallberg and D. A. C. Williams (1972), (Table 14, Column 5 this paper), and are considered to be genetically related to the peridotite as shown in Figure 44.

In the Marshall Pool Syncline the high-Mg basalt outcrops as a unit stratigraphically below the extrusive peridotite; it also occurs to a lesser extent within the extrusive peridotite pile in the central Mount Clifford area.

Coarse-grained serpentinized peridotite

This type is not well exposed due to a chalcedonic cap-rock covering. It consists of coarse euhedral olivine up to 5 mm in diameter, and lacks the flow zones of the other peridotite. It is found primarily at the base of the extrusive peridotite pile in the central Mount Clifford area, and is considered an intrusive sill. It is probably genetically related to the extrusive peridotite, and may represent a high level intrusion during the early part of the extrusive phases.

Talc-carbonate schist

This represents highly altered serpentinite or talc-tremolite-chlorite rock. It is typically found in thin bodies close to major faults.

It is not clear whether the ultramafic complex, as now exposed, is an entire lava pile, or a remnant wedge of a once more continuous ultramafic layer folded into the adjacent rocks by movements related to the Keith-Kilkenny lineament. However, the lensoid nature of the outcrop, and its lateral continuity are evidence of a primary feature. It can be postulated that the ultramafic complex formed close to the primeval Keith-Kilkenny lineament and developed on a platform of tholeiitic pillow basalt. This platform also contained layered gabbroic sills and thin but persistent horizons of banded chert. The lavas developed as an outward-thinning pile on the platform. In this respect, it is not unlike an oceanic ophiolite complex.

ULTRAMAFIC LAVAS

There are two main occurrences of peridotite lavas in the Mount Clifford area:

(1.) Within the Marshall Pool syncline, where the lavas are associated with coarse-grained intrusive ultramafic rock and high-Mg basalt, and are interbedded with numerous thin sedimentary horizons.

(2.) A large elbow-shaped flow complex, with associated coarse-grained intrusive ultramafic rock, trending north-northwest from Mount Clifford, is treated in detail in this paper.

The peridotite lavas extend north-northwest from Mount Clifford for 12.9 km along the strike and the outcrop is 3.2 km across at its widest point. Topographically the outcrop forms an area of rolling hills with steep sided valleys which are strike controlled. Parallel micro-lineaments (see Fig. 36A) represent the surface expression of individual lava flows but over much of the area they are absent due either to poor exposure or to lack of a distinctive flow morphology.

Throughout the Mount Clifford area the thicker flows occur at the base of the pile and become thinner towards the top. This suggests that the magma issued from a single vent which gradually became choked causing the lava to issue from numerous smaller vents and fissures. On the eastern side, the lavas dip steeply east, but to the west they are folded into a shallow northeast plunging syncline. Dips on the northern and southern limbs of this syncline range from 40° to 60°. The lavas lens out to the north-northwest and south-southeast and are right-side-up.

Like the ultramafic lavas described by Pyke and others (1973) from Munro Township, Ontario, there are two basic morphologies for the Mount Clifford lavas. Most noteworthy and easily recognized are the flows in which the upper half consists of a coarse-grained spinifex-textured pyroxene peridotite and the lower half of a medium to fine-grained porphyritic olivine peridotite. Less easily delineated are the flows, similar to those described by Viljoen and Viljoen (1969) from the Barberton area of South Africa, in which the only variation is a greater concentration of porphyritic olivine in the lower half of the flow.

In the area designated A in Figure 35 the features of the spinifex type flow are easily recognized. The upper spinifex zones weather in positive relief, whereas the massive porphyritic peridotite is poorly exposed. However, weathering may also produce a spinifex zone that is very broken. Rubble strewn exposures prevent detailed mapping of individual flows but the positive relief ridges outline flows several hundred metres long. A traverse of 130 m across strike revealed a total of 26 flows ranging from 0.85 m to 7.7 m thick, and averaging 5 m thick. A nearby stream section exposed a complete flow unit only 0.5 m thick.

In the area designated B in Figure 35, the spinifex zones are thin whilst the flows appear to be of considerable thickness. Thin beds of carbonaceous siltstone, interspersed within the lavas, are the loci of thin gabbroic sills.

Unlike the Canadian and South African examples, Mount Clifford contains a number of flows with a distinctly vesicular top. Such flows were noted in the southeastern extension of the lavas, a little to the west of Western Mining Corporation DDH 169 (Fig. 35), where although the outcrop is poor, thinly layered northwest trending rocks are evident. Several narrow zones, about 1 m thick, of vesicular peridotite are separated by 10 m thick zones of coarse porphyritic peridotite. A gradation in grain size suggests a northeasterly facing.

MORPHOLOGY OF THE FLOW UNITS

Throughout the Mount Clifford and Marshall Pool areas a regular textural and mineralogical zonation of the flows is evident. A core section from W.M.C. DDH 169, 1.8 km northwest of Mount Clifford, that passed through a flow 1.24 m thick, allows us to identify precisely several zones that are typical of the flows in general. This zonation is illustrated in Figure 38, and their description is:

Zone:

A_1—Chilled and fractured flow top.

A_2—Fine-grained, spinifex-textured pyroxene peridotite.

A_3—Spinifex-textured pyroxene peridotite.

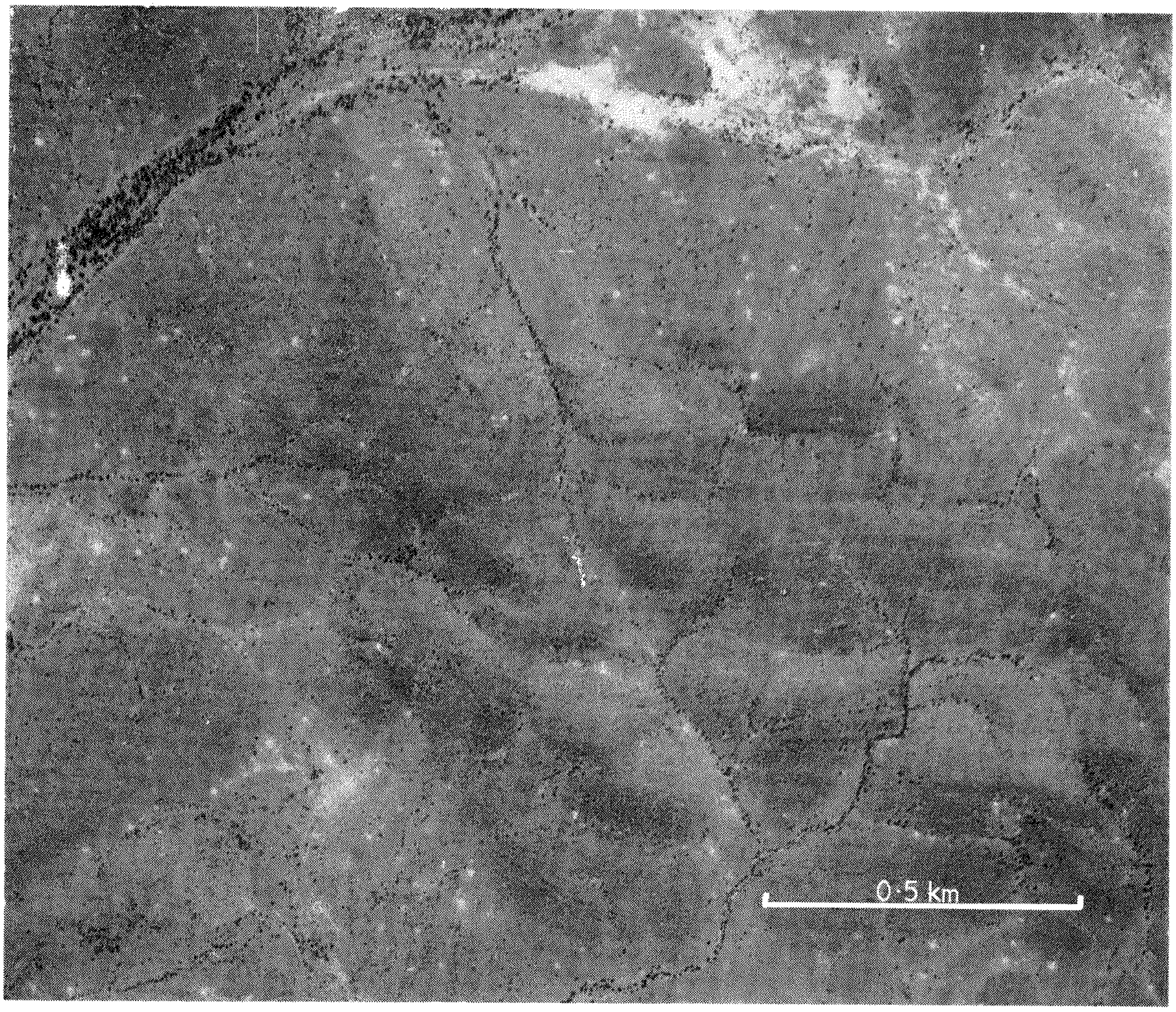
B_1—Foliated olivine peridotite.

B_2—Porphyritic olivine peridotite.

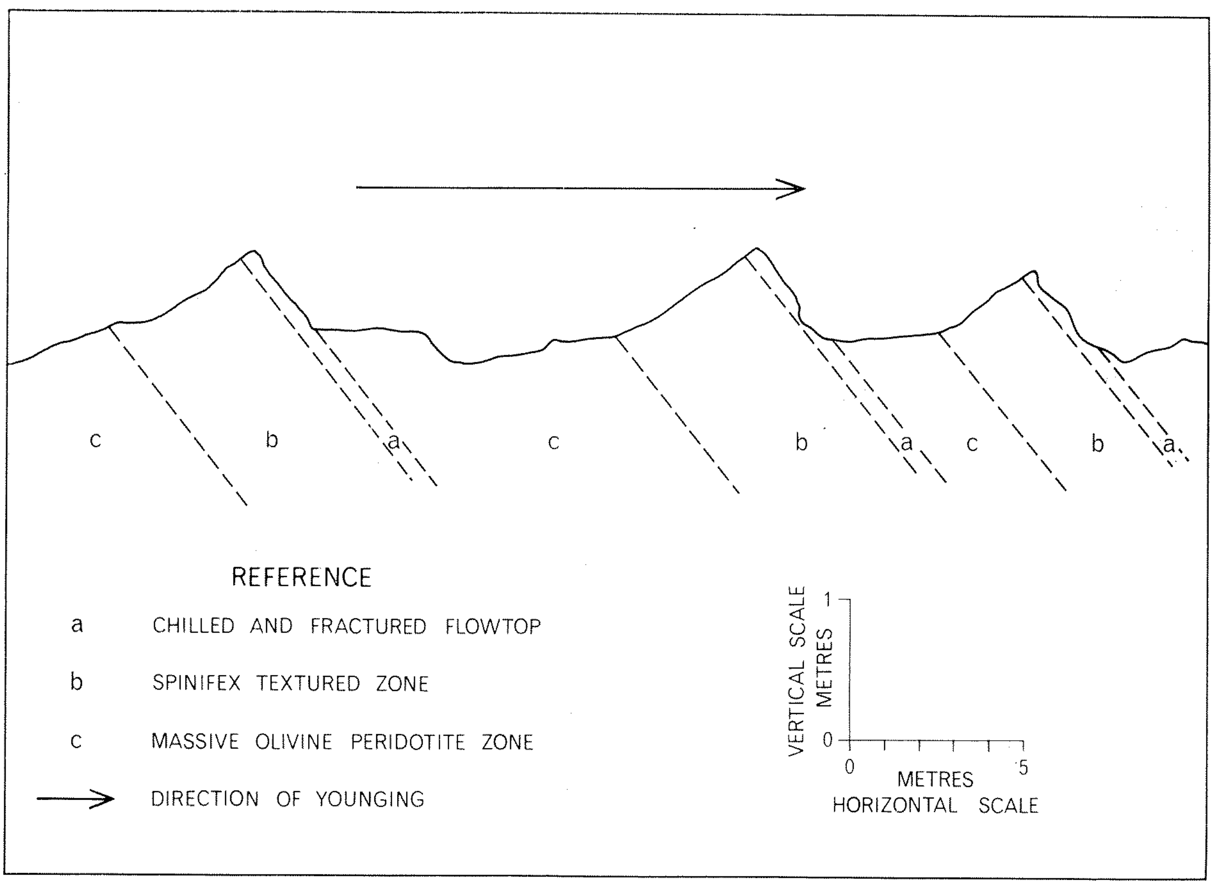
B_3—Lower chilled zone.

Where zones A_2 and A_3 outcrop as a ridge the flow top, A_1, is distinctive due to its pale weathering colour. The A_1 zone is usually less than 20 cm thick and consists of a dense blue-black serpentinite with many irregular fractures. The surface expression of these fractures gives the appearance of spheroidal weathered dolerite on a small scale (Fig. 37A).

Zones A_2 and A_3 are easily distinguished in the field from the structureless, chilled flow top. In weathered specimens the A_2 zones show coarse bladed spinifex texture in which the large olivine blades stand out in positive relief. The blades



A



B

Figure 36.

A. Air-photograph of area ' A ' (Fig. 35) showing micro-strike photo-lineaments representing individual lava flows.

B. Diagrammatic cross-section parallel to dip, through surface outcrop of the peridotite lavas.

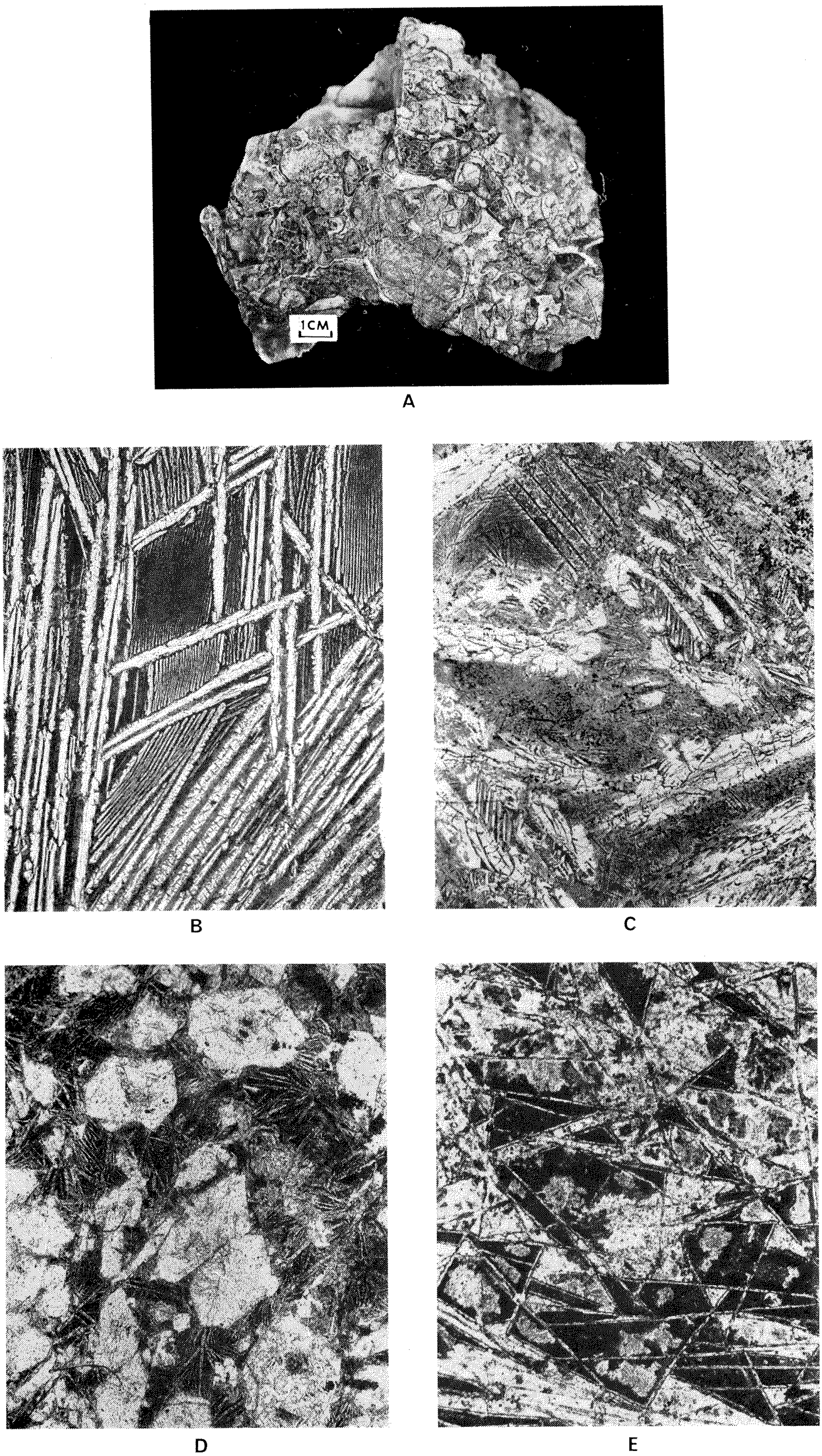


Figure 37.

Photographs of typical textures of Mount Clifford ultramafic rocks.

A. Chilled and fractured flow top.
B. 32773, x 4. Pyroxene peridotite of zone A_3, showing plate spinifex textures. A second generation of olivine lamellae has formed in the polyhedral areas enclosed by the large olivine plates.
C. 38224, x 6. Random spinifex texture from zone A_2. This sample is from a thick flow and shows the skeletal development of olivine and interstitial clinopyroxene.
D. 32775, x 15. Porphyritic peridotite of zone B_2. Note the development of interstitial clinopyroxene.
E. 32772, x 20. High-Mg basalt. Elongate blades of olivine with interstitial clinopyroxene and minor plagioclase.

Note : all specimens are completely altered, olivine to serpentine or chlorite, and clinopyroxene to tremolite.

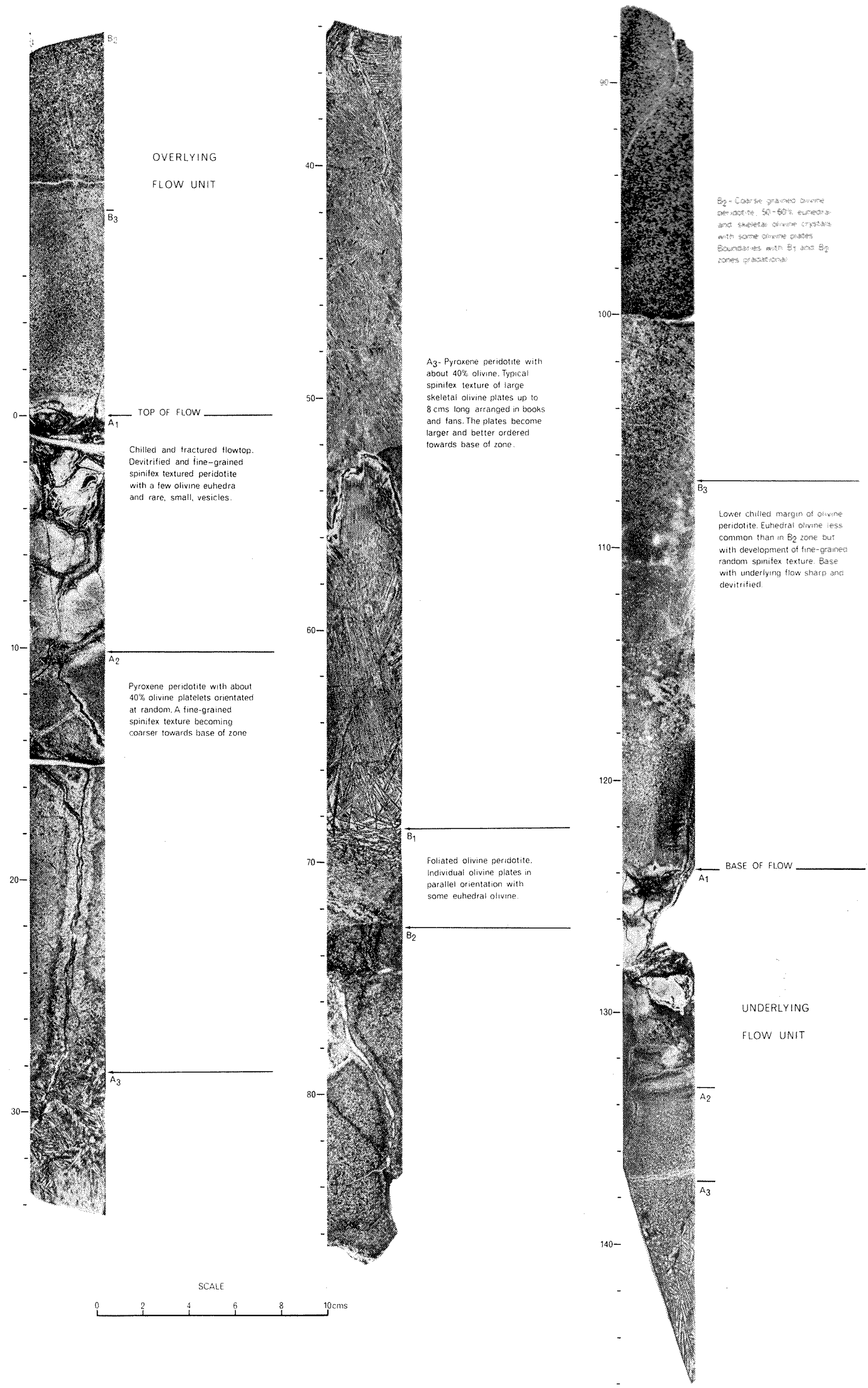


Figure 38. Polished core section from W.M.C. DDH 169, showing the textural variation through a thin ultramafic flow.

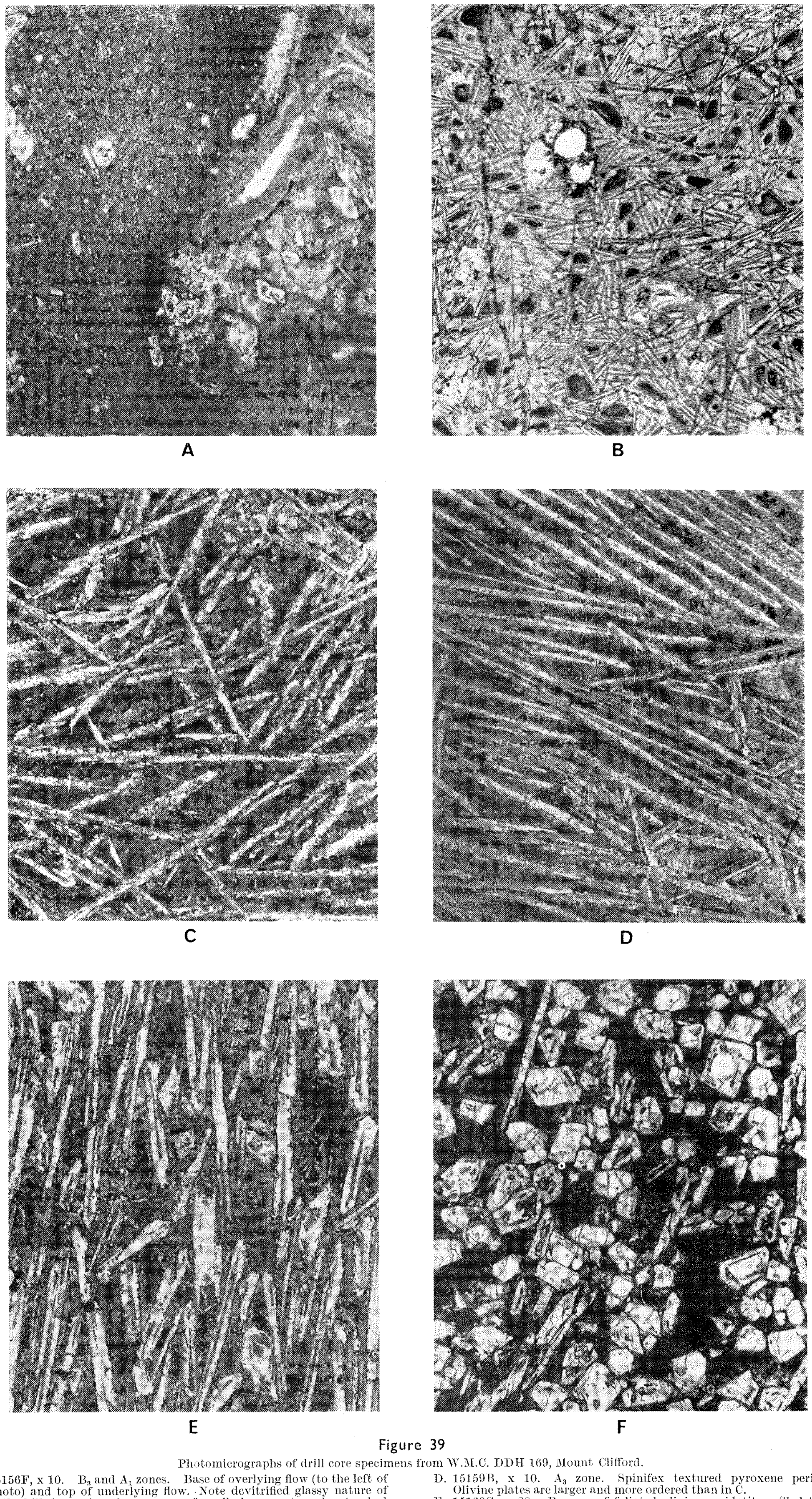


Figure 39

Photomicrographs of drill core specimens from W.M.C. DDH 169, Mount Clifford.

A. 15156F, x 10. B_3 and A_1 zones. Base of overlying flow (to the left of photo) and top of underlying flow. Note devitrified glassy nature of both chilled margins, the presence of small phenocrysts and a streaked out chlorite filled vesicle in the underlying flow.

B. 15157B, x 20. A_1 zone. Small scale random spinifex texture in the upper chilled margin of the flow. Note small spherical vesicles and rare phenocrysts. Compare with texture of high-Mg basalt Fig. 37E.

C. 15158C, x 23. A_2 zone. Pyroxene peridotite with randomly orientated olivine plates.

D. 15159B, x 10. A_3 zone. Spinifex textured pyroxene peridotite. Olivine plates are larger and more ordered than in C.

E. 15160G, x 20. B_1 zone of foliated olivine peridotite. Skeletal and doubly terminated olivine plates in sub-parallel orientation.

F. 1516D, x 20. B_2 zone of porphyritic olivine peridotite. Note the skeletal nature of many olivine crystals and the small proportion of platy olivine present.

Note : All specimens are totally altered, A-D are now chlorite-tremolite rocks ; E and F are serpentine-tremolite rocks.

show a gradation in size, from large at the base to small at the top, and thus provide a primary facing indicator.

The zone of foliated olivine peridotite, B_1, is narrow and rarely visible in the field. However, it is prominent in core sections where it provides the most conspicuous internal boundary within the flow. The zone is not always present and varies in width up to about 10 cm.

The porphyritic olivine peridotite zone, B_2, is the major zone in the lower half of the flow. It is a medium to fine-grained green-black serpentinite. On weathered surfaces small euhedral olivine crytals are seen.

The lower chilled zone, B_3, is not often seen in the exposures. Where visible it is similar in appearance to the upper chilled zone, but lacks the fractures.

PETROGRAPHY OF THE ULTRAMAFIC FLOWS

A common feature of all ultramafic rocks from the Mount Clifford area is the extensive alteration of primary minerals to serpentine, chlorite and tremolite. The metamorphism is essentially isochemical except for the introduction of a small amount of CO_2. That metamorphism did not involve large-scale transfer of components is indicated by the preservation of original igneous textures, and that iron, expelled from olivine during serpentinization, has not been distributed throughout the rock but forms a fringe of granules of magnetite around the pseudomorph. The scheme of alteration is not constant, but commonly olivine is altered to serpentine or chlorite and clinopyroxene to tremolite. In the drill core example the upper chilled margin and the spinifex-textured zones have been altered to chlorite-tremolite rocks. Towards the base of the A_3 zone, chlorite, after olivine, becomes more highly coloured and strongly pleochroic from green to pale orange and is probably the calcium-rich variety, xanthophyllite. Throughout the B_1, B_2, and much of the B_3 zones in which porphyritic olivine is dominant, serpentine replaces chlorite and the rock becomes a serpentine-tremolite rock. In the lowermost 10 cm of the flow, the alteration scheme is again chlorite-tremolite. It is tempting to suggest that the different alteration schemes in the lower and upper parts of the flow give rise to the different resistances to the weathering. Surface specimens collected from all zones, however, were found to be serpentine-tremolite rocks. None of the Mount Clifford specimens contained original olivine or pyroxene. However, despite complete replacement, the original igneous textures of the rocks are often beautifully preserved (Figs. 37 and 39) so that descriptions will be based on the original rather than the metamorphic mineralogy.

The following descriptions refer mainly to the drill-core sample of a single flow unit.

A_1 Chilled and fractured flow top

The upper half of the flow top is variable and in thin section has an agglomeratic appearance. Some patches are of devitrified glass containing about 14 per cent small euhedral olivine phenocrysts up to 0.5 mm across (Fig. 39A), while others, with fewer phenocrysts, are made up of small matted plates of olivine up to 0.4 mm long (Fig. 39B). The glassy patches often merge into the spinfex-textured parts and fractures pass indiscriminately through the rock. These fractures probably indicate cracking on cooling as there is no evidence of brecciation. The fractures in the flow top are filled with fibrous tremolite and green and brown chlorite. The marginal glassy peridotite is strongly dusted with anhedral grains of oxide and sulphide. A few small vesicles about 0.5 mm across are seen in this part of the flow (thin sections 15157A, B and Fig. 39B).

The lower half of the flow top grades into the random spinifex texture of zone A_2. Fractures, vesicles and euhedral olivine become less common and the olivine plates grow to a maximum length of about 1.5 mm. The interstitial material is a devitrified glass with no crystalline clinopyroxene, whilst the overall texture of the altered rock is similar to a high-Mg basalt (Compare Figs. 37E and 39B). The chilled margin is also noteworthy for its lack of dendritic opaque minerals which, in this zone, are distributed as a "dust" throughout the rock.

A_2 Pyroxene peridotite with random spinifex texture

The boundary between the A_1 and A_2 zones is gradational, and less obvious in thin section than in the polished core (Fig. 38). Small-scale spinifex texture becomes progressively coarser and more organized towards the base. The zone is characterized by dendritic chromite and feathery clinopyroxene as the interstitial material, rather than glass. Blades of olivine make up about 35-40 per cent of the rock (Fig. 39C) and range in length from 1.5 mm near the top (15157D) to 8 mm near the boundary with the underlying A_3 zone. The length : breadth ratio of the plates varies from about 20 : 1 to 10 : 1, and for the most part, the plates are randomly orientated about triangular and rhomboidal areas of feathery to acicular clinopyroxene and dendritic chromite. Near the base of the zone (15158D) the large olivine plates occasionally form small fans, and although the interstitial clinopyroxene forms acicular crystals up to 1 mm long, the chromite remains as dendritic crystals about 0.5 mm across.

A_3 Pyroxene peridotite with large-scale spinifex texture

This, the largest zone in each flow, is distinctive both in the field and microscopically. It is characterized by large books and fans of olivine plates

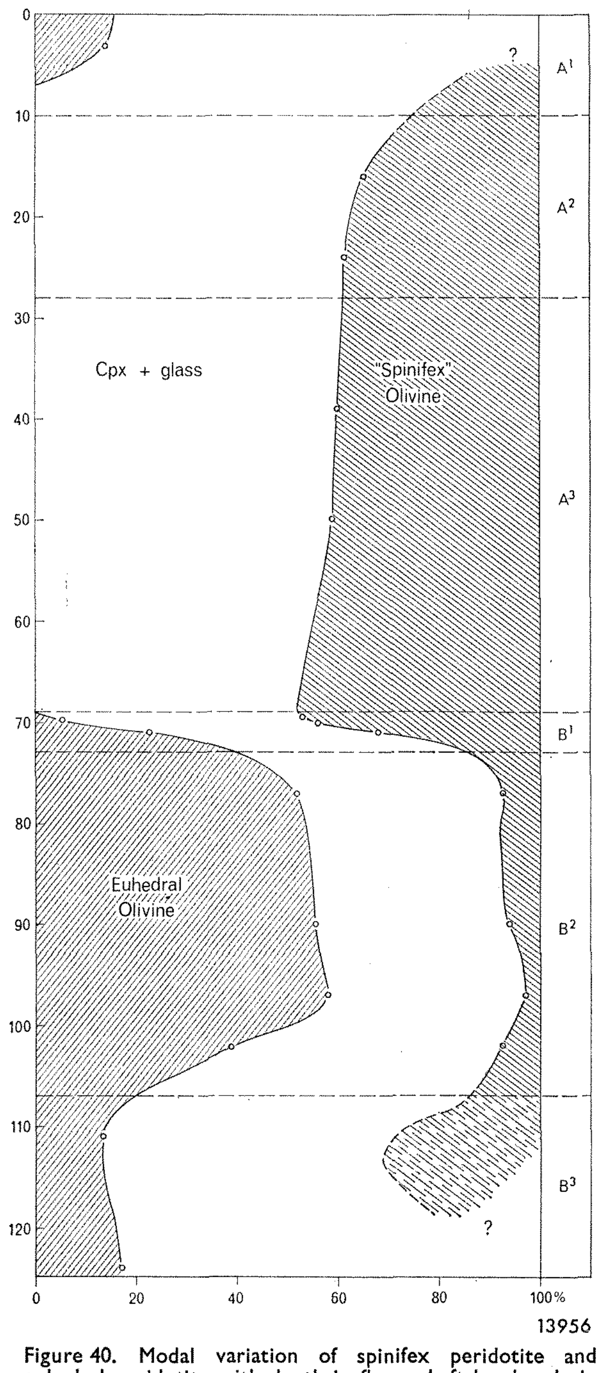


Figure 40. Modal variation of spinifex peridotite and euhedral peridotite with depth in flow. Left hand scale in cm below flow top. Right hand scale gives zones within the flow.

with their long axes sub-vertical and the apices of the fans pointing towards the top of the flow (Figs. 37B, 38, 39D). This type of spinifex texture has been fully described by Nesbitt (1971) and Pyke and others (1973).

Modal analyses (Fig. 40) show that the zone consists of 40 per cent bladed olivine and 60 per cent interstitial material. The latter consists of acicular clinopyroxene and dendritic chromite similar to that in the A_2 zone. The length of the olivine plates in the core section varies from about 2 cm near the top to about 8 cm at the base, and in thicker flows, seen in the field, may be up to 30 cm long. In thin section the blades are rarely more than 0.5 mm thick, show an internal skeletal structure and have a length : breadth ratio of up to 50 : 1.

B_1 *Foliated olivine peridotite*

Between the spinifex zone, A_3, and the underlying porphyritic peridotite zone, B_2, a narrow zone of foliated peridotite is usual. The B_1 zone is generally poorly exposed but is well represented in the W.M.C. DDH 169 core, where such zones vary in thickness from 3 to 10 cm. As noted by Pyke and others (1973) the junction between the spinifex zone and the foliated zone is the most distinctive zone boundary in the flow (Fig. 38). The foliated peridotite is characterized by elongate skeletal olivine plates (Fig. 39E) in sub-parallel orientation. Interstitial acicular clinopyroxene and dendritic chromite, similar to that in higher zones, are present. In addition there are euhedral olivine crystals whose abundance increases rapidly downward. The base of the zone is taken where euhedral olivine becomes dominant over platy olivine. This transition is illustrated in Figure 40 where modal analyses show that over a distance of 2 cm olivine plates cease to be the dominant mode of crystallization. The plates themselves are unlike those of the overlying spinifex zone in that they are rarely longer than 3 mm, have a length : breadth ratio of 10 : 1 or less, and are more skeletal than the plates for the A_3 zone. Also the plates are often doubly terminated indicating growth at both ends, whereas spinifex fans develop in one direction only.

B_2 *Olivine peridotite*

This zone is characterized by the presence of about 55 per cent modal euhedral olivine and 5 per cent platy olivine (Fig. 40). The olivine is set in a matrix of fine-grained feathery clinopyroxene, glass and a few small euhedra of chromite (Fig. 39F, see also Figs. 37C and D). The olivine euhedra are between 0.7 and 1.0 mm long and somewhat skeletal. A few larger euhedra, up to 1.5 mm across, are markedly skeletal. The platy olivine forms skeletal crystals up to 3 mm long and 0.3 mm thick, similar to those of the B_1 zone but without preferred orientation (Fig. 39F). The chromite euhedra are about 0.1 mm across and much less plentiful than the dendritic chromite of the spinifex zones.

The development of both olivine and interstitial pyroxene appears to depend, in part, on the thickness of the flow. In surface specimens (20543-4), from a flow 3 m thick, not only are the olivine crystals larger (up to 2 mm across) but the clinopyroxene shows the skeletal and acicular development typical of the spinifex zones of the core sample.

Towards the base of the B_2 zone (15164 A, B) the olivine euhedra become smaller and less numerous. In interstitial areas small spinifex-style plates of olivine begin to develop and over a distance of a few centimetres the olivine peridotite grades into the basal chilled zone.

B_3 *Lower chilled zone*

The lowermost part of the core section is similar to the uppermost zone. However, fractures are absent. Throughout this lower zone there are small olivine phenocrysts, but the dominant texture is a fine-grained irregular spinifex with interstitial feathery clinopyroxene which grades downward into a glassy material with hair-like olivine blades. The lowermost centimetre, or so, seems to have been completely glass and the contact with the underlying flow is sharp (Fig. 39A). The larger spinifex plates are up to 1.5 mm long and are randomly orientated, but the smaller plates nearer the base are matted and foliated parallel to the base. Olivine phenocrysts in the glassy parts of the chilled zone are smaller and less skeletal than those in the overlying B_2 zone. In one slide (15165D) there is a crop of very small euhedral olivine crystals (0.1 mm or less) which appear to have formed in preference to spinifex-type plates. Chromite is present throughout most of the chilled zone as small dendritic crystals but in the lowermost glassy portions it is present only as a dusting of minute opaque grains.

Vesicular flow units

Surface specimens of two vesicular flow units southeast of the Mount Clifford area are so thoroughly serpentinized that little remains of their original textures. Specimens obtained from the centres of the flows (20549-51) appear to have been composed of coarse-grained peridotite with subhedral olivine crystals 3-4 mm across making up at least 70 per cent of the rock. Specimens from a narrow vesicular zone (20547, 8) appear to be a similar rock with slightly smaller olivine and large chlorite-filled vesicles up to 1 cm across. Textures similar to the dendritic olivine displayed in the Murphy Well ultramafite (Lewis and I. R. Williams, 1973) are not present, but the vesicles often have a pyroxene-rich "tail" identical to those associated with vesicles in the Murphy Well rocks. The "tail" marks the upward path of the vesicle and is filled by acicular skeletal clinopyroxene up to 1 mm long, and glass. Some vesicles were evidently trapped by the olivine crystals and failed to produce a tail, but others have irregular tails up to 8 mm long with a small circular vesicle 2 mm across at the upper end. Although most vesicles are spherical to sub-spherical some of the larger ones are irregular in shape.

CHEMISTRY

Bulk chemical analyses and C.I.P.W. norms of 13 samples from the core section are presented in Table 11. Some of the chemical variations exhibited by these samples are shown in Figures 41 and 42. Analyses of additional rocks from the Mount Clifford area, including a high-Mg basalt from the Marshall Pool syncline, are given in Table 12. For comparison analyses of peridotitic lavas and high-Mg magma types from various Archaean terrains are given in Tables 13 and 14.

If analyses 4 and 5 of Table 11 are taken to be typical of the upper spinifex zones of the flow, and analysis 9 to be typical of the lower porphyritic zone, then it will be seen that there are significant chemical differences. The porphyritic olivine peridotite is rich in MgO but is comparatively poor in Al_2O_3, CaO and total Fe, and this is reflected in the greater amount of olivine in the mode of the olivine peridotite (60 per cent) than in the spinifex-textured rocks (40 per cent). This difference is further emphasized by the olivine occuring in different forms (Fig. 40).

Chemical variations throughout the flow are shown in Figure 41. Nickel and sulphur follow the MgO curve and are concentrated in the porphyritic zone whereas chromium and titania follow the total Fe curve and are concentrated in the spinifex zones. Nickel is present in the ultramafic rocks of the Yilgarn Block both as sulphides and in small amounts in olivine (see e.g. Lewis and I. R. Williams, 1973). Except in the chilled margins Ni follows the MgO curve faithfully, indicating that in these low-sulphur ultramafics from

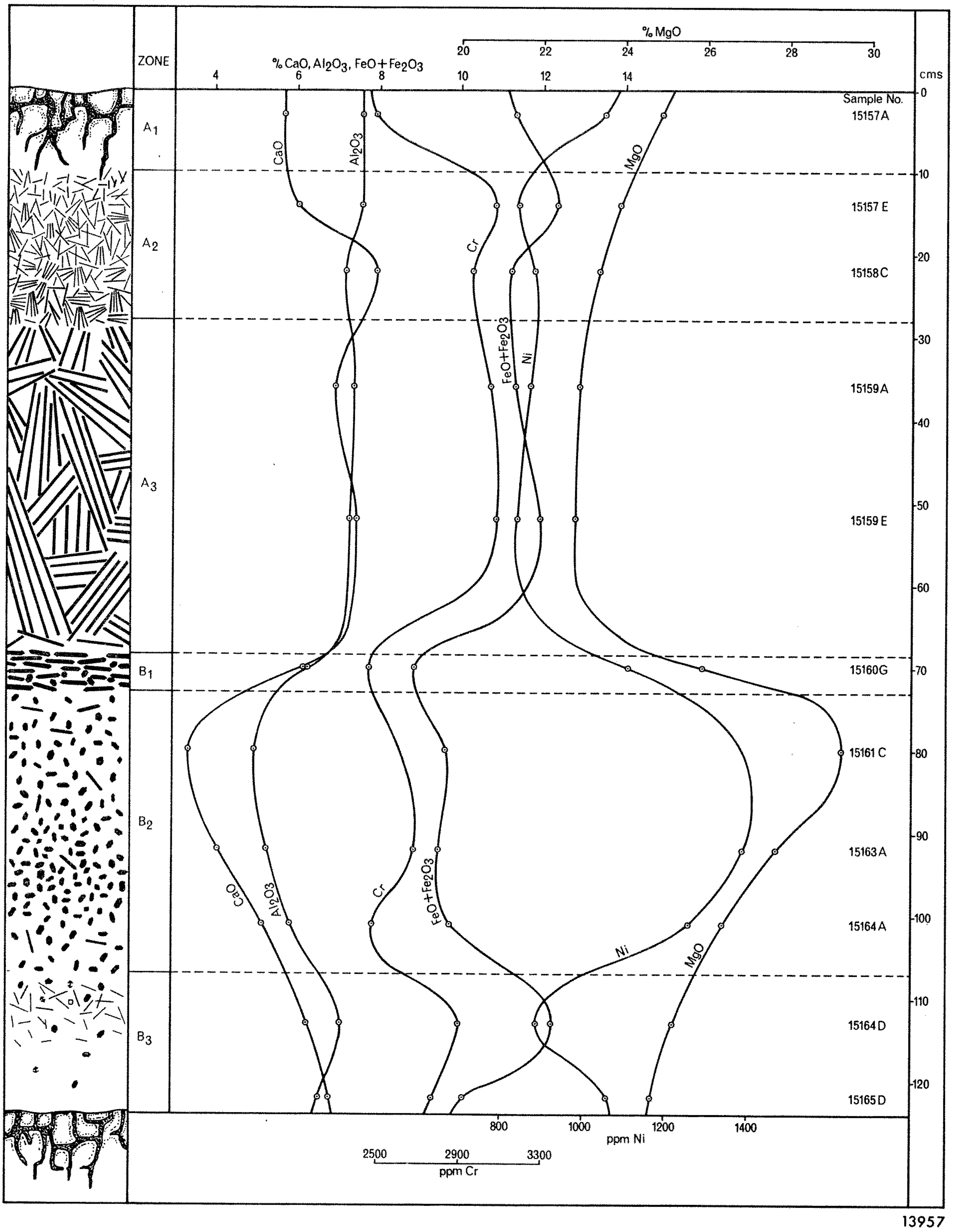


Figure 41. Chemical variation within a single flow unit.

37038—(5)

TABLE 11. ANALYSES OF ULTRAMAFIC LAVA FROM MT. CLIFFORD

	1	2	3	4	5	6	7	8	9	10	11	12	13	
	15156E	15157A	15157E	15158C	15159A	15159E	15160G	15161C	15163A	15164A	15164D	15165D	15165E	A
SiO_2	45·1	41·6	41·8	42·3	43·2	42·8	44·6	43·3	43·5	43·3	42·5	44·2	42·1	42·89
Al_2O_3....	6·4	7·6	7·6	7·2	7·4	7·3	6·3	5·0	5·3	5·9	7·1	6·6	7·6	6·76
Fe_2O_3....	2·1	3·4	3·8	2·9	2·6	3·3	2·8	2·7	2·9	3·4	4·5	3·1	4·1	3·20
FeO	6·87	7·96	8·56	8·35	8·73	8·66	6·11	6·95	6·58	6·38	7·73	7·00	7·52	7·78
MgO	24·6	24·9	23·9	23·4	22·9	22·8	25·9	29·3	27·7	26·4	25·2	24·7	24·9	24·95
CaO	7·49	5·70	6·03	7·96	6·99	7·43	6·24	3·40	4·09	5·20	6·28	6·82	5·63	6·11
Na_2O	0·49	0·49	0·46	0·63	0·49	0·45	0·40	0·40	0·46	0·38	0·51	0·65	0·38	0·48
K_2O	0·1	0·1	0·0	0·0	0·1	0·1	0·1	0·2	0·2	0·1	0·0	0·0	0·0	0·09
TiO_2	0·32	0·28	0·38	0·36	0·37	0·37	0·28	0·22	0·26	0·27	0·34	0·32	0·36	0·32
MnO	0·17	0·16	0·19	0·20	0·20	0·20	0·15	0·17	0·16	0·15	0·17	0·17	0·15	0·18
H_2O^+	6·50	7·65	7·24	6·51	6·63	6·56	6·81	8·90	8·24	7·67	6·92	6·76	7·59	7·01
H_2O^-	0·43	0·46	0·38	0·22	0·30	0·34	0·68	0·93	1·02	0·93	0·29	0·33	0·40	0·49
CO_2	0·62	0·51	0·27	1·51	0·26	0·91	0·25	0·20	0·11	0·27	0·28	0·36	0·27	0·52
P_2O_5	0·03	0·04	0·04	0·05	0·02	0·06	0·03	0·01	0·01	0·03	0·05	0·04	0·04	0·03
Total	101·2	100·8	100·6	101·6	100·3	101·2	100·7	101·7	100·5	100·3	101·9	101·1	101·1	100·8
Trace Elements (ppm)														
Cr	2 680	2 490	3 070	2 960	3 050	3 070	2 460	....	2 680	2 480	2 900	2 770	3 000	....
Co	85	90	90	85	90	90	75	....	100	90	85	90	95	....
Ni	980	1 050	840	880	870	840	1 110	....	1 390	1 260	890	1 060	930	....
Cu	35	350	30	25	20	60	30	....	20	45	30	45	80	....
Zn	80	60	70	60	60	60	90	....	70	60	50	70	50	....
S	250	460	80	80	70	100	290	....	480	410	70	230	150	....
Ba	5	5	5	5	5	5	5	....	5	5	5	5	5	....
Sr	50	30	30	80	50	60	20	....	20	20	30	30	20	....
Zr	60	40	10	50	20	40	20	....	30	10	30	10	50	....
C.I.P.W. Norm														
Or	0·59	0·59	0·00	0·00	0·59	0·59	0·59	1·18	1·18	0·59	0·00	0·00	0·00	0·59
Ab	4·48	4·57	4·23	5·84	4·48	4·15	3·64	3·72	4·32	3·55	4·65	5·92	3·47	4·40
An	16·15	19·93	20·13	18·19	19·16	19·06	16·33	12·44	12·95	15·56	18·54	16·23	20·81	17·56
Ap	0·07	0·09	0·09	0·12	0·05	0·17	0·07	0·02	0·02	0·07	0·12	0·09	0·09	0·07
Di	18·90	8·55	9·64	19·53	14·45	16·34	13·50	4·92	7·43	10·00	11·80	15·94	7·46	12·11
Wo	9·93	4·47	5·03	10·21	7·55	8·53	7·10	2·59	3·91	5·25	6·17	8·36	3·90	6·34
En	7·36	3·20	3·52	7·23	5·31	5·94	5·31	1·94	2·92	3·88	4·36	6·09	2·79	4·56
Fs	1·61	0·88	1·09	2·09	1·59	1·88	1·09	0·39	0·60	0·86	1·28	1·49	0·77	1·20
Hy	25·94	18·96	21·35	10·66	22·33	19·46	30·11	32·98	32·29	30·12	18·08	22·93	24·86	22·35
En	21·28	14·86	16·29	8·27	17·20	14·78	24·99	24·47	26·77	24·65	13·98	18·43	19·47	17·69
Fs	4·66	4·09	5·06	2·39	5·14	4·67	5·13	5·52	5·51	5·47	4·10	4·50	5·39	4·66
Ol	32·70	45·38	42·04	44·38	36·33	38·53	34·10	44·10	39·99	38·10	45·80	37·32	41·37	41·14
Fo	26·35	34·81	31·32	33·64	27·33	28·58	27·81	36·11	32·59	30·61	34·62	29·41	31·70	31·88
Fa	6·35	10·57	10·72	10·74	9·00	9·95	6·29	7·99	7·40	7·49	11·19	7·91	9·67	9·26
Mt	1·59	1·88	2·03	1·88	1·88	2·03	1·59	1·59	1·59	1·59	1·88	1·74	2·03	1·88
Il	0·66	0·59	0·78	0·74	0·76	0·76	0·57	0·46	0·55	0·57	0·70	0·66	0·74	0·66
Salic%	21·1	25·0	24·4	23·8	24·3	23·7	20·5	17·1	18·4	19·7	22·9	22·1	24·2	22·4
Femic %	78·9	75·0	75·6	76·2	75·7	76·3	79·5	82·9	81·6	80·3	77·1	77·9	75·8	77·6

NOTE : Norms calculated on volatile free basis and after adjusting Fe^{3+} : Fe^{2+} ratio to 1:9 (see text). *Analysts:* Govt. Chemical Laboratories, FeO, Na_2O, and H_2O by chemical methods, remainder by X.R.F. 1. Base of overlying flow. 2. Chilled and fractured flow top, A_1 zone. 3 and 4. Pyroxene peridotite A_2 zone. 5 and 6. Pyroxene peridotite, A_3 zone. 7. Foliated olivine peridotite, B_1 zone. 8, 9 and 10. Olivine peridotite, B_2 zone. 11 and 12. Basal chilled, B_3 zone. 13. Top of underlying flow. A. Weighted average of analysis 2–12. For location of samples on core section see Fig. 38.

TABLE 12. ADDITIONAL ANALYSES FROM THE MT. CLIFFORD AREA

	1	2	3	4	5	6	7	8	9	10
	32773	32775	38280	32778	38282	32771	35962	38281	35960	32772
SiO_2	42·3	44·6	42·2	40·9	40·5	40·5	42·9	41·9	43·4	49·8
Al_2O_3	6·1	7·3	5·8	2·9	2·9	3·8	1·8	2·1	6·8	12·4
Fe_2O_3	5·8	2·2	5·7	3·3	3·9	3·6	2·9	2·8	6·6	2·4
FeO	3·49	7·38	4·22	4·65	4·10	4·54	4·00	1·99	5·73	8·55
MgO	29·5	25·2	29·2	36·3	36·5	36·6	38·00	39·9	26·9	11·8
CaO	5·59	6·84	5·05	0·11	0·17	0·73	0·08	0·14	4·29	7·23
Na_2O	0·30	0·22	0·24	0·00	0·01	0·05	0·03	0·02	0·21	4·09
K_2O	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00	0·00
TiO_2	0·28	0·44	0·28	0·18	0·17	0·18	0·07	0·09	0·54	0·81
MnO	0·17	0·20	0·18	0·16	0·15	0·17	0·09	0·08	0·20	0·21
H_2O^+	7·68	6·50	7·54	11·57	11·53	11·00	11·70	11·91	6·89	2·86
H_2O^-	0·54	0·36	0·36	0·70	0·85	0·37	0·44	0·70	0·40	0·31
CO_2	0·05	0·04	0·03	0·02	0·02	0·03	0·02	0·04	0·06	0·06
P_2O_5	0·04	0·06	0·02	0·00	0·00	0·01	0·02	0·00	0·06	0·10
Total	101·8	101·3	100·8	100·7	100·7	101·6	101·4	100·7	102·1	100·6
Trace Elements (ppm)										
Cr	2 570	1 780	1 030	1 860	1 530	1 290	1 440	1 720	2 280	1 090
Cu	10	10	10	10	10	10	10	10	50	60
Ni	1 400	1 240	1 420	1 850	1 910	1 840	1 670	2 190	1 400	350
Zn	50	80	90	50	200	50	60	90	60	90
S	60	50	40	40	80	30	50	180	70	60

Analysts: Government Chemical Laboratories ; FeO, H_2O and CO_2 by chemical method, all other elements by X.R.F.

1. Spinifex-textured pyroxene periodtite, Mt. Clifford.
2, 3 Olivine peridotite, Marriot Prospect, Mt. Clifford (Area B Fig. 35).
4, 5, 6 Olivine peridotite, Mt. Clifford North extension.
7. Olivine peridotite, near Bannockburn Well, Mt. Clifford.
8. Olivine peridotite, near W.M.C. DDH 169, Mt. Clifford.
9. Intrusive peridotite, Mt. Fouracre.
10. High-Mg basalt, Mt. Clifford North extension.

Mount Clifford the partitioning of Ni between a sulphide phase and the olivine lattice is in equilibrium. A similar equilibrium exists between Cr in chromite and in the clinopyroxene lattice.

A significant feature of the chemistry of the Mount Clifford rocks is that the weighted average of the 11 analyses from the flow (Table 11, Column A) is in good agreement with the analysis of the basal chilled zone (Table 11, Column 12) and fair agreement with the upper chilled zone and the foliated B_1 zone (Table 11, Columns 1 and 2). This suggests that these zones represent essentially undifferentiated portions of the flow. The high Al_2O_3 in the upper chilled margin may be due to chlorite which fills the fracture veins.

The norms in Table 11 were calculated after exclusion of volatiles and adjustment of the Fe^{3+} : Fe^{2+} ratio to 1 : 9 in order to compensate for oxidation of iron during serpentinization. Normatively the rocks contain from 12 per cent to 21 per cent anorthite, and up to 33 per cent orthopyroxene, minerals which have not been observed in the mode. Orthopyroxene and plagioclase are not present in the interstitial glass of the Mount Clifford rocks because wherever the glass is sufficiently devitrified to determine it is replaced by feathery tremolite after an original clinopyroxene. In other studies where fresh pyroxene was available for analysis (Nesbitt, 1971; Pyke and others, 1973; Lewis and I. R. Williams, 1973) it has been shown that the clinopyroxene of these ultramafic rocks is a high alumina augite containing 6 per cent to 9 per cent Al_2O_3 in the molecule. The result of incorporating Al_2O_3 into the clinopyroxene rather than the anorthite molecule is to release the CaO of the anorthite to form more clinopyroxene thus also absorbing the orthopyroxene calculated in the norm. It is probable that the clinopyroxne of the Mount Clifford rocks would also have been a high alumina variety. The norms indicate that under different cooling conditions none of the Mount Clifford rocks would be strictly ulramafic but would be classified as picrites. The rapid cooling of the magma, however, has given rise only to olivine, clinopyroxene and an iron-rich residual glass so that mineralogically the rocks are ultramafic.

TABLE 13. ULTRAMAFIC LAVAS FROM W. AUSTRALIA, CANADA, SOUTH AFRICA AND CYPRUS

	1	2	3	4	5	6	7	8
SiO	40·37	40·8	39·3	41·0	41·58	42·06	40·36	43·00
Al_2O_3	4·66	10·0	5·91	5·54	3·44	2·21	1·97	4·64
Fe_2O_3	5·41	2·94	3·68	3·46	5·20	4·73	5·84	2·42
FeO	4·03	6·49	3·31	6·16	6·01	5·23	3·75	6·47
MgO	31·06	23·3	33·9	32·0	26·71	29·93	35·17	33·45
CaO	4·17	6·86	2·58	4·21	5·99	5·18	3·45	3·99
Na_2O	0·11	0·23	0·20	0·28	0·12	0·16	0·05	0·25
K_2O	0·03	0·07	0·12	0·07	0·03	0·02	0·00	0·05
TiO_2	0·22	0·25	0·17	0·21	0·38	0·31	0·41	0·18
MnO	0·17	0·16	0·10	0·13	0·19	0·16	n.d.	0·15
H_2O^+	9·05	5·91	9·23	5·47	9·03	8·62	7·76	3·83
H_2O^-	0·34	0·86	1·06	0·73	0·18	0·15	0·21	1·22
CO_2	0·11	0·28	0·31	0·42	n.d.	n.d.	n.d.	n.d.
P_2O_5	0·08	0·02	0·03	0·01	n.d.	0·02	n.d.	....
Cr_2O_3	0·17	0·45	0·29	0·38	0·30	0·31	n.d.	0·51
NiO	0·18	n.d.	n.d.	n.d.	0·15	0·18	0·25	....
Total	100·16	98·62	100·19	100·07	99·70	99·76	99·22	100·16

n.d.—no data.

1. Peridotite average of 7 analyses from Murphy Well (Lewis and Williams 1971, p. 64, Nos. 3–10).

2–4. Ultramafic flow, Munro Township, Ontario. 2. A_2 zone ; 3. B_2 zone ; 4. B_3 zone (Pyke and others 1973).

5–7. Peridotite flow, Barberton, South Africa. 5. AU5. pillowed peridotite from top of flow ; 6. V_2peridotite, centre of flow ; 7. VU32A, peridotite, base of flow (Viljoen and Viljoen 1969).

8. Ultrabasic pillow lava, vitrophyric types, Cyprus (Gass 1958).

TABLE 14. REPRESENTATIVE ANALYSES OF PERIDOTITES, HIGH-MG BASALTS AND THOLEIITES

	1	2	3	4	5	6	7	8	9
SiO_2	43·70	42·10	48·4	46·2	49·9	51·4	43·54	47·90	50·83
Al_2O_3	6·10	4·35	7·4	5·3	10·6	14·8	3·99	11·84	14·07
Fe_2O_3	2·94	4·45	9·8	9·6	1·9	1·5	2·51	2·32	2·88
FeO	5·27	5·69	....	....	8·0	9·1	9·84	9·80	0·06
MgO	27·85	30·77	24·9	33·3	14·1	6·7	34·02	14·07	6·34
CaO	6·25	3·74	8·0	3·6	9·5	10·7	3·46	9·29	10·42
Na_2O	0·19	0·17	0·24	0·17	1·54	2·7	0·56	1·66	2·23
K_2O	0·02	0·03	0·05	0·02	0·13	0·18	0·25	0·34	0·82
TiO_2	0·28	0·18	0·33	0·24	0·51	0·92	0·05	1·65	2·03
MnO	0·20	0·20	0·18	0·15	0·17	0·21	0·21	0·15	0·18
H_2O^+	....	....	....	....	3·1	1·0	} 0·76	0·59	0·91
H_2O^-	6·92*	8·48*	5·3*	9·7*	....	....			
CO_2	....	....	....	....	0·1	0·1	....	....	....
P_2O_5	....	....	0·04	0·03	0·07	0·13	....	0·19	0·23
Cr_2O_3	n.d.	n.d.	0·43	0·44	0·24	....	....	....	....
NiO	n.d.	n.d.	0·18	0·25	n.d.	....	....	....	....
Total	99·72	....	....	....	....	99·44	100·00	....	....

* Loss on ignition

1. Plate spinifex peridotite, Scotia W.A. SD3/266 (Nesbitt 1971).
2. Olivine peridotite adjacent to 1. Scotia W.A. (Nesbitt 1971).
3. Average of 11 olivine-poor peridotites from Mt. Hogan ultramafic lenses (D. A. C. Williams 1973).
4. Average of 14 peridotites from cores of Mt. Hogan ultramafic lenses (D. A. C. Williams 1973).
5. Average of 35 high-Mg basalts. Eastern Goldfields W.A. (Hallberg and Williams 1972).
6. Average of 123 tholeiitic basalts from Kalgoorlie-Norseman W.A. (Hallberg 1972).
7. Average peridotite (Nockolds 1954).
8. Average tholeiitic olivine basalt (Nockolds 1954).
9. Average tholeiitic basalt (Nockolds 1954).

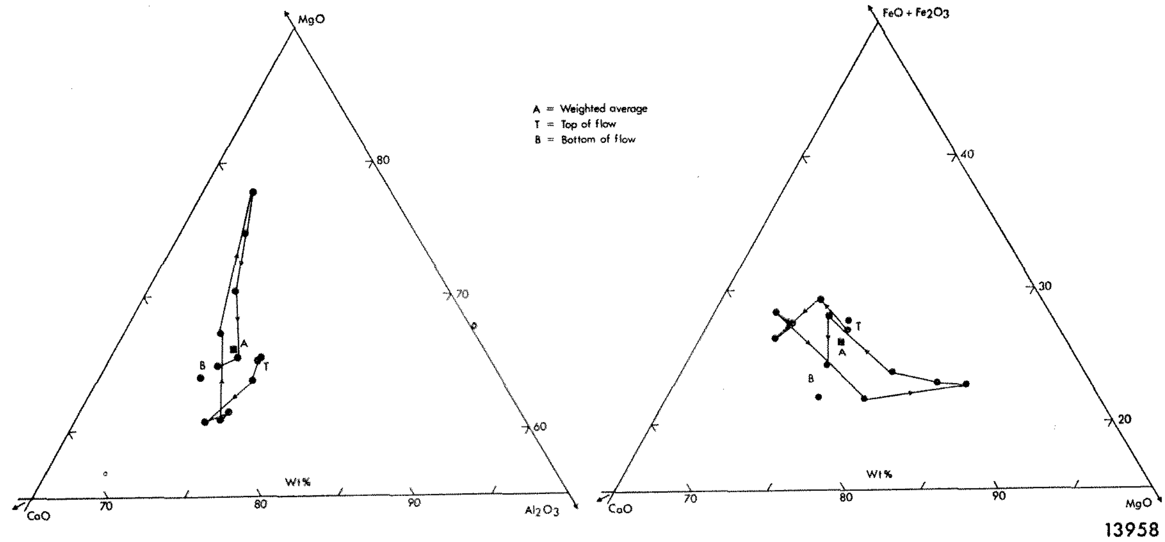


Figure 42. MgO–CaO–Al_2O_3 and total Fe–CaO–MgO variation diagrams of the Mount Clifford ultramafic rocks.

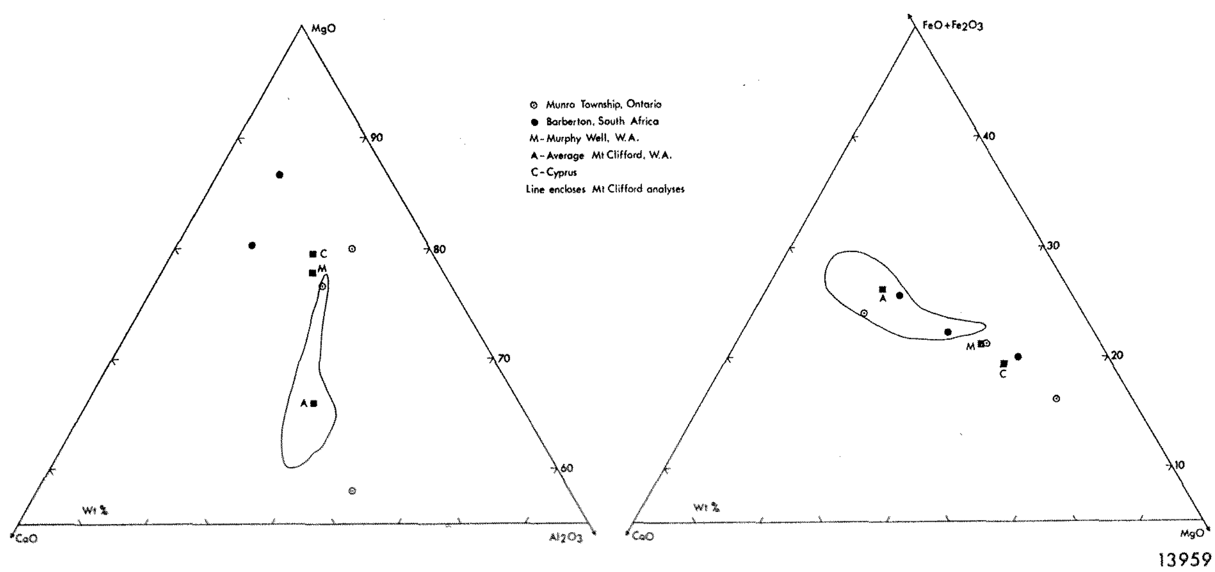


Figure 43. Comparison of ultramafic lavas.

Comparison of the Mount Clifford analyses with those from the Munro Township ultramafic flows (Table 13, Columns 2-4) shows that the spinifex zone at Mount Clifford is slightly more siliceous and less aluminous than the Canadian example but otherwise the analyses are in good agreement. The considerably lower MgO content of the porphyritic zone of the Mount Clifford lavas (Table 11, Column 9) compared with the Munro Township flows indicates a lower concentration of olivine. Nevertheless Figure 43 shows that the Munro lavas are similar to the Mount Clifford flows whereas peridotite lavas from the Barberton Mountainland of South Africa (Table 13, Columns 5-7; Viljoen and Viljoen, 1969a) fall in a different field. The South African rocks are high in MgO but lower in CaO and especially in Al_2O_3 with the result that the CaO : Al_2O_3 ration is consistently greater than unity. Although some of the Mount Clifford analyses show a ratio slightly greater than 1.0 the majority range down to 0.68. With respect to the Murphy Well ultramafic lava (Lewis and I. R. Williams, 1973) and the ultrabasic pillow lava from Cyprus (Gass, 1958, and this paper Table 13, Columns 1, 8) the Mount Clifford lavas are less peridotitic but fall on the same compositional trend.

Comparison of the Mount Clifford lavas with other peridotite and high-Mg basalt from Western Australia (Table 14 and Fig. 44) reveals a general similarity in the magma type that these analyses represent.

DISCUSSION

That rocks similar to the Mount Clifford ultramafites are true peridotitic lavas is now widely accepted, as is the hypothesis that they crystallized from a liquid magma with only a small proportion of phenocrysts. Both upper and lower chilled margins show that the units are complete and the marked asymmetry of the flow zones, coupled with the regularity of such features across strike, supports the hypothesis that the flows were laid down one after the other.

The very fluid nature of an ultramafic magma would allow it to spread rapidly over a wide area with the result that a lava pile would be built up of many thin flows. The remarkable lateral persistence of flows only a few metres thick has been documented by Pyke and others (1973). In the Mount Clifford area this feature is emphasized by the persistence of strike ridges of spinifex-textured peridotite several hundred metres long (Fig. 36). In the Munro Township exposures of small bulbous flows about a metre long were also mapped. The Mount Clifford lavas are not so well exposed, however, small discontinuous flows are found among the thicker flows. These may represent tongues of liquid advancing in front of a major lava flow rather than pillows as found by Viljoen and Viljoen (1969a) in South Africa. There is no clear indication of pillows in the Mount Clifford peridotites.

After extrusion the chilled upper surface of the lava must have formed rapidly. The formation and preservation of this thin zone and the maintenance of still conditions, in order that spinifex texture might develop within the liquid interior, suggests that the lava poured into a basin which effectively ponded the flow. The presence of thin shale horizons between the flows indicates that the eruptions were submarine.

Spinifex texture has been shown to form by the quenching of an ultramafic liquid which was free of phenocrysts or other potential nucleii (Nesbitt, 1971; Lewis, 1971). In contrast the lower porphyritic and more olivine-rich layer (B_2 zone) is probably derived from an accumulation of olivine phenocrysts which formed nucleii around which further crystallization could take place. The mechanism by which this differentiation of olivine phenocrysts took place is not clear but at least two processes are possible, namely flow differentiation, and crystal settling. Viljoen and Viljoen (1969a, p. 98) maintain that the small size of the olivine nucleii would inhibit crystal settling. Therefore they favour the flow differentiation model in which crystals will tend to migrate away from the margins of a flowing body of liquid. If the flow rate was low (Bhattacharji, 1967) phenocrysts would concentrate at, or just below, the centre of the flow. This process appears to be confirmed by the shape of the graph for modal euhedral olivine in Figure 40. However, if the liquid fraction of the magma, as represented by the spinifex zones A_2 and A_3, was capable of crystallizing 40 per cent olivine then it can be calculated that the B_2 zone contained only 33.7 per cent phenocrysts before the magma finally crystallized. If these phenocrysts are then distributed throughout the magma their proportion falls to 12.2 per cent which is in fair agreement with the 15 per cent phenocrysts observed in the chilled margins. It has been noted above that the chemical composition of the chilled zones approximates to the average composition of the flow, and it seems probable that differentiation did not take place until after the lava had erupted and the chilled margins formed.

The crystal settling model imposes limitations on the cooling history of the magma. Principally it implies that the magma remained liquid for some time after extrusion, enabling the olivine phenocrysts to grow and settle. A magma as low in silica as the Mount Clifford ultramafic flows would have a low viscosity and a high melting point. Viljoen and Viljoen (1969a) have shown that an ultramafic liquid can exist at about 1 400° C. The fluidity of an ultramafic magma has been demonstrated by Lewis and I. R. Williams (1973) from studies of the morphology of vesicles in such a flow. Vesicles observed in some flows at Mount Clifford exhibit similar features and testify to a highly mobile magma. However, the presence of spinifex texture and interstitial glass even in the centre of the flow shows that crystallization, when it finally occurred, was very rapid. The paradox which requires that the magma remain fluid while olivine crystals settle, yet requires rapid chilling to produce glass, may be resolved if a suggestion of Wyllie (1960) is accepted. From consideration of experimental data on the system CaO-MgO-Fe-SiO_2, Wyllie suggests that the slope of the liquidus surface in the peridotite range is rather flat. The effect of such a plateau would be that the major part of a peridotite magma would crystallize over a small temperature range. Therefore, if a magma is extruded at temperatures above this "plateau"—with highly forsteritic olivine phenocrysts in equilibrium with the liquid fraction—there will be a temperature, and time interval, during which settling can occur with little additional crystallization. This interval will be followed by a short period during which the remainder of the magma will "freeze".

The composition of olivine found by microprobe in ultramafic flows falls within the narrow range of Fo_{89} to Fo_{93}. This probably represents the upper end of the plateau in the liquidus surface.

Nesbitt (1971) invoked a degree of superheating to clear the upper spinifex zones of potential nucleii before final crystallization. However, if extrusion at temperatures above the level of the liquidus "plateau" is accepted, then the nucleii could be cleared simply by crystal-settling through a magma of low viscosity.

Under this interpretation, which is favoured by the authors, the chilled margins represent a skin of rock of about the same composition as the original magma, which sufficiently slowed heat loss from the main part of the flow to allow crystal settling to accomplish the zonation now observed in the flows. Variations in the temperature of extrusion and the rate of heat loss would (Pyke and others 1973, p. 974) be sufficient to arrest differentiation, so forming the type of flow which does not have an upper spinifex zone.

The final crystallization of the magma after extrusion illustrates several points of interest. The foliated B_1 zone contains a concentration of short olivine plates which are also found in the porphyritic B_2 zone. Such plates probably represent early-formed, free floating crystals, which nucleated after extrusion but before the spinifex type plates, governed by cooling from the upper surface, finally predominated. The small plates, their long axes parallel to the top of the underlying olivine-liquid mush, would settle more slowly than euhedral olivines. In the thin (1.24 m thick) flow studied the time interval for final crystallization would be short and it is apparent that olivine crystallized simultaneously in two entirely different habits. In the upper zone, free of phenocrysts, the olivine formed large plates, whereas in the lower zone skeletal over-growths on existing euhedral olivines were forming. This supports the conclusion of Drever and Johnston (1957) that the habit of olivine is dependent upon small variations in the physical environment of crystallization.

Early formed chromite euhedra also settled during differentiation, and are only found in the porphyritic zone. From the chemistry of the flow, however, (Fig. 41) it is seen that chromium is concentrated in the upper zones either as part of the pyroxene lattice or as dendritic chromite. This suggests that under the conditions of extrusion, the bulk of the chromium was held in solution until the last stages of crystallization. This is in contrast to the layered sills of high-Mg basalt composition where chromium is concentrated near the base of the sills (Hallberg and D. A. C. Williams, 1972).

MAGMA TYPE

In Figure 44 the Mount Clifford rocks are plotted on F-M-C and A-M-C diagrams along with other peridotites, high-Mg basalts and tholeiites from the Eastern Goldfields. Nockolds' (1954) average peridotite, olivine tholeiite and tholeiite are also plotted on the same diagrams for comparison. Analyses with greater than 10 per cent combined water have not been used following a suggestion by Viljoen and Viljoen (1969b) that in such rocks complete serpentinization has expelled much of the CaO and Al_2O_3. This is confirmed by reference to Table 12 analyses 4-8 which show that high water content correlates with low CaO in rocks which are otherwise similar to those of Table 11.

The triangular diagrams show that the peridotite, pyroxene peridotite and high-Mg bassalt, lie on a well-defined trend which, as Nesbitt (1971, p. 336) states, may be a fractionation trend away from the MgO pole. The A-M-C trend is clearly defined, and it is of interest that the average tholeiite of Nockolds and the average Archaean tholeiite of Hallberg (1972) lie on the end of this trend. Although major element chemistry of Archaean ultramafic rocks indicates a differentiation trend which ends with the tholeiite basalts, Hallberg and D. A. C. Williams (1972) suggest that these rocks are not derived from a single magma source. Trace element trends within the peridotite to high-Mg basalt range do not continue into the tholeiites. In addition, while the ultramafic rocks show a wide variation in composition, tholeiites from the Yilgarn Block cluster within a very narrow composition range.

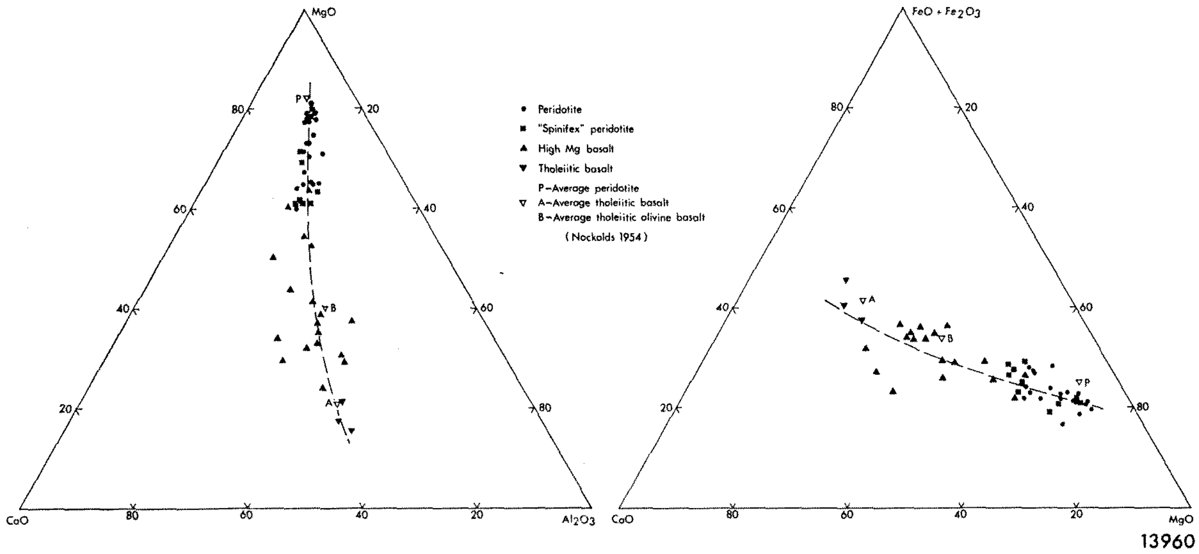


Figure 44. MgO–CaO–Al_2O_3, and total Fe–CaO–MgO variation diagrams of the high–Mg rock suite from the Archaean of Western Australia.

Data from this study and Nesbitt (1971), McCall and Leishman (1971), D. A. C. Williams (1972), Hallberg (1972), Hallberg and D. A. C. Williams (1972).

The Mount Clifford rocks are representative of a highly magnesian magma, that because of a thin crust and consequently steep temperature gradient in Archaean times was able to reach the surface and erupt as a lava. The relationship of this magma with the tholeiite magma of Archaean and Phanerozoic times remains uncertain.

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NOTES ON THE PATERSON RANGE GOLD PROSPECTS

by J. G. Blockley

ABSTRACT

The recently discovered Paterson Range gold prospects lie in a little prospected part of the Great Sandy Desert. They consist of quartz and quartz-limonite reefs, with pyrite boxworks and free gold, intruded concordantly into a sequence of sandstone, siltstone, shale and dolomite provisionally correlated with the Middle Proterozoic Bangemall Group. Granite, dated at 600 m.y., intrudes the sediments 25 km west of the prospects.

Most deposits occur in domes or anticlines, and many have a saddle-reef form. The principal prospect, with indicated reserves of 2 million tonnes averaging about 14 g of gold per tonne, follows a shale horizon around the outcrop of a well-formed dome.

The prospects differ from most other gold deposits in Western Australia in being Middle Proterozoic and in having as host rocks, sediments laid down on a stable shelf. Most other deposits are Archaean or Lower Proterozoic, and occur in greenstones belts or geosynclinal sequences. The saddle-reef form is also unusual. The only other gold deposits of comparable age, setting, and form, are at Bangemall on the southern edge of the Bangemall Basin. Further prospecting seems warranted in the Precambrian rocks of the western part of the Great Sandy Desert, and elsewhere in the folded margins of the Bangemall Group.

INTRODUCTION

The Paterson Range gold prospects lie near the northern end of the Paterson Range between latitudes 21° 35′ and 21° 47′ S and longitudes 122° 05′ and 122° 15′ E. The area is in the western edge of the Great Sandy Desert. The prospects occur in low rocky hills that protrude through the desert sand.

Newmont Pty. Ltd., which has tenure over the deposits has established a base known as Telfer Camp at lat. 21° 42′ S, long. 122° 12′ E. Access to the area is by a bulldozed dirt track which joins the Port Hedland to Woodie Woodie road near the Ragged Hills lead mine. Travelling time from the camp to Marble Bar, the closest town, is about 8 hours. Most personnel and light supplies are brought in by charter aircraft landing at a newly constructed strip near the camp.

Gold and copper concentrations were found in the Paterson Range area by Mr. Ronald Thomson, Geological Consultant to Day Dawn Minerals N.L. in 1971. At about the same time a private prospector, Mr. J. P. Turcaud, attempted to interest a number of companies in gossans with anomalous copper, lead and zinc values that he had located in the area. In following up the earlier work of Day Dawn Minerals N.L., Newmont Pty. Ltd. discovered free gold in a number of gossans in localities known as Main Dome and West Dome, within a larger structure called the Telfer Dome. It covered the more prospective ground with Mineral Claims, and more recently, with Gold Mining Leases and T.R.s for gold.

The prospects were inspected by J. H. Lord and the writer on the 23rd and 24th of August, 1973.

REGIONAL GEOLOGY

The gold prospects occur in a sequence of folded, slightly metamorphosed, cross-bedded sandstone, siltstone, shale, dolomite and calcarenite typical of sediments deposited in a stable shelf environment (Krumbein and Sloss, 1953). They closely resemble rocks of the Middle Proterozoic Bangemall Group, and are here tentatively assigned to this unit, although final correlation will depend on the results of proposed regional remapping programme in the area. Previous mapping by the Bureau of Mineral Resources (Wells, 1959) placed these sediments in the Lower Proterozoic at a time when the age relationships of the rock units in the Pilbara region were poorly understood (Fig. 45).

About 100 km south of the prospects, the Bangemall Group sediments overlie unconformable gneiss and schist dated by J. R. de Laeter at about 1 500 m.y. About 25 km west of the prospects, the sediments are intruded (Wells, 1959) by alkali-feldspar granite dated at about 600 m.y. (Trendall, 1974). Much of the area shown as granite on the B.M.R. reconnaissance map is in fact occupied by limestone or dolomite.

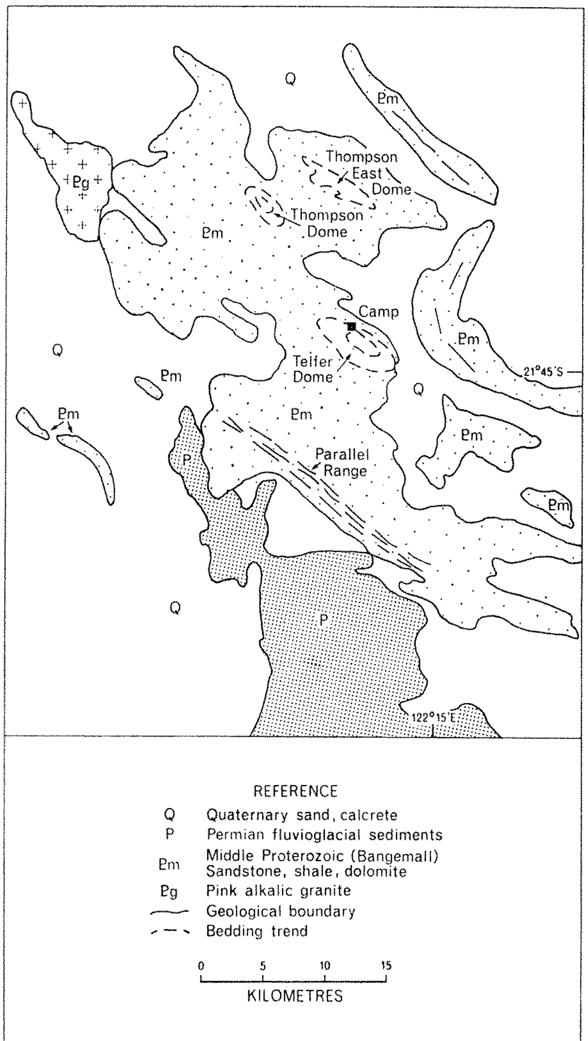

Figure 45. Paterson Range gold prospects—regional geology (after Wells, 1959).

MINERALIZATION

Gold occurs in reefs ranging in composition from almost pure vitreous quartz, through limonitic quartz with pyrite boxworks, to limonitic gossan. Most reefs are conformable, following thin horizons of shale or siltstone within sandstone units, although some are intruded along faults or cleavage planes and cut the bedding. The richer reefs are found in domes and anticlines, and many are conformable or saddle form. Free gold is visible in the outcrops of several reefs, surface assays are typically 10-60 g per tonne ranging up to 245 g per tonne. It is usually in the limonite, pointing to a secondary origin from primary gold contents in pyrite. The wall rocks of many of the veins also contain pyrite boxworks and are reported to carry low gold values.

Company geologists have put forward two possible modes of origin of the gold. One is that the gold was syngenetic being concentrated into the reefs during folding and metamorphism. The other is that the mineralization is related to granite intrusions such as that at Mount Crofton. There are objections to both of these hypotheses. Syngenetic gold deposits are usually found in conglomerate beds (e.g. Witwatersrand, Nullagine), but no conglomerates are known in the sequence near the prospects. Experience in Western Australia and elsewhere (e.g. Klominsky and Groves, 1970) indicates that gold is related to granodiorites or adamellites rather than to alkali granite. Further work will be required to determine the origin of the gold.

MAIN DOME PROSPECT

The principal gold prospect, and the one on which most work has been done, occurs in the Main dome (Fig. 46). This is a prominent well formed dome of sandstone, siltstone and shale having a prominent exposure which stands out well on air-photographs. It is about 2.7km long and 1.0 km wide, with its long axis striking at 300°. The stratigraphic succession seen in the dome is, from youngest to oldest:

Unit	Thickness (m)
Outer shale	+30
Rim sandstone	30-40
Upper Vale shale	4
Median sandstone	25
Footwall sandstone	50
Middle Vale shale	10-12
Lower Vale shale	1
Core sandstone	+60

(All names are informal)

The most prospective reefs are in the Middle Vale shale. They form lenses, mainly on the footwall side of the shale, around the entire outcrop of the unit. However, the thickest development is on the south-eastern flank of the dome. In the northern and southern closures of the dome, the Middle Vale reef straddles the main anticlinal axis in true saddle-reef form.

Drilling done by Newmont Pty. Ltd. along the Middle Vale reef has so far indicated about 2 million tonnes of ore averaging about 14 g per tonne of gold.

Several small gossans have been found in the Upper Vale and Lower Vale shales, but most seem unimportant. The Eastern reefs, on the north-east side of the domes in the Outer shale, consist of gossan and grey quartz containing some gold.

West Dome

Another dome with an en echelon relationship to the Main dome is situated about 1.2 km farther west. It contains a number of gossans and limonitic quartz reefs with gold contents of generally less than 3 g per tonne. The gossans inspected occur on the crest of the fold and appear to have formed as saddle reefs. Other gossans on the south-west side of the dome are shown on the Newmont maps, but were not examined.

Thomson Dome

About 15 km northwest of the base camp is the Thomson dome in which stratiform gossans occur at two horizons within pyritic sandstone on the southern flank. Gold contents in the gossans range up to 3.4 g per tonne.

Comparisons with other gold deposits in Western Australia

Most gold won from Western Australia has come from deposits within the greenstone belts of the Archaean nuclei, usually in volcanic rocks or in sediments of volcanic origin. They consist of sulphide or telluride lodes (e.g. Wiluna and Kalgoorlie respectively), tensional quartz veins (e.g. Coolgardie and Cue), or fracture fillings and replacements of banded iron formation (e.g. Mount Magnet and Laverton). Other deposits, with a much smaller total production, lie in late Archaean or Lower Proterozoic rocks and consist mainly of auriferous quartz veins injected along the cleavage planes of folded geosynclinal sediments. Examples are the gold deposits of Mosquito Creek, the Ashburton Valley and Halls Creek. The saddle-reef form is

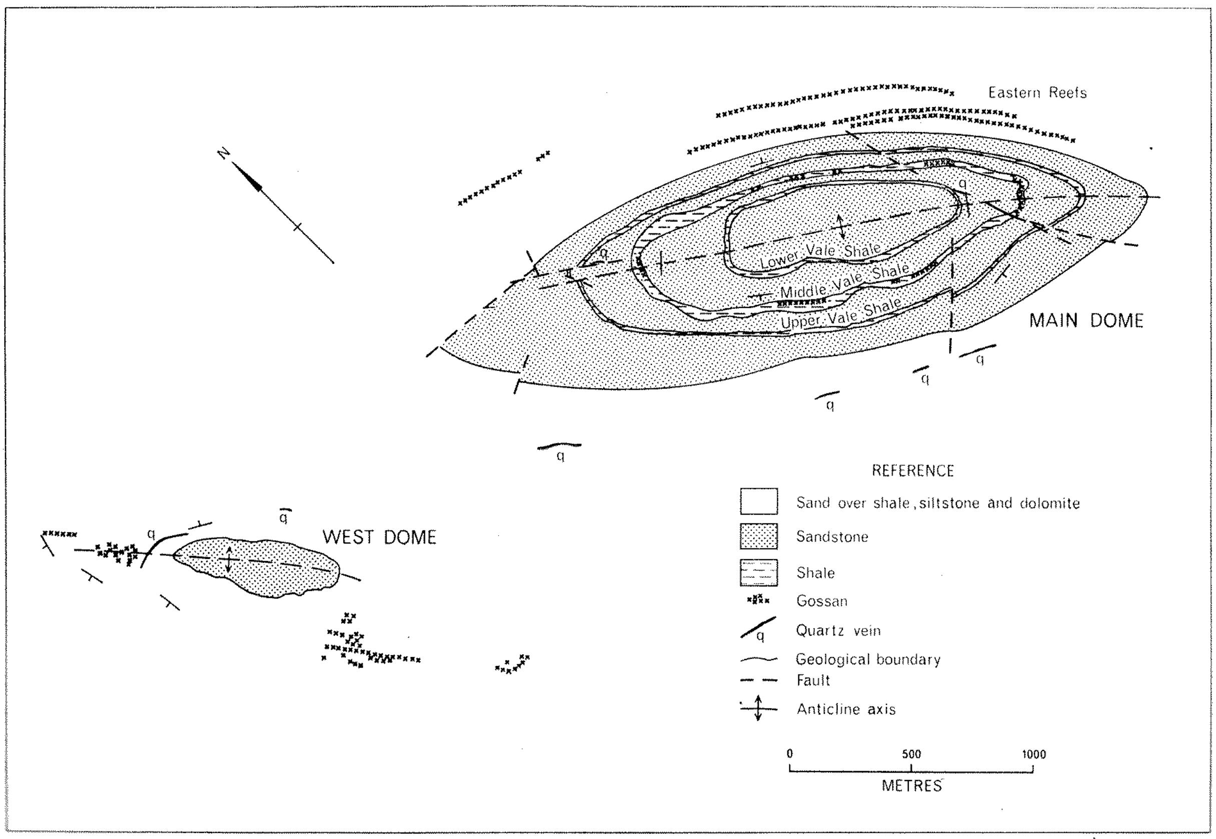

Figure 46. Telfer Dome gold prospects—geological map (after Newmont Pty. Ltd.).

rare in Archaean and Lower Proterozoic deposits, the only other example is at Breens Camp, 50 km west of Marble Bar (Blatchford, 1913).

The Paterson Range gold prospects differ from most others in the State in three respects: they are much younger probably 600 to 1 000 m.y.; many of them are saddle reefs; and their host rocks are sediments typical of a stable shelf rather than a geosyncline, and lack any appreciable volcanic component.

The only other gold deposists in the Bangemall Group are at Bangemall, near the southern edge of the Bangemall Basin. The veins here occur in an anticline of sandstone and shale, overlain by chert, and intruded by dolerite sills. Maitland (1909) notes that the most important feature of the field is the saddle-reef form of the goldbearing quartz veins. These grade from white vitreous quartz, through cavernous ferruginous quartz into limonite with pyrite kernels. Except for the dolerite sills and the nearby chert, the geological setting and the form of the deposits are very similar to those in the Paterson Range area.

CONCLUSIONS

The Paterson Range gold deposits are only the second recorded occurrence of gold within rocks of the Bangemall Group. Their discovery in this little prospected area should lead to further exploration within the Middle and Lower Proterozoic rocks of the Paterson Range, Rudall and Gunyana 1 : 250 000 Sheets.

The similarity of the deposits in the Paterson Range to those at Bangemall indicates that all the folded margins of the basin should be examined more closely for gold, and possibly other minerals.

There seems to be a reasonable chance that the Paterson Range gold prospects will eventually support a mining operation.

ACKNOWLEDGEMENTS

Thanks are due to Geologists of Newmont Pty. Ltd. who supplied the detailed stratigraphic and assay data used in this report and checked the manuscript.

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DIAMOND EXPLORATION IN WESTERN AUSTRALIA

by J. D. Carter

ABSTRACT

Diamond exploration in Western Australia as reported to the Mines Department is reviewed. Exploration has been carried out in the Nullagine district of the Pilbara Block, in the Northern Canning Basin principally between the Lennard and Fitzroy Rivers, and near the Serpentine River about 50 km southeast of Perth.

At Nullagine some 70 diamonds have been recovered since the first discoveries in 1895. Subsequent exploration has not disclosed kimberlite or kimberlitic minerals, and commercial occurrences of diamonds have not been located.

In the Northern Canning Basin attention has been centred on lamproite intrusions of Miocene age. A report that kimberlitic material underlies Mount Abbott was not confirmed by follow-up investigations. Although nine small diamonds were reported as having been found in the Lennard River, later exploration failed to find further diamond or kimberlitic minerals.

Kimberlitic pyrope garnet has been reported from the Serpentine River, but kimberlites themselves have not been found.

INTRODUCTION

Exploration for diamond in Western Australia has been carried out by companies holding Temporary Reserves (T.Rs.—Crown Land reserved for mineral exploration). There is little published information on these investigations apart from a brief reference by Lawrence (1971). The account now given has the purpose of bringing together the principal results of exploration operations as reported to the Mines Department.

Since the first discovery of diamonds in 1895 near Nullagine in the Pilbara Goldfield, the potential of the State for diamond has been a subject of speculation. Some prominence has been given to the likelihood that India, an important producer of diamonds, was connected to the northwestern part of Australia until the break-up of Gondwanaland in the Early Cretaceous. Results of diamond exploration, however, have not been encouraging. Altogether only about 70 diamonds have been recovered near Nullagine and although the Lennard River in the Northern Canning Basin is reported to have yielded nine diamonds, intensive follow-up investigations failed to disclose further gems. At one other locality, near the Serpentine River about 50 km southeast of Perth, there is an indication that kimberlite* or a secondary source rock of diamond may be exposed in the district. Here garnets considered to have been derived from kimberlite have been recovered from a stream draining the western margin of the Yilgarn Block.

Exploration for diamond usually involves a search for indicator minerals (I.M.). The diagnostic suite includes pyrope garnet, which is often chromium-bearing, magnesian ilmenite, and chromium-bearing diopside. According to Mannard (1968) at least three-quarters of the known kimberlite pipes have been traced by I.M.. In Australia the only proved kimberlites are those near Terowie 230 km north of Adelaide, and in describing these Colchester (1972) remarks that chrome diopsides "are always present as accessory phenocrysts in the kimberlite matrix". In Western Australia the search for I.M., particularly pyrope and magnesian ilmenite, has been the principal means of exploration.

* Kimberlite is an ultrabasic rock which is the primary source of diamond. It is defined in Dawson (1967).

The review is compiled from reports of operations chiefly on T.Rs. provided by individuals and companies, namely J. F. B. Jeppe, R. C. Horwitz, Conzinc Riotinto Australia Exploration Pty. Ltd. (C.R.A.E.), Mining Advisers Pty. Ltd. (M.A. Pty. Ltd), the group Exoil N.L., Transoil N.L. and Petromin N.L., and The Stellar Minerals Pty. Ltd. A number of principal reports are included in the reference list at the end of this paper.

NULLAGINE

GENERAL

Nullagine, in the Pilbara Goldfield, about 240 km south-southeast of Port Hedland, was the scene of Western Australia's first diamond discovery, in 1895. Since then occasional diamonds have been found there, principally during the search for gold. It was not until 1965 that systematic exploration for diamonds was begun. As a result 20 gems were recovered during ventures conducted by J. F. B. Jeppe, C.R.A.E. and M.A. Pty. Ltd.

Prior to 1965 records of finds are vague, but at least 70 diamonds have been recovered, as shown below:

NULLAGINE DIAMOND DISCOVERIES

1895*	F. R. Groom described 17 diamonds
1900	230 t conglomerate yielded 25 diamonds
1915	C. Frazer reported a 3½ carat† diamond
1922	E. S. Simpson reported three diamonds
1924	H. Bowley examined two diamonds presumed to be of Nullagine origin
1933	A. Aiken found two diamonds
1965	J. F. B. Jeppe found five diamonds
1969	C.R.A.E. found one diamond
1970	M.A. Pty. Ltd. found 14 diamonds

* Records of finds from 1895 to 1933 are compiled from Simpson (1951).

† One carat equals 200 mg.

None of the Nullagine diamonds are known to have been assessed by an expert valuer though certain descriptions suggest diamonds of gem quality. An example is the diamond reported by C. Frazer and referred in Simpson (1951) as "This stone was a complete crystal and was said to have made a valuable gem."

The precise locations of the early finds are uncertain. Sites of discoveries referred to by Simpson (1951) are Brooks Hill lying about 2 km northwest of Nullagine, and Grants Flat, 1 km west of the town, where the large stone reported by C. Frazer was recovered (Fig. 47). Noldart and Wyatt (1962) state that the immediate source of the diamonds is an auriferous conglomerate, termed the Beatons Creek Conglomerate, found at the base of the Lower Proterozoic Fortescue Group at various localities near Nullagine.

Recent exploration at Nullagine has shown that diamonds are contained in conglomerate younger than the Beatons Creek Conglomerate. The younger conglomerate and associated sediments are termed informally the "Brooks Hill beds" and attributed provisionally to the Tertiary.

GEOLOGY

The stratigraphy of the Nullagine region is currently under review. This description is compiled from reports of C.R.A.E., M.A. Pty. Ltd. and the Geological Survey of Western Australia. The geology, illustrated by Figure 47, is subdivided as follows:

Age	Deposits	Intrusions
Quaternary	Alluvium—Recent : fluviatile sands and gravels Alluvium—intermediate levels : fluviatile sands and gravels with basalt detritus; fluviatile sands and gravels derived from Beatons Creek Conglomerate Alluvium—high level: fluviatile sands and gravels derived from Beatons Creek Conglomerate	
Tertiary	"Brooks Hill beds": fluviatile sands, gravels and conglomerates variably ferruginized	
Lower Proterozoic	Fortescue Group: undifferentiated lavas; undifferentiated sedimentary rocks with Beatons Creek Conglomerate at base	Dolerite, quartz-feldspar porphyry
Archaean	Mosquito Creek Beds*: metamorphosed rocks including conglomerates	

* The status of the Mosquito Creek Beds is under review

The Mosquito Creek Beds of the Archaean underlie the undulating country around Nullagine and east of the town. About 2 km west of Nullagine the lowest part of the Proterozoic Fortescue Group forms an escarpment marking the eastern limit of the group. Locally the base of the group is formed by the Beatons Creek Conglomerate, an auriferous formation which is reportedly diamondiferous. Sofoulis (1958) describes the conglomerate:

> Boulders present in the basal horizon are derivative of older fine grained sandstones, quartzites, slates, grits, conglomerates, jaspilitic rocks, identical in character with the metamorphosed sediments of the Mosquito Creek Formations and in conjunction with the shape and size of such, there is little doubt that these boulders were furnished from a Mosquito Creek land surface and in close proximity to the present position of the conglomerate.

The origin of the Cainozoic strata at Nullagine is similar to that of deposits of the same age in the Hamersley Iron Province to the west and the description of the latter given by MacLeod (1966) serves to illustrate these strata:

> On geomorphological grounds they can be broadly divided into two age groups. The older deposits had accumulated prior to the commencement of a rejuvenated cycle of stream erosion and have been much dissected during this younger cycle. The younger deposits represent the more recent products of this erosion and redistribution following the rejuvenation of the drainage systems.

The "Brooks Hill beds" represent the older deposits, while fluviatile sands and gravels found at varying levels represent the younger sediments.

"Brooks Hill Beds"

Elongate limonite-capped mesas formed by "Brooks Hill beds" stand up to 45 m above the valley floors of the Nullagine River and its tributaries such as Bonnie Creek. They are flat lying. A summary of the lithology of the beds is provided by Lovett (1971):

> Generally, an upper and lower unit with sometimes an intermediate one can be discerned. The basal unit usually consists of sands and conglomerates varying in lithology and thickness. Sometimes, however, this unit is absent and instead the intermediate or upper unit overlies the bedrock. The upper unit is typified by limonite-cemented clay, sand, and grit, commonly with a high proportion of fossilised wood fragments. The thickness of the unit appears to be greatest in the mesas upstream at Garden Pool.

Variations in lithologies and thicknesses of the units are shown in Table 15.

TABLE 15. "BROOKS HILL BEDS"—SECTIONS.
(after Lovett, 1971)

Nullagine River—Bonnie Creek confluence	Brooks Hill N.W. extension	Banana Hill
upper unit— Limonitic pisolites and wood fragments in a limonitic clay cement. 15 to 24 m	Cemented limonitic clay and sand, wood fragments. 3 m	Cemented limonitic sand and clay. 7·5 m
intermediate unit— Iron pisolites, basalt fragments and clay matrix. 3 to 6 m	Bleached and kaolinized clay and sand; minor conglomerate lenses. 15 m	Clay and sand. 1·8 m
lower unit— Ill-sorted boulder conglomerate in a bleached clay matrix. 1·8 to 3·6 m	Interbedded conglomerates, sand and clay (diamondiferous) 3 m	Pebble conglomerate and sand (diamondiferous) 3·7 m
	Kaolinized basalt	Mosquito Creek Beds

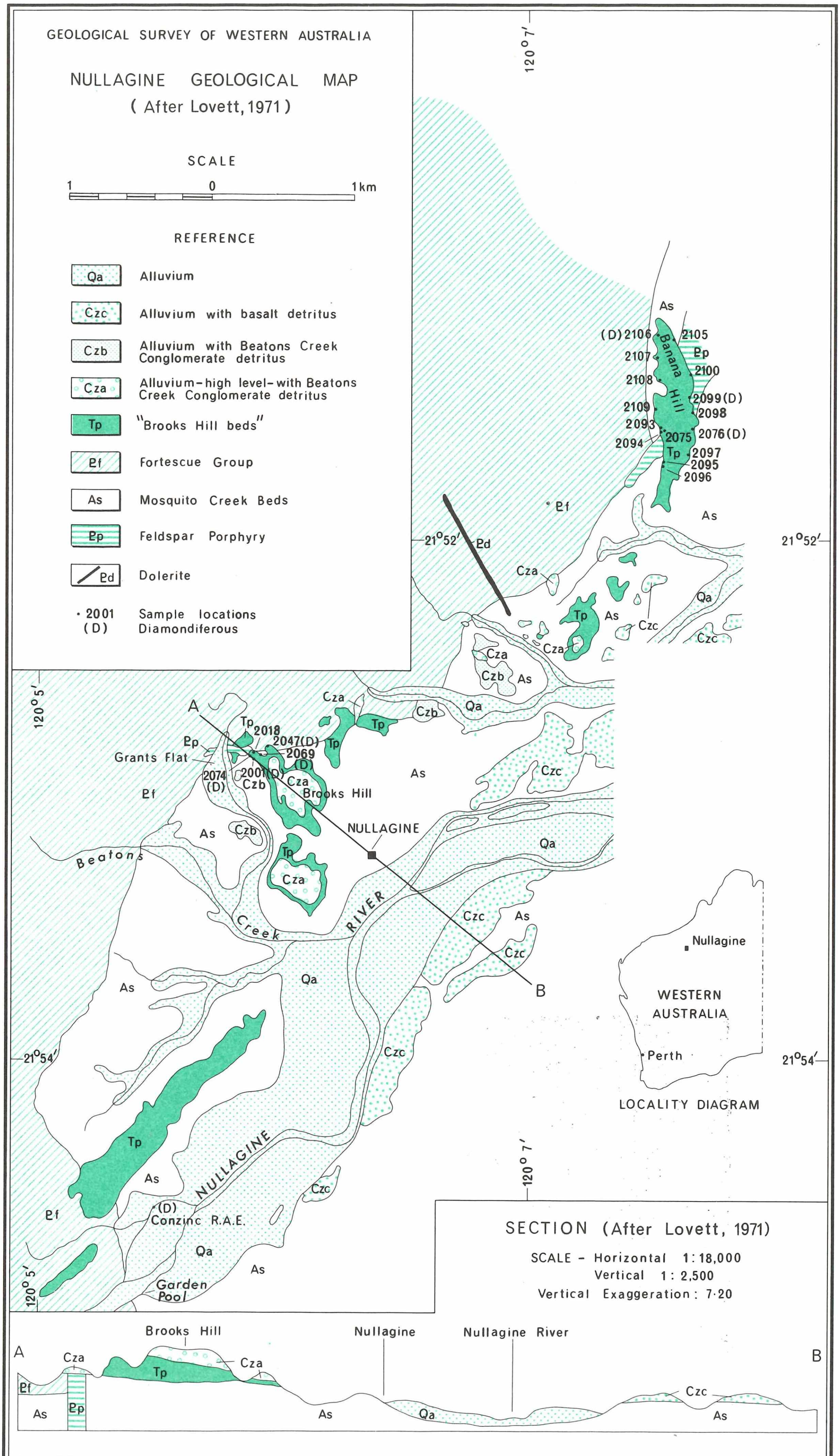

Figure 47.

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Fluviatile Deposits

Four categories of fluviatile deposits are present as illustrated on Figure 47: high-level channel deposits overlying the lateritic capping of some of the mesas, fluviatile sediments of two varieties forming terraces at lower levels but above the valley floor and fluviation of the Nullagine River.

Igneous Intrusions

Igneous intrusions are represented by dolerite dykes and feldspar porphyry bodies.

EXPLORATION

Prior to 1965 two very brief investigations of the diamond occurrences were made. Groom (1896) during a short visit to Nullagine confirmed the diamond find, observing that the gems were recovered at or near Brooks Hill and were enclosed in conglomerate. Nearly 60 years later Sofoulis (1958) described an examination of T.Rs. Nos. 1393H to 1398H and some 390 km^2 of country in the vicinity of Nullagine. In this report there is mention of diamonds occurring in the basal conglomerate of the Proterozoic rocks though no example of a diamond being recovered from these rocks *in situ* is cited.

In 1965 and 1967 respectively, systematic exploration for diamonds was begun during interconnected operations over T.Rs. No. 3582H (J. F. B. Jeppe) and 4175H (C.R.A.E.). In September 1967 these were substituted by T.R. No. 4508H occupied by C.R.A.E. Rights of Occupancy were transferred to J. F. B. Jeppe in December 1970 when exploration was continued by M.A. Pty. Ltd. The T.R. was relinquished in April 1971.

T.R. No. 3582H

Operations over the T.R. of 840 km^2 apparently were small in scale. There are reports that numerous small samples and bulk samples amounting to more than 39 t were taken, but there is no record of sample locations. It is not clear whether samples were tested for I.M. There are references in reports of C.R.A.E. and M.A. Pty. Ltd. to the recovery of five small diamonds including a stone found *in situ* at Brooks Hill but information on only three diamonds is available (Table 16).

T.Rs. Nos. 4175H and 4508H

Exploration by C.R.A.E. over an area of some 4 000 km^2 included photogeology, which produced no positive results. Some sampling of Tertiary sediments and stream deposits was also carried out.

Stream samples are described as being taken from suitable points such as behind rock bars; the samples after sieving yielding fractions weighing 14 kg. Forty-six samples were examined. Heavy mineral residues obtained by gravity concentration and heavy-fluid separation were inspected optically. One small diamond (15 microns in size) was discovered in alluvium of a tributary of the Nullagine River. Although garnet and ilmenite were identified, these minerals apparently were not tested to determine whether they were kimberlitic in origin. Drainage examined during the stream-sediment sampling programme is shown on Figure 48.

No diamond or I.M. were recovered from the "Brooks Hill beds", although these were tested by sampling the basal unit at six localities. Three were mesas near Nullagine (including the northwest extremity of Brooks Hill where J.F.B. Jeppe had previously discovered a diamond *in situ*), and the remainder at mesas lying south of Nullagine. Farther to the south, mesas in Bonnie Creek (shown on the Roy Hill 1 : 250 000 Geological Sheet as Robe Pisolite) were examined with the conclusions that "The prospects for finding extensive gravel deposits in the Bonnie Creek Valley mesas, which could be the sources of alluvial diamonds, are very low" (Lishmund, 1967).

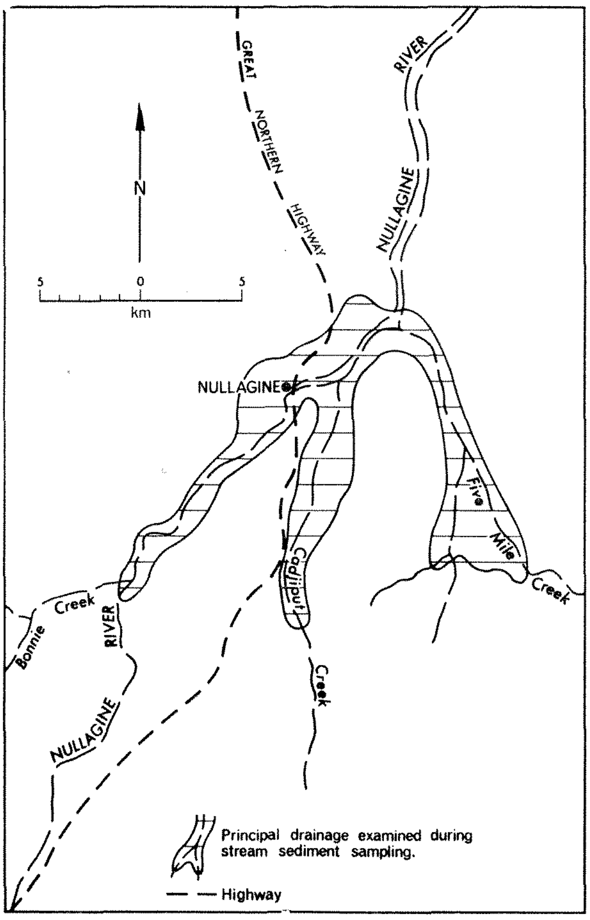

Figure 48. Nullagine area, showing stream-sediment sampling (after Conzinc Riotinto Australia Pty. Ltd. and Mining Advisers Pty. Ltd.).

In addition, an examination of deposits ascribed to the Oakover Formation in the vicinity of Carawine Pool, on the Oakover River, recorded that these strata composed of "dirty buff-coloured gravels" should be searched for I.M. (Lishmund, 1967). Gravels in the Oakover Formation have not been recorded by the Geological Survey of Western Australia.

T.R. No. 4508H was also explored by M.A. Pty. Ltd. This exploration had dual objectives. Firstly, to find a pre-Cainozoic diamond source rock by means of stream-sediment sampling. Secondly, to test the diamond potential of Cainozoic sediments near Nullagine, principally the "Brooks Hill beds". Fourteen diamonds were recovered by gravity concentration from the base of the "Brooks Hill beds" although none were found in the stream sediments. Heavy-mineral residues were obtained by gravity concentration. Garnet and ilmenite were both identified in stream sediments, and the "Brooks Hill beds" were examined optically for garnet and by electron-probe microanalysis for ilmenite, but no grain was considered to be of kimberlitic origin.

A bulldozer and back-hoe were used to sample the base of the "Brooks Hill beds" at Brooks Hill and at Banana Hill to the north (Fig. 47). Twenty samples totalling 42 m^3 were taken. Each consisted of between 1 and 2 m^3 of basal unit and, except at two localities, 0.3 m^3 of bedrock. Jigging and optical examination of residues led to the recovery in the field of fourteen diamonds from six samples. Some features of the finds, shown in Table 16, are a stone weighing 1.03 carats, with two tiny stones (Sample No. 2001), and two stones with a combined weight of 0.6 carat (Sample No. 2106), and six small stones of combined weight less than one carat from a palaeochannel at the northwest extremity of Brooks Hill (Sample No. 2074).

TABLE 16.

DIAMONDS FOUND AT NULLAGINE 1965-1970.

(after Lovett, 1971)

Sample* Number	Date	Weight (carats)	Quality†	Remarks
J1	1965	0·18	Gem	Found by J. F. B. Jeppe
J2	1965	0·15	Gem	Found by J. F. B. Jeppe
J3	1965	0·96	Industrial	Found by J. F. B. Jeppe
27	1969	(size 15 microns)	....	Recovered by C. R. A. E. Pty. Ltd. from stream alluvium
2001/A	1970	0·08	Gem	"Brooks Hill beds"
2001/B	1970	0·09	Industrial	Brooks Hill
2001/C	1970	1·03	Gem	Brooks Hill
2069	1970	0·14	Industrial	Brooks Hill
2074A	1970	0·28	Gem	Brooks Hill
2074B	1970	0·21	Gem	Brooks Hill
2074C	1970	0·17	?Gem	Brooks Hill
2074D	1970	0·13	Industrial	Brooks Hill
2074E	1970	0·11	?Gem	Brooks Hill
2074F	1970	0·05	Gem	Brooks Hill
2076	1970	0·12	Gem	"Brooks Hill beds" Banana Hill
2099	1970	0·13	Gem	"Brooks Hill beds" Banana Hill
2106A	1970	0·48	Gem	"Brooks Hill beds" Banana Hill
2106B	1970	0·12	?Gem	"Brooks Hill beds" Banana Hill

* Nos. 2001/A to 2106/B were found during investigations by Mining Advisers Pty. Ltd.

† None of the stones is known to have been appraised by an expert valuer.

Note : Basal portions of the older alluvium were sampled at three points and various features elsewhere were tested, all without result.

In the search for kimberlite or a secondary distribution source, 79 stream sediment samples were collected from watercourses draining the Proterozoic. Samples ranged from 0.4 to 2.3 m^3 in volume and at all but two points were obtained from the base of the alluvium. No I.M. or diamond were recovered. Drainage examined during the stream-sediment sampling programmes is shown on Figure 48.

NORTHERN CANNING BASIN

GENERAL

A description of the geology of the Northern Canning Basin, situated in the West Kimberley Goldfield in the northern part of the State, is given by Guppy and others (1958). The principal features referred to here are shown on Figure 49.

There has been some speculation that the Kimberley region is favourable for the occurrence of diamond, with interest focused on a small group of minor leucite-bearing intrusions of lamproite forming plugs and craters, described by Wade and Prider (1940). Prider (1960) includes a scheme suggesting a genetic relation between the lamproitic rocks and kimberlite. Wellmann (1973) gives age determinations indicating a Miocene age for the lamproites.

EXPLORATION

There have been three exploration ventures since 1967: one conducted by the group Exoil N.L., Transoil N.L. and Petromin N.L. when nine diamonds were recovered from alluvium of the Lennard River; a second by The Stellar Minerals N.L. and a third by the Bureau de Recherches Geologiques et Minieres Australia the results of which are described briefly by Lawrence (1971).

Exoil N.L., Transoil N.L. and Petromin N.L.

Operations were conducted over T.R. No. 4665H of about 670 km^2, and its severance T.R. No. 5184H, between 1967 and 1970. The T.Rs. were cancelled in 1971. Investigations took place in four phases.

In 1967 grab samples of lamproite, lamproitic debris and alluvium were collected and examined for I.M. and diamond. Lamproitic material was collected from the following plugs:

Wolgidee Hills
Hills Cone
White Rocks
Noonkanbah Hill
Moulamen Hill
P Hill
Fishery Hill
Machells Pyramid
Mount Cedric
Djada Hill
Mount North

Alluvium was also sampled in the Fitzroy River channel west of Mount Abbott. No diamond or I.M. were identified.

In 1968 a combined aeromagnetic and radiometric survey of 1 770 line-kilometres was flown at a height of 150 m above mean ground level, with flight lines spaced 422 m apart. Results were not encouraging and there was no ground follow-up.

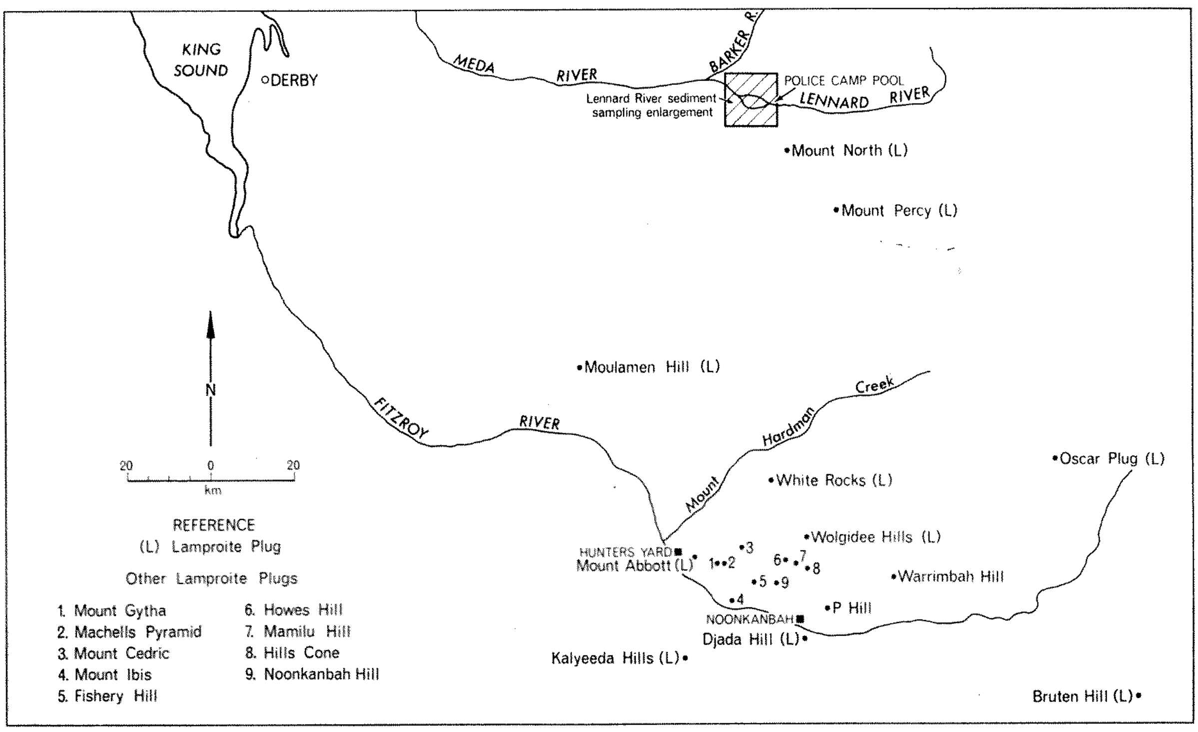

Figure 49. Northern Canning Basin showing lamproite plugs.

In October, 1969, alluvium in the beds of the Lennard River and adjoining tributaries was sampled for I.M. At each of the 37 positions numbered on Figure 50, two samples were taken. After sieving individual samples weighed between 11 and 22 kg; the total sample weight amounted to about a tonne. Heavy-mineral suites were examined for pyrope and chromium-bearing diopside but neither mineral was found. Ilmenite, the dominant opaque mineral, was not tested for a possible kimberlitic origin.

Four diamonds were recovered during the I.M. search and the entire one tonne sample was then examined for diamond. A total of nine gems were said to have been found, with a combined weight of 1.65 carats. Descriptions of these are given in Table 17 and the reported locations of the finds are shown on Figure 50.

TABLE 17. DIAMONDS REPORTED FROM THE LENNARD RIVER, 1969.

Sample Number	Weight (carats)	Quality	Remarks
20	0·25	?Industrial	One whole stone and two cleavage fragments
22	0·25	?Industrial	Whole stone
25	0·33	?Industrial	Two whole stones
31	0·32	?Industrial	One whole stone
37	0·5	?Industrial	One almost whole stone and a cleavage fragment

In 1970, follow-up investigations consisted of regional soil sampling for I.M. in the Lennard River area and large-scale sampling of the Lennard and Fitzroy Rivers for diamond. During the soil survey several hundred samples were collected from the general area shown on Figure 50. Sampling procedure consisted of excavating samples of approximately a cubic metre from which heavy minerals were extracted by gravity concentration. No diamond or I.M. were found.

Alluvium in the Lennard River was tested for diamond and I.M. in the vicinity of sites from which diamonds had been recovered. Sample points were selected where natural concentrations of heavy minerals were to be expected and sites were excavated to bedrock, potholes and natural barriers being cleaned out. (Sites A to Q, Fig. 50). At each of 15 locations approximately one tonne of sieved material was treated by machine jigging, the heavy minerals being sorted by hand. None of the samples yielded diamond or I.M. Duplicate samples treated and examined by a second laboratory confirmed the field result. Ilmenite was identified but not tested for kimberlitic origin.

Alluvium in the Fitzroy River at 25 localities between Noonkanbah Yard and Hunters Yard was similarly sampled and treated. No diamonds or I.M. were found. Ilmenite was recovered but was not tested for a kimberlitic origin.

The report concludes "despite all efforts by a South African leading authority in diamond exploration no further diamonds were found and no minerals normally associated with diamonds were observed . . . In view of these conclusions it can only be assumed that results of the early sampling were not representative of the area from which the samples were taken" (Haynes, 1971).

The Stellar Minerals Pty. Ltd.

From 1968 to 1971 The Stellar Minerals N.L. explored the Fitzroy Trough for diamond with emphasis on the investigation of the lamproite plugs in the Noonkanbah district. Eleven T.Rs.

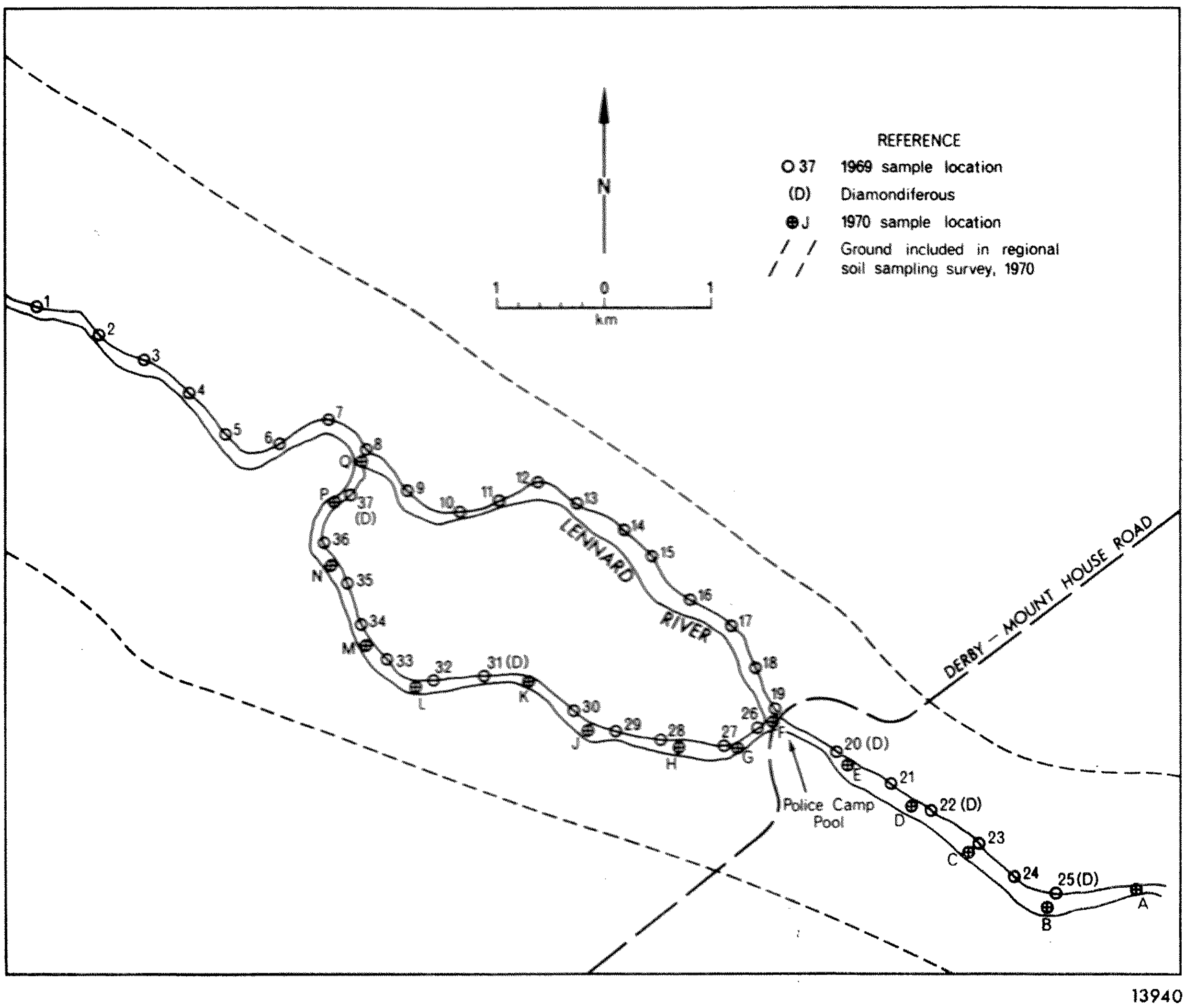

Figure 50. Lennard River sediment sampling (after Exoil N.L., Transoil N.L. and Petromin N.L.)

were occupied embracing lamproites, a cryptovolcanic structure (Mount Abbott) and Cainozoic sedimentary deposits:

- T.R. No. 4630H Wolgidee Hills and lamproites to the south and west lying between P Hill and Mount Gytha[1]
- T.R. No. 4631H Mount Abbott[2]
- T.R. No. 4632H White Rocks[1]
- T.R. No. 4633H The Sisters (Kalyeeda Hills)[1]
- T.R. No. 4634H Warrimbah Hill[3]
- T.R. No. 4635H Moulamen Hill[1]
- T.R. No. 4636H Mount North[1]
- T.R. No. 4637H Mount Percy[1]
- T.R. No. 4643H Oscar Plug[1]
- T.R. No. 4644H Mount Hardman Creek[3]
- T.R. No. 4659H Bruten Hill[1]

1. = Lamproites
2. = Cryptovolcanic structure
3. = Cainozoic sediments

Four of the T.Rs. exceeded 150 km^2: 4630H (746), 4644H (259), 4634H (233) and 4631H (155); the remainder varied between 15 and 93 km^2. Exploration techniques included rock, soil and stream-sediment sampling, shallow drilling, and ground magnetic and radiometric surveys. Geophysical surveys were discontinued when initial tests failed to give useful results at selected localities.

Although the T.Rs. were the subject of considerable exploration there were no encouraging results. Diamond was not found. In early stages of operations it was reported that kimberlite had been located near Mount Abbott and that pyrope occurred near The Sisters (Kalyeeda Hills). Extensive follow-up at both localities failed to confirm these results.

Principal operations on T.Rs. are summarized below. Except where stated samples were treated and examined for diamond or I.M. Heavy minerals were extracted by gravity concentration and examined optically. Some garnet and ilmenite were investigated by electron-probe microanalysis.

T.R. No. 4630H: Wolgidee Hills. A two tonne sample was taken from the centre of the Hills; about a tonne of lamproite detritus was obtained from twelve pits on a line extending westwards from the centre of the body. One hundred and seventy five soil samples of volume 7.6 m^3 were collected. A Gemco auger drill was used to sink 105 holes with total depth of 547 m. Also 13 auger holes were drilled on a lineament between Wolgidee Hills and Mamilu Hill.

P Hill. Six bulk samples and six soil samples were taken from around the lamproite. Total drilling from 22 auger holes, near the plug and on the surrounding plain, amounted to 406 m.

Hills Cone. Four samples totalling 0.2 t were obtained from pits and seven soil samples were collected. Twenty three auger holes were sunk for a total depth of 142 m, and 11 holes for 111 m along a line joining Hills Cone and Mamilu Hill.

Mamilu Hill. Four pits were sunk into lamproite and seven soil samples collected. Drilling consisted of 29 auger holes for 178 m. Holes were drilled on the lineament between Mamilu Hill and Howes Hill.

Howes Hill. Seven soil samples were collected and 30 auger holes totalling 130 m sunk. Holes were drilled along a line to Mount Cedric.

Mount Cedric. Eight bulk samples and 22 soil samples were obtained. Drilling consisted of 27 auger holes for 181 m and further holes were put down along a line to Mount Abbott.

Machels Pyramid and Mount Gytha. Eleven bulk samples and 15 soil samples were collected. Drilling included 37 auger holes for 148 m as well as holes drilled along a line between Mount Gytha and Mount Abbott.

T.R No. 4631H, Mount Abbott. This feature is described by Prider (1960) as a cryptovolcanic structure with no igneous rock exposed. Kimberlite minerals were reported to have been found at Mount Abbott, specifically from a pit nearly two metres deep (two pyrope grains), and from a second pit and trenches all less than a metre in depth exposing weathered bedrock with pyrope, ilmenite and green diopside. Further trenches were dug to an average depth of about two to three metres, together with 24 drill holes averaging 15 m in depth. It was reported that tuffisite and tuffisite breccia containing kimberlite minerals were present in at least five localities. Minerals said to have been recovered included garnet, within the range of kimberlite pyrope, picroilmenite (magnesian ilmenite) and picrochromite (magnesian chromite).

Further work, including drilling 100 auger holes for a total of 479 m in 1970-71, however, led to the conclusion that no kimberlites, diamonds or kimberlitic indicator minerals were present in the area.

T.R. No. 4632H, White Rocks. Exploration included trenching, the collecting of 7 soil samples and the sinking of 46 auger holes for a combined depth of 213 m. There is no information on results of treatment of cuttings from drillholes.

T.R. No. 4633H, The Sisters (Kalyeeda Hills). Pyrope was recovered from a shallow pit sunk near lamproite in 1968. Follow-up work included 75 auger holes drilled for 506 m and 13 soil samples. None of this material contained minerals of kimberlitic origin.

T.R. No. 4634H, Warrimbah Hill. This T.R. covered scattered outcrops of Warrimbah Conglomerate, a deposit of massive well rounded water-worn pebbles and boulders which may be of Pleistocene age (Veevers and Wells, 1961). The conglomerate was tested at Warrimbah Hill by trenching and sampling. A bulk sample of 17 m^3 was also collected but there is no information on any results of treatment.

T.R. No. 4635H, Moulamen Hill. About 2 m^3 of conglomerate, described as Tertiary age, from the western end of the Erskine Range was treated without result.

T.R. No. 4636H, Mount North. Two shallow pits and a trench were sunk in watercourses draining the feature, and sampled material comprising at least 1.5 m^3 was treated without result.

T.R. No. 4637H, Mount Percy. A pit about 3 metres deep was sunk in decomposed lamproite and sampled without result.

T.R. No. 4643H, Oscar Plug. Three grab samples taken from the small plug and associated dyke were collected and treated without result. Three soil samples did not contain kimberlitic material.

T.R. No. 4644H, Mount Hardman Creek. Alluvium (1.5 m^3) was collected from a pit and 14 trenches and treated without result. A further bulk sample of 9.3 m^3 failed to yield kimberlitic material.

T.R. No. 4659H, Bruten Hill. Two grab samples from the lamproite, 5 soil samples from the base of the plug and 4 alluvial samples from nearby Christmas Creek were tested without result.

"Kimberley Region" exploration by Bureau de Recherches Geologiques et Minieres

Lawrence (1971) refers briefly to exploration for diamond in the "Kimberley Region" but does not give specific locations or any results of exploration. The ground covered was some 100 000 km^2 and embraced approximately 2 500 km length of the larger rivers. To obtain a sample density of one sample per 1 000 km^2, samples were taken every 25 km, usually down to riverine bedrock and ranged in size from 2 to 20 m^3. A total of some 1 000 m^3 of alluvium may have been treated in this manner.

SERPENTINE RIVER AREA

In an address to the Western Australia Division of the Geological Society of Australia in 1972 R. C. Horwitz described exploration for I.M. in the south-west of the State. The region was selected because of the highly dissected nature of the Archaean terrain. This study was not extended into the Eastern Goldfields since considerable exploration for placer gold had not located diamond.

Pyrope was recovered from heavy-mineral residues panned from sands and gravels of the Serpentine River bed between the South-West Highway crossing and the Darling Scarp, approximately 50 km southeast of Perth. A single pyrope garnet was also found in a residue obtained from the Medulla Brook just east of the Darling Fault and south of the road to Jarrahdale (Horwitz, R. C., pers. comm.).

The garnets, pin-head in size, are considered to form a characteristic grouping by reason of size, brown colour, densities and refractive indices which range between 1.735 and 1.77. An opinion has been expressed that these garnets belong to a small titanium-rich, brown garnet group, which is known and diagnostic of kimberlites, but is not described in the literature.

No other exploration for diamond is known to have been carried out in this area.

CONCLUSIONS

NULLAGINE

At Nullagine diamonds occur in the basal portion of the "Brooks Hill beds" and in recent stream sediments. However, the volumes and grades of both categories of diamondiferous gravels have not been assessed. So far as is known no parcel of Nullagine diamonds has been the subject of expert valuation, a prior requisite to assessment of the grade of the diamondiferous deposits. Although no I.M. have been identified, it appears that the volumes of heavy mineral residues examined have been insufficient to allow a firm conclusion to be reached on whether I.M. are present or not.

On the problem of an immediate source of the Nullagine diamonds there is some evidence pointing to the Beatons Creek Conglomerate. The diamondiferous basal unit of the "Brooks Hill beds" contains material similar to rocks composing the Beatons Creek Conglomerate (Lovett, 1971). Diamonds have been found only near Nullagine where the conglomerate is well developed and have not been found where this formation does not occur. There is no record of an examination of the Beatons Creek Conglomerate for diamond by the systematic sampling and large volume (100 t) treatment of this rock.

NORTHERN CANNING BASIN

In the Northern Canning Basin, despite conflicting results of operations at Mount Abbott and along that portion of the Lennard River shown on Figure 50, the scales of operations have been such that the prospects of these areas yielding diamond are slight.

SERPENTINE RIVER AREA

No useful conclusion can be drawn from current knowledge of diamond prospects along the western margin of the Yilgarn Block immediately south of Perth.

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THE MEENTHEENA FLUORITE DEPOSITS, PILBARA GOLDFIELD

by A. H. Hickman

ABSTRACT

Some of the largest known fluorite deposits in Western Australia occur at Meentheena, 75 km east of Marble Bar. The fluorite, which has intruded a Lower Proterozoic sequence of basalt, andesite and agglomerate, is a hydrothermal deposit formed during Proterozoic deformation. The areal distribution of the mineral is controlled by a conjugate fracture system established during this period of movement. As yet it is uncertain whether the fluorite is primary, originating from a deep-seated alkalic magma, or if it represents remobilized Archaean fluorite from the underlying basement.

The Meentheena fluorite deposits are well situated to supply any future steel industry in the Pilbara region.

INTRODUCTION

The presence of fluorite in the Meentheena area was discovered in 1971. Subsequent pegging of the area by Barakee Mining and Exploration Pty. Ltd. was followed by geological mapping, costeaning and open-cut mining. At present Meentheena Fluorite Pty. Ltd., the operating company, is conducting a drilling programme to determine the depth of mineralization and to obtain a more detailed estimate of ore reserves.

LOCATION, ACCESS AND FACILITIES

Meentheena is situated on the Nullagine River 220 km east-southeast of Port Hedland and 75 km east of Marble Bar. Road access from Port Hedland is by way of Great Northern Highway for 240 km to Mount Edgar Station and thence by graded track eastwards for a further 50 km. An airstrip has been constructed 1 km north of the exploration camp and a bore has been drilled to provide a permanent water supply. Water is also available from the nearby Tumbiana Pool on the Nullagine River.

GEOLOGY OF THE MEENTHEENA AREA

The regional geology of the area around Meentheena is shown on the Nullagine sheet of the 1 : 250 000 Geological Series (Noldart and Wyatt, 1962; Thom and Hickman, in prep.) and on Figure 51.

The fluorite deposits occur as fissure veins within folded and faulted Lower Proterozoic volcanic rocks. No large igneous intrusions are exposed close to the prospects but quartz veining is extensive and several narrow rhyolitic dykes intrude the area.

STRATIGRAPHY

The rock succession of the Meentheena area belongs to the lower part of the Lower Proterozoic Fortescue Group, as shown below:

STRATIGRAPHY OF FORTESCUE GROUP IN THE MEENTHEENA AREA

Formation	Lithology	Thickness
Kuruna Siltstone	sandstone, siltstone and pisolitic tuff	20 m
Nymerina Basalt	dark grey mottled basalt, some vesicular flows	300 m
Tumbiana Formation:	sedimentary rocks:	
carbonate member	ripple bedded siliceous limestone	30 m
tuff member	pisolitic tuff with minor siltstone and shale	100–200 m
Kylena Basalt	massive, often vesicular basalt and andesite	500–800 m
Hardey Sandstone	sandstone, conglomerate, tuff and shale (includes grey felsic porphyry, partly amygdaloidal)	50–200 m
Mt. Roe Basalt (Oldest)	basaltic and andesitic amygdaloidal lava with thick agglomerate and lapilli tuff (includes some felsic lava)	300+ m
	UNCONFORMITY	
	Archaean granite and greenstones.	

Although the deposits are situated close to the centre of the large Proterozoic outcrop shown on Figure 51 they occur on a structural high, all of them being within the Mount Roe Basalt the lowest formation of the Fortescue Group. It seems certain from information gained through regional mapping that unless the Mount Roe Basalt is exceptionally thick in this area the underlying Archaean basement cannot lie far beneath the present erosion surface, probably no more than 100-200 m.

West of the Nullagine River a thick sequence of agglomerate, lapilli tuff and gritty tuff forms a large part of the Mount Roe Basalt, whereas to the east the formation consists primarily of massive vesicular basalt and andesite. Amygdales and vugs within the lavas are filled with quartz, calcite and phyllosilicate minerals. Porphyritic basalt is predominant toward the base of the unit.

The agglomerate and tuff west of the river is composed of well rounded to very angular fragments (up to 10 cm in diameter) of quartz, quartzite, chert, granite, basalt and schist. Most of these rocks were derived from the underlying Archaean basement and were ejected from a nearby early Proterozoic vent. The agglomerate represents an explosive phase of volcanicity which deposited pyroclastic rocks over most of the Pilbara. Isolated wedge-shaped bodies of a similar lithology and age also occur in the Marble Bar, Pyramid, Mount Bruce and Roebourne Sheet areas.

STRUCTURE

The Meentheena fluorite deposits are situated on the faulted culmination of a broadly domal structure (Fig. 52). This structural high is truncated sharply to the west of the prospects by the Meentheena Fault, a high-angle fracture striking almost due north at Meentheena. Regional mapping has shown the fault to be essentially a dextral wrench with a horizontal displacement of approximately 4 km. Vertical movement is also present, but less pronounced, and probably only amounts to a few hundred metres (western block downthrown). The Meentheena Fault is an important regional structure extending 100 km from Cookes Creek in the south to the Little de Grey River in the north. Meentheena is situated close to the middle of its course.

The structural complexity in the area of the fluorite deposits is far greater than is normally encountered in Proterozoic terrain of the eastern Pilbara. Between the larger faults depicted on Figure 51 there is a well developed conjugate system of minor fractures. These reach a maximum density in the area of the prospects where they are mineralized not only by quartz, as is common elsewhere, but also by fluorite. The presence of slickensides, belts of crush breccia and intensely sheared vein quartz all testify to considerable movement along many of these fissures.

Figure 51 indicates that the fold pattern of the Meentheena area is not simple. It forms essentially a dome-and-basin pattern with predominantly north to northwest-trending axes. Fold geometry in the immediate area of the prospects has not been investigated in detail, but in general the fluorite occurs high on the northwest flank of an open and irregularly shaped elongate dome.

FLUORITE DEPOSITS

The areal distribution of the main fluorite-bearing veins is shown on Figure 52. Two sets of veins striking respectively at 60° and 135° are present. A typical vein consists of an outer zone of quartz with a wide central zone of interlayered quartz and coarse-grained massive anhedral fluorite. The fluorite sometimes exhibits a banded texture parallel to the vein walls. This phenomenon is common in many other fluorite deposits of the world and has been variously ascribed to rhythmic introduction, or rhythmic variations in the concentration of the mineralizing solutions.

Fluorite bodies within individual veins are rarely tabular but tend to outcrop as pinch-and-swell structures. An absence of drilling data precludes any reliable statement on the three-dimensional geometry of the ore bodies.

The walls of the fissure veins are generally composed of silicified and brecciated country rock. This siliceous breccia contains angular fragments of quartz, chert and bleached country rock in a matrix of white fluorite. Purple fluorite appears to have been introduced at a relatively late stage and veins the rock intricately. Fragmentation of the early quartz and fluorite reflects some degree of disturbance and collapse during mineralization. More than one generation of quartz is present. Some of the veins contain sheared (platy) quartz intruded by later undeformed quartz and fluorite.

Thick veins of calcite are present on the periphery of the mineralized area but no barite, a mineral frequently associated with fluorite, has been detected anywhere in the area. Small occurrences of galena, malachite and goethite have been noted east of the Nullagine River where brochantite and atacamite are also present.

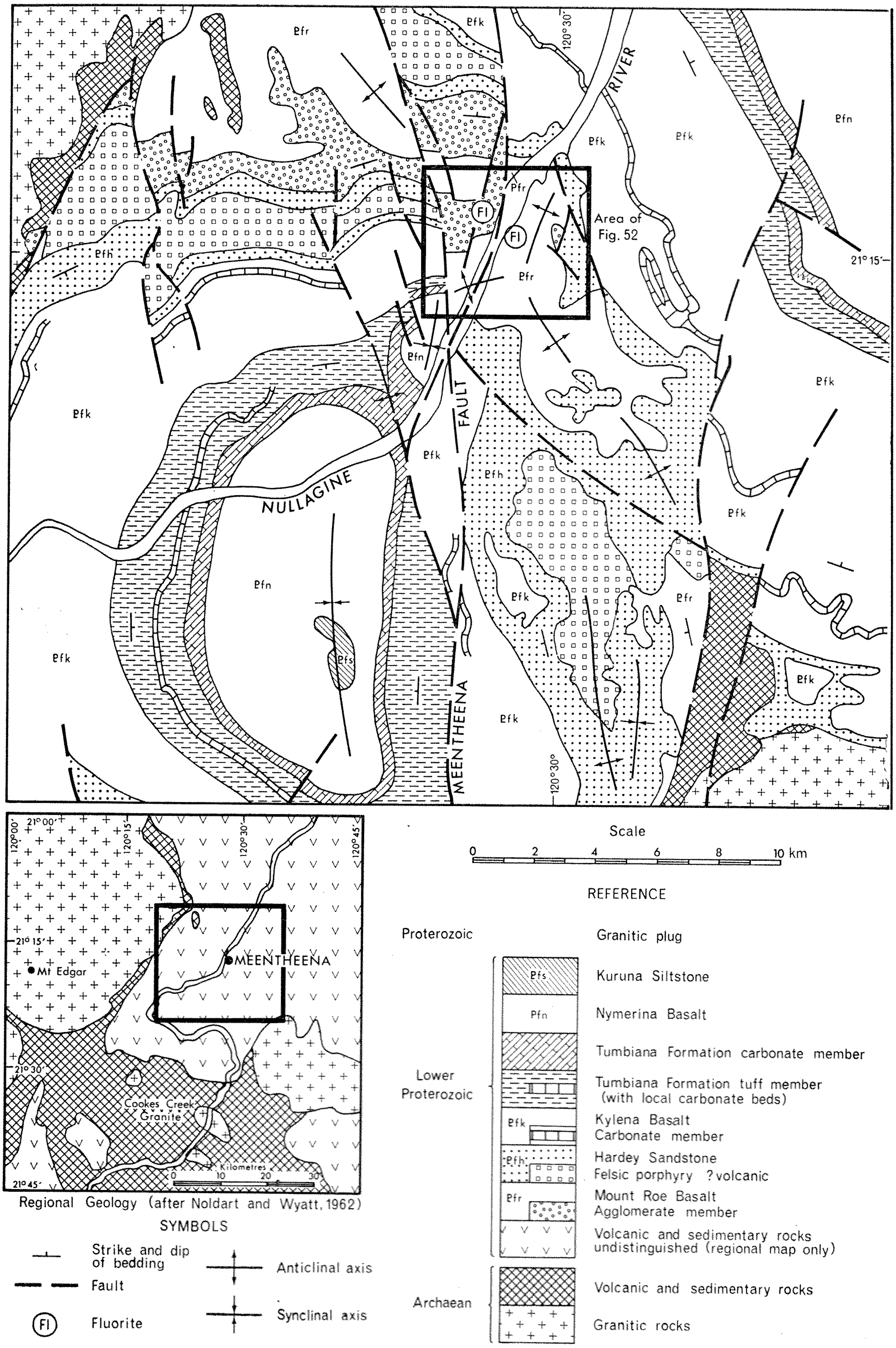

Figure 51. Meentheena area geological map.

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Veins of rhyolitic breccia containing fluorite have been noted at various localities within the prospects. Rhyolitic dykes devoid of fluorite are also present (Fig. 52).

ORIGIN

The structural environment of the Meentheena fluorite deposits is similar to that of many other fluorite mining areas in the world. The fluorite is epigenetic and was deposited in a fracture system from ascending hydrothermal solutions. Two sources may be envisaged for the fluorite:

(1) A deep-seated Proterozoic alkalic magma beneath the Meentheena area.

(2) A fluorite-rich Archaean granite underlying the prospects.

The mineralogy of the deposits suggests that they are epithermal. The absence of tin, tungsten and molybdenum minerals indicates this (Peters, 1958). There is little evidence to suggest that the area is underlain by a large Proterozoic alkalic intrusion. The presence of rare rhyolitic dykes does not in itself substantiate this interpretation especially as these dykes contain no fluorite. Granitic plugs approximately 10 km west of the deposits are of granodiorite composition and contain only minor traces of fluorite.

A late Archaean fluorite-rich granite occurs 35 km south of Meentheena at Cookes Creek. This rock contains about 2 per cent accessory fluorite (J. Lewis, pers. comm.) and is extensively veined by quartz, fluorite and barite. Should such a granite form part of the Archaean basement beneath the Meentheena area it is possible that local severe deformation during Proterozoic folding and fracturing might have mobilized the mineral. Under such conditions fluorite veins could be formed in the lower levels of the Proterozoic succession.

Until more detailed drilling results are available each of the above interpretations is tenable.

GRADE AND ORE RESERVES

The total reserves of the larger veins are estimated at 13 000 tonnes per vertical metre of 50 per cent CaF_2 ore. Total reserves of the entire Meentheena area exceed 30 000 tonnes per vertical metre but most of this material is of low grade. Open-cut mining of the deposits and flotation separation of the fluorite from its only significant impurity, quartz, is probably feasible.

A total of 8 000 tonnes of ore has now been extracted and is stockpiled 3 km north of the company's exploration camp (lat. 21° 16′ S, long. 120° 27′ E).

The ore reserves indicated by this investigation are comparable with those of the State's only other known major fluorite occurrence at Speewah, 110 km south of Wyndham.

CONCLUSIONS

The Meentheena fluorite deposits are structurally controlled by a Proterozoic fracture system and were formed by precipitation from ascending hydrothermal solutions.

The deposits are well situated to supply any future steel industry located in the Pilbara region.

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PETROGRAPHY, CHEMICAL COMPOSITION, AND GEOCHRONOLOGY OF TWO DOLERITE SILLS FROM THE PRECAMBRIAN WEELI WOLLI FORMATION, HAMERSLEY GROUP.

by J. R. de Laeter*, R. Peers, and A. F. Trendall.

ABSTRACT

The intracratonic Hamersley Basin had a maximum extent of about 150 000 km² over what is now the northwest part of Western Australia, between latitudes 20°-24° South, and longitudes 116°-122° East. Deposition probably started no later than 2 300 m.y. ago and terminated about 1 800 m.y. The 2 400 m thick Hamersley Group is the middle group of three deposited in the basin, and is characterized by abundant banded iron formation (BIF). The Weeli Wolli Formation occupies the middle fifth of the Hamersley group, and consists of BIF, shale, and dolerite in the approximate proportions 3 : 1 : 6. The lower part of a diamond corehole that passed through 118 m of the formation transected two dolerite sills, 33 m and 76 m thick, separated by 44 m of BIF and shale. The dolerite is neither macroscopically nor microscopically unusual, and appears to have had typical primary mineralogy although this is now modified by both deuteric and metamorphic effects. However, twenty complete analyses show high average K_2O (2.7 per cent) and low CaO (5.56 per cent). Vertical chemical variation through both sills shows that differentiation was negligible, and that the high average K_2O is due to marginal samples which have very high (up to 7.1 per cent) K_2O probably derived from assimilation of adjacent shale. The anomalously low CaO is probably accounted for by cross-cutting veins of carbonate and axinite. Twelve representative dolerite samples taken through both sills for Rb-Sr isotope analysis are widely scattered on an isochron diagram. It is possible to interpret the scatter in terms of four separate ages: a young (900-1 200 m.y.) up-dating expressed by one sample; an earlier up-dating (1 689 ± 222 m.y.) expressed by four samples; an age of dolerite intrusion (c. 2 100 m.y.) expressed by three samples; and an age of shale deposition (c. 2 200 m.y.) acquired by four marginal dolerite samples by digestion of adjacent shale.

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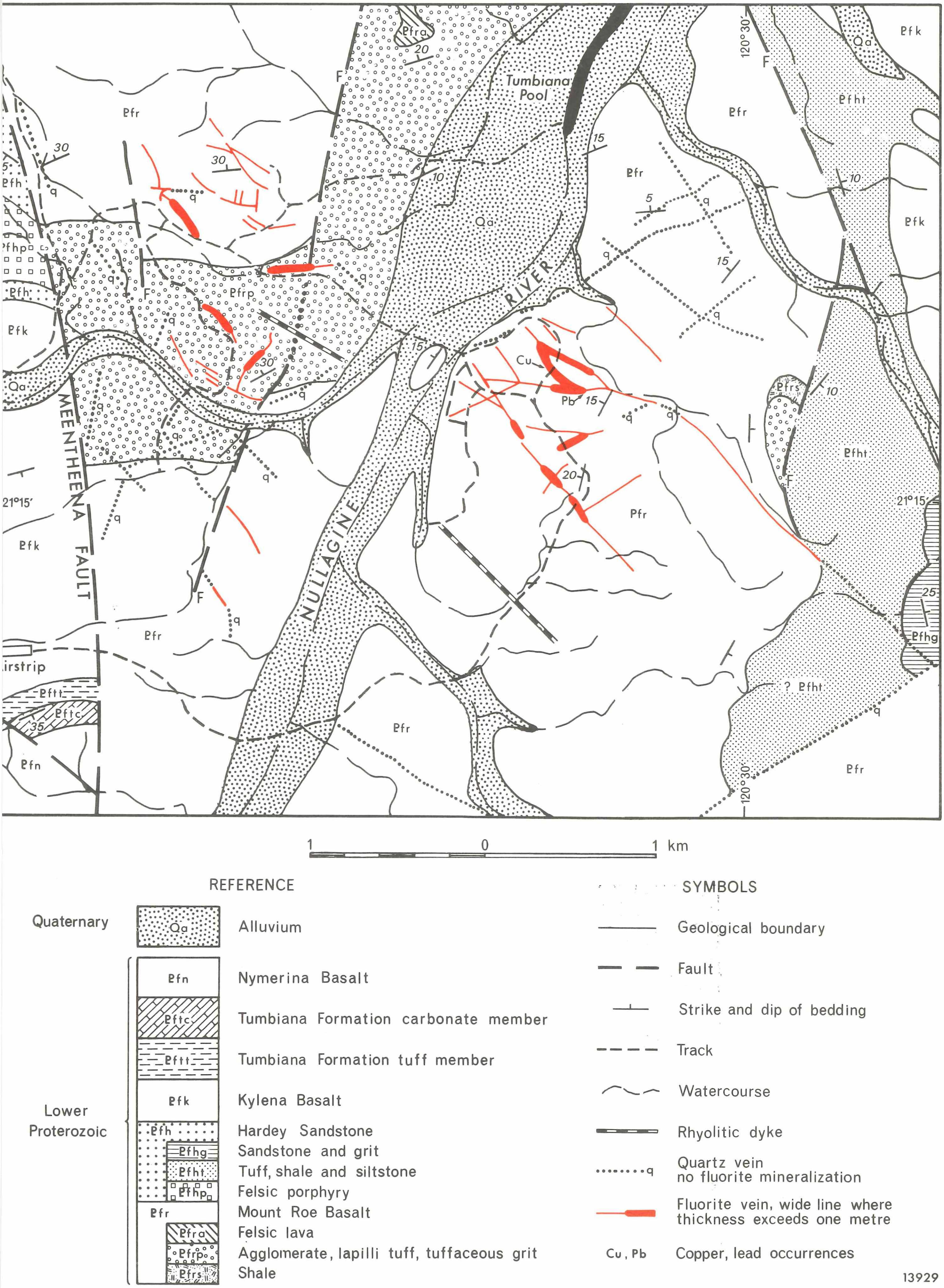


Figure 52. Meentheena fluorite deposits—geological map.

INTRODUCTION

The Weeli Wolli Formation is one of eight constituent formations of the Hamersley Group, a major depositional unit of the intracratonic Hamersley Basin, which extended over some 150 000 km^2 of the northwestern part of Western Australia during the early Proterozoic. The development of the Hamersley Basin, and the present geology of the area, have been described in detail by Trendall and Blockley (1970), and shorter summaries are also available (Trendall, 1968, 1972, 1973a).

The 2 400 m thick Hamersley Group is characterized by an abundance of banded iron formation (BIF), and the Weeli Wolli Formation, which forms roughly the central fifth of the thickness of the group, itself consists of BIF, shale, and dolerite, in the approximate proportions 3 : 1 : 6; its usual thickness is about 450 m. By comparison with other units of the Hamersley Group the Weeli Wolli Formation is poorly exposed. For this reason a continuously cored diamond drillhole, referred to as DDH WW1, was drilled at 22° 17′ 30″ S, and 118° 24′ 00″ E, about 44 km south of Wittenoom, in the Hamersley Range area, in 1970. It passed through 272 m of the Weeli Wolli Formation, of which 154 m was dolerite, in four separate sills. A graphic log showing these, forms Figure 53. The hole was inclined northward at an angle of 60° through the north limb of a gentle anticline, so that it transected the stratification perpendicularly.

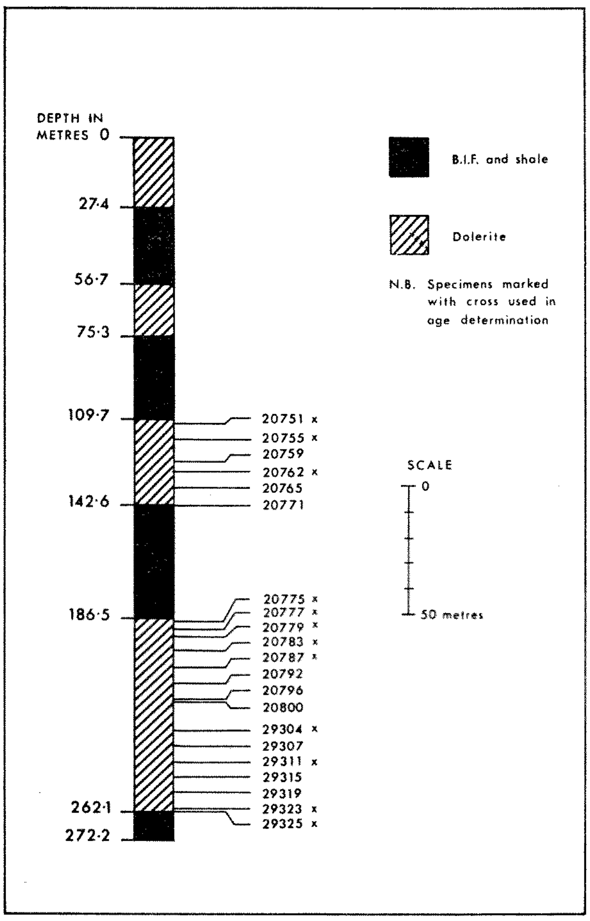


Figure 53. Graphic log of the part of the Weeli Wolli Formation encountered in DDH WW1, showing sample positions.

Although DDH WW1 was drilled to obtain a fresh representative sample of the BIF, on which a preliminary note has been published (Trendall, 1973b), the recovery of complete core sections through the sills made it desirable to place an account of these on record. Twenty samples, which appeared to be completely free of surface weathering effects, were therefore selected from the lowest two sills (referred to informally as the lower and upper sills in this paper), for petrographic examination and chemical analysis. The remarkably high potassium contents revealed by these analyses, and by the visible abundance of potassic feldspar, suggested that the rocks might be chemically suitable for whole-rock Rb-Sr isotopic analysis.

The Rb-Sr ratios of ten of these twenty samples showing a wide range of values were measured accurately by X.R.F.S., and the unspiked Sr^{87}/Sr^{86} ratios were also determined separately. Two further samples were added later to resolve ambiguities; one of these was not one of the twenty analysed samples (20777). Although the Rb-Sr results remain equivocal, all the data obtained merit publication, especially since substantial further work, which cannot be given high priority, would be needed to resolve the remaining problems. The purposes of this paper are therefore to present the petrographic, chemical and geochronological data so far available, and to discuss their significance in the light of previously existing knowledge of Hamersley Basin development, including some unpublished information.

The Rb-Sr isotopic and X.R.F.S. analyses reported here were carried out by J. R. de Laeter in the Physic Department of the Western Australian Institute of Technology. This paper is the sixth report of results of the joint geochronology programme initiated between the Institute and the Geological Survey in 1968.

PETROGRAPHY

The photomicrographs of Figure 54 and 55 show typical examples of the dolerite types present in both of the sampled sills. The mineral composition of the 21 thin sections cut appears in Table 18. A generalised description of these sections follows, with comment on significant variations within them.

Most of the dolerites have a relict subophitic to intergranular texture, and are composed essentially of plagioclase, pyroxene and opaque minerals; all of these constituents are replaced by secondary minerals to a greater or lesser extent. Although the form of the primary plagioclase is well preserved, no plagioclase more calcic than albite remains. Abundant saussurite, and the presence of calcic secondary minerals such as carbonate, epidote, and axinite, indicate that the primary feldspar was a calcic plagioclase. In addition to this "albitization", all of the plagioclase from the lower sill and some from the upper sill appears to have been replaced by K-feldspar. The K-feldspar is evenly kaolinized, and readily distinguished from the plagioclase. However, its presence was confirmed by staining.

About half of the specimens examined retain some relict pyroxene which, without exception, is a clinopyroxene. Typically it occurs as ragged cores which are dark pink in plane polarised light due to included hematite "dust". Replacement of the pyroxene evidently took place along cleavage and fracture planes and at the grain margins. The principal alteration products are amphibole, chlorite and ferrostilpnomelane, with amphibole predominating. Amphibole occurs as aggregates of ragged blades which partly or wholly pseudomorph pyroxene. It is pleochroic with X = pale green, Y = apple green, and Z = pale blue green, but the colour is commonly more intense at the margins indicating a slight variation in chemical composition. Most of the secondary amphibole is actinolite, but the more strongly coloured amphibole may be ferroactinolite or hornblende. A small amount of a primary brown hornblende is present in several specimens. Chlorite is abundant both as a secondary mineral after pyroxene and as an interstitial mineral. Its most common form is a fibrous, radiating aggregate, that has yellow green to pale emerald green pleochroism, and striking anomalous blue birefringence. The co-existence of two chlorites in some samples from the lower sill was confirmed using X-ray methods. The second chlorite forms extremely fine-grained aggregates which are difficult to resolve, and it is variously coloured pale yellow green and olive green. Ferrostilpnomelane is absent from the upper sill, but abundant in the lower, although its abundance in individual samples is extremely variable. Typically it occurs as radiating fibrous aggregates pseudomorphous after pyroxene, but where it is really abundant it is present throughout the rock. It is pleochroic, either colourless to pale green or pale yellow green to olive green but is easily distinguished from chlorite by its birefringence, and from amphibole on the basis of its extinction angle.

The interstitial pockets between the relict plagioclase and pyroxene grains are variously infilled. Most commonly the infilling is a fine-grained granophyric intergrowth of quartz and K-feldspar with included acicular apatite crystals. Less commonly, quartz and chlorite occur interstitially and in the most altered samples the infilling is carbonate or axinite.

Opaque grains are present throughout both sills, but are more abundant in the lower sill. Two varieties were recognized, small grains of fresh pyrite which are yellow in reflected light, and large skeletal grains of a black mineral partly replaced by a mixture of leucoxene and sphene. In a few specimens none of the original mineral remains.

Perhaps the most striking feature of these dolerites is the abundance of the secondary calcium-rich minerals carbonate, epidote and axinite. All three of these tend to be coarsely crystalline, with the appearance of having invaded the rock, and on textural evidence alone do not appear to be primary. Axinite is a particularly characteristic mineral if the section is a little thick and its distinctive lilac pleochroism can be observed. The epidote of these dolerites occurs both as a constituent of saussurite, and as large subhedral pistachio-green grains. Both axinite and carbonate are abundant as coarse veins which cut the dolerite core at intervals along its length.

The specimens that vary from the above descriptions are amygdaloidal, xenolithic or chilled. Specimens 20751, 20759 and 20771 from the upper sill are amygdaloidal. The amygdales are roughly spherical and vary in diameter up to 5 mm. They are variously infilled with epidote, chlorite, quartz, sphene, axinite and pyrite (Fig. 55A). In specimen 20759 the amygdales are imperfectly rimmed by devitrified material. Specimen 20771 from the base of the upper sill is extremely fine grained and includes undoubted, though now recrystallized, xenolithic material (Fig. 55B). The matrix is a poorly crystallized mixture of plagioclase, epidote, actinolite, sphene and chlorite with some porphyroblastic axinite. The xenolith illustrated measures 4 mm by 1 mm, has well-defined layering which is probably relict sedimentary, and is composed of cherty quartz, chlorite, epidote, axinite, a yellowish garnet (probably grossular), pyrite and amphibole.

Several other structures included in this rock, one composed of a K-feldspar mosaic with minor epidote, chlorite and pyrite, and the other rich in axinite, could also be interpreted as xenoliths. Similarly, in specimen 20775 from the top of the lower sill, there are irregular patches of coarse-grained carbonate, epidote and axinite with subordinate ferrostilpnomelane and K-feldspar which may represent recrystallized xenoliths or imperfect amygdales.

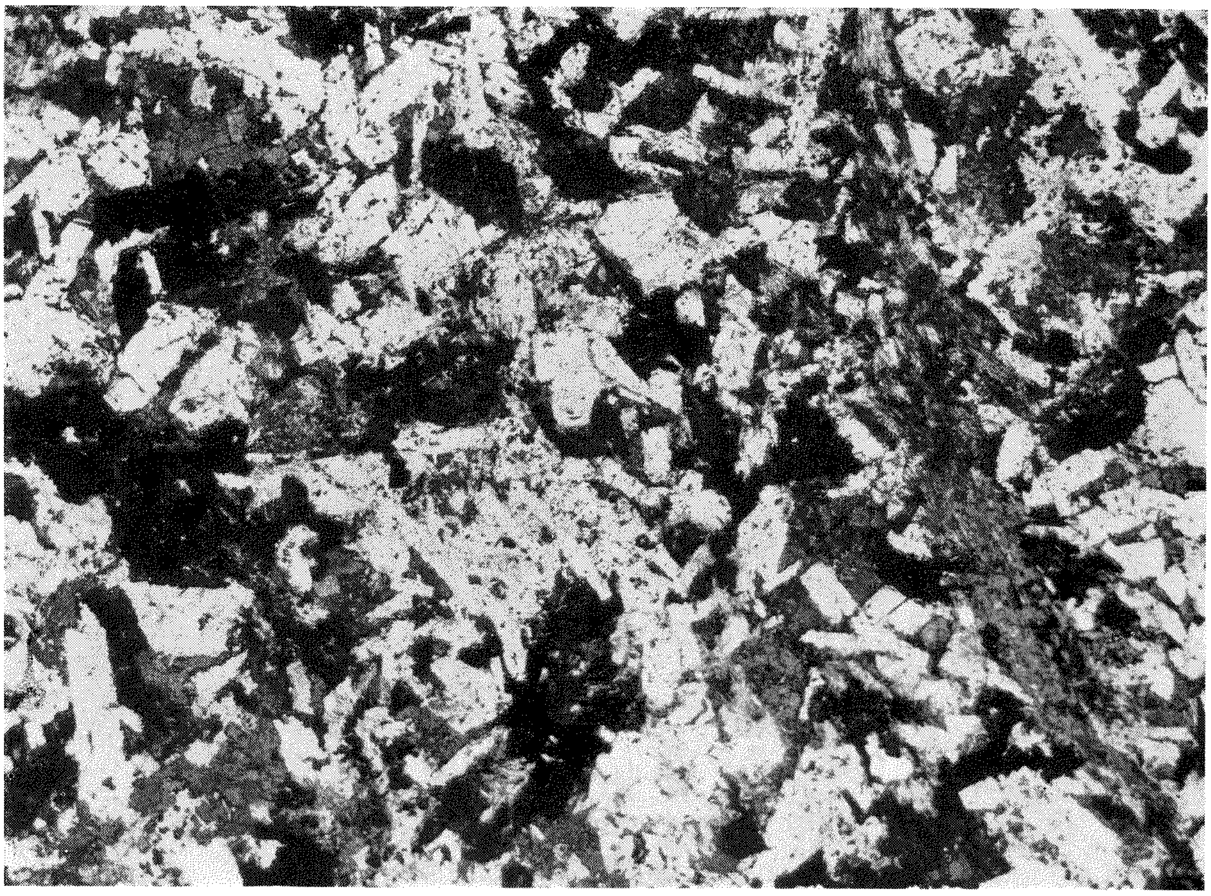
CHEMICAL COMPOSITION

The compositions of the 20 samples analysed are set out in Table 19, together with the computed C.I.P.W. norms. In Figure 56 the variation with depth of selected elements is displayed. All the analyses were carried out by the Government Chemical Laboratories; all determinations except FeO, Na_2O, H_2O^+, H_2O^- and CO_2 were by X.R.F.S.

TABLE 18. SUMMARY OF COMPOSITIONAL VARIATION WITHIN THE DOLERITES OF DDH WW1

		Primary Minerals			Secondary Minerals								Accessory Minerals				
		Plagioclase (albite)	Clinopyroxene	Interstitial quartz/K-feldspar	Amphibole (actinolite)	Chlorite	Ferrostilpnomelane	Epidote	Axinite	Carbonate	Sphene and leucoxene	K-feldspar	Black opaque	Pyrite	Apatite	Amygdales	Comments
Upper Sill	20751	x		x	x	x		x			x	x	x			x	Vesicles infilled with epidote, chlorite, quartz and sphene.
	20755	x		x	x	x		x			x		x		x		Plagioclase rimmed by radiating quartz-alkali feldspar intergrowth.
	20759		x	x	x	x		x			x			x	x	x	Epidote and chlorite infill vesicles which are rimmed by devitrified glass. One amygdale has partial rim of pyrite.
	20765	x	x	x	x	x		x			x			x	x		Amphibole zoned to brown hornblende.
	20771	x			x	x		x	x		x			x		x	Chlorite, epidote, quartz, pyrite and axinite infill vesicles. Rock is chilled and includes xenoliths.
Lower Sill	20775	x	x		x	x	x	x			x	x	x		x	?	Possible xenoliths or amygdales, now carbonate, epidote, axinite, ferrostilpnomelane and K-feldspar.
	20777	x	x		x	x	x	x			x	x	x		x		
	20779	x	x		x	x	x	x	x	x	x	x	x		x		
	20783	x		x	x	x	x	x	x	x	x	x	x	x			Primary brown hornblende zoning to actinolite.
	20787	x	x	x	x	x	x	x	x		x	x	x	x	x		
	20792	x	x	x	x	x	x	x	x	x	x	x	x	x	x		Includes some brown hornblende.
	20796	x	x	x	x	x	x	x	x	x	x	x	x	x	x		Includes some interstitial quartz and axinite,
	20800	x	x	x	x	x		x	x	x	x	x	x	x	x		
	29304	x			x	x		x			x	x		x	x		Interstitial quartz and chlorite. Two chlorites present.
	29307	x			x	x			x		x	x		x	x		Two chlorites present.
	29311	x		x	x	x	x	x	x		x	x	x	x	x		Two chlorites present.
	29315	x		x	x	x	x	x	x	x	x	x	x	x	x		
	29319	x	x	x	x	x	x			x	x	x	x	x	x		
	29323	x		x	x	x	x	x	x	x	x	x	x	x	x		
	29325	x			x	x	x			x	x	x	x		x		

x = present



A

2·0 mm

B

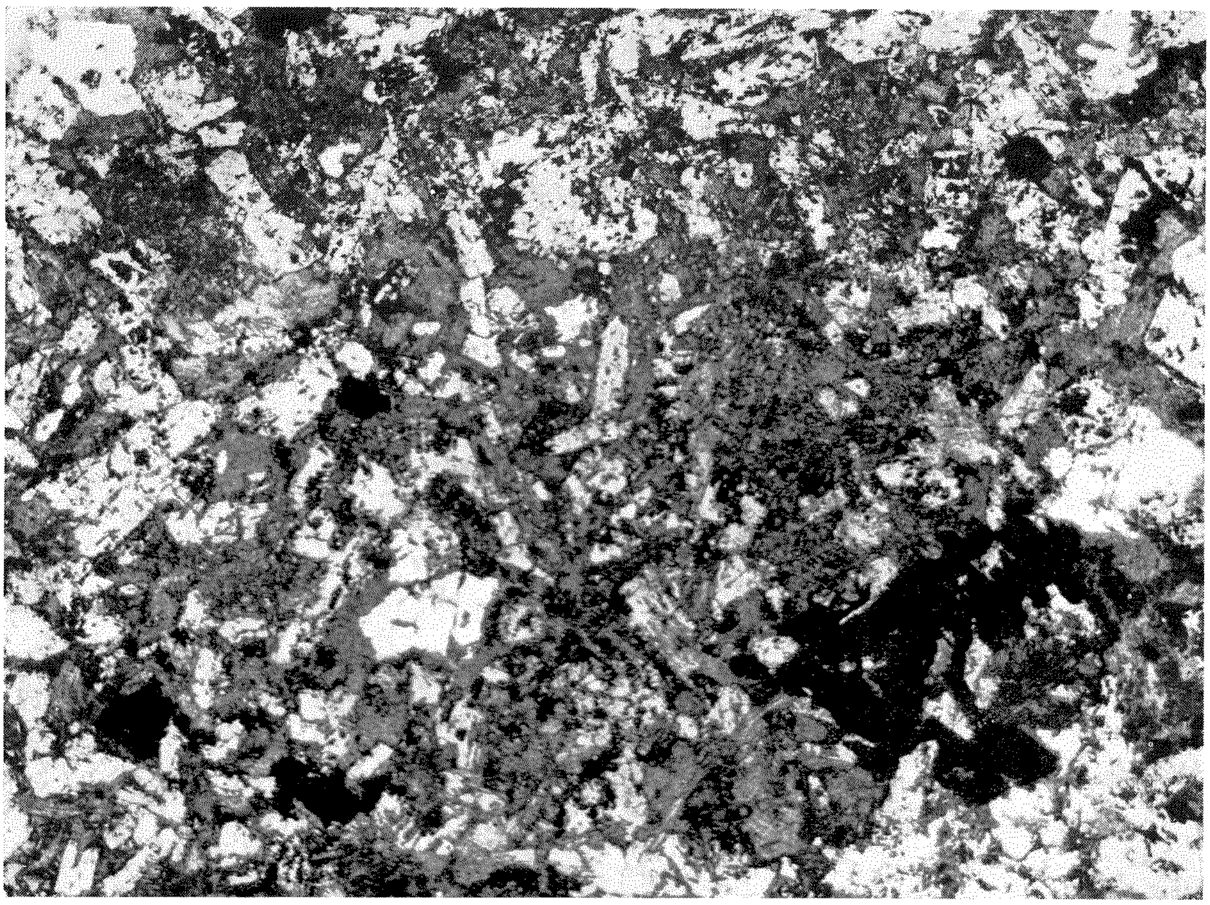


FIGURE 54

Photomicrographs of two samples from the lower sill of DDH WW1

A. 20779. Plane polarised light. Altered dolerite from 194 m, composed of plagioclase (pale grey laths), clinopyroxene (dark grey), amphibole and ferrostilpnomelane (fibrous laths), epidote (grey with moderate relief) and an opaque mineral (black, skeletal form).

B. 29315. Plane polarised light. Altered dolerite from 248 m, composed of plagioclase (pale grey laths), chorite and amphibole pseudomorphous after pyroxene (fibrous grey), interstitial quartz (clear, white), an opaque mineral being replaced by sphene (black skeletal) and epidote (grey with relief).

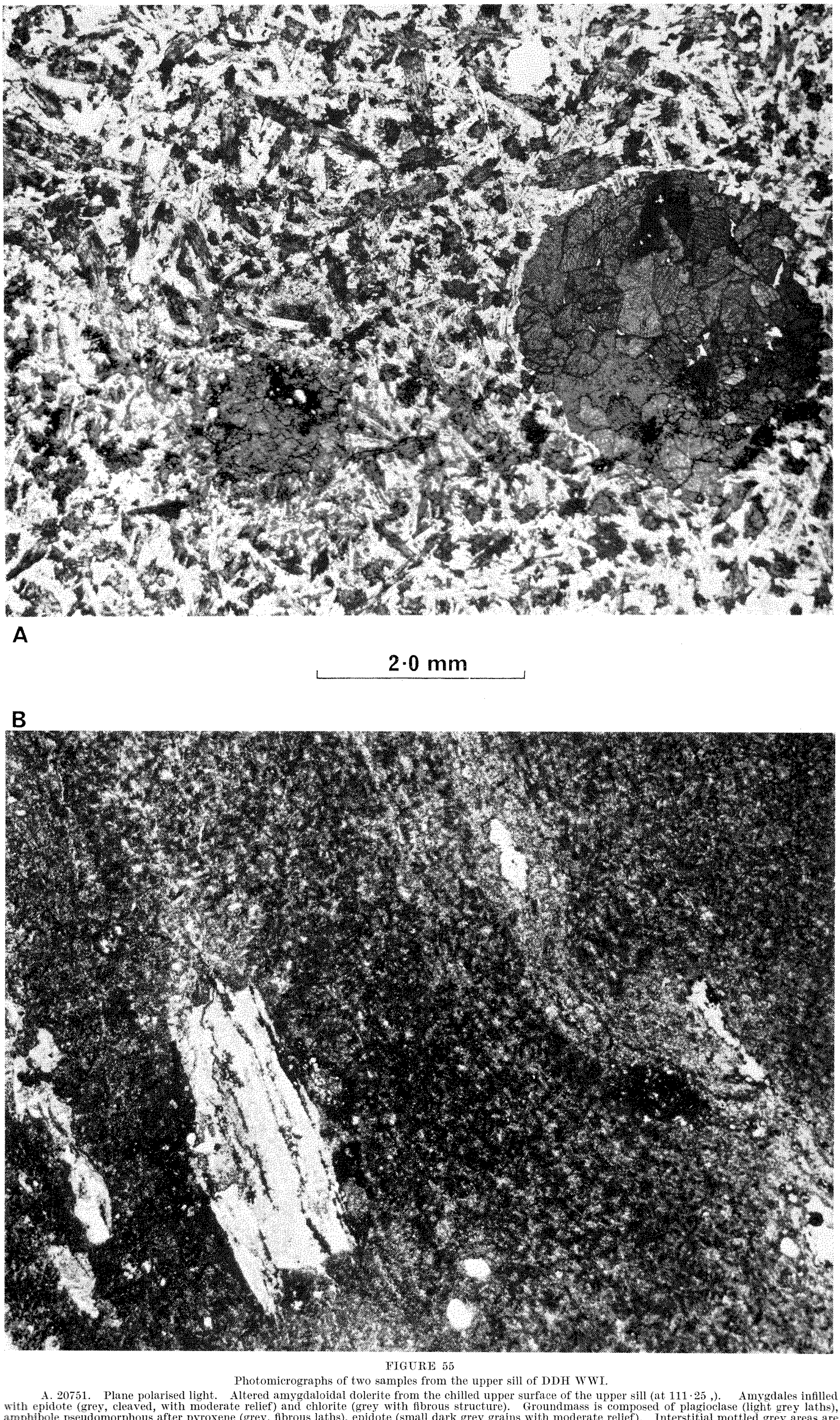


FIGURE 55

Photomicrographs of two samples from the upper sill of DDH WWI.

A. 20751. Plane polarised light. Altered amygdaloidal dolerite from the chilled upper surface of the upper sill (at 111·25 ,). Amygdales infilled with epidote (grey, cleaved, with moderate relief) and chlorite (grey with fibrous structure). Groundmass is composed of plagioclase (light grey laths), amphibole pseudomorphous after pyroxene (grey, fibrous laths), epidote (small dark grey grains with moderate relief). Interstitial mottled grey areas are quartz-K-feldspar intergrowth. The clear white patch at the centre top of the photomicrograph is a hole in the thin section.

B. 20771. Plane polarised light. Altered xenolithic dolerite from the base of the upper sill (at 143 m). Recrystallized xenolith at left is composed of cherty quartz (clear, white), chlorite and amphibole (pale, grey, mottled), epidote (grey with moderate relief, also dark grey and finely granular), axinite (clear pale grey), garnet (dark grey, moderate relief cluster top centre of xenolith and pyrite (black). Other xenolithic fragments are composed of cherty quartz and chlorite. The matrix is a poorly crystallized mixture of feldspar, epidote, amphibole, chlorite and sphene with some axinite.

TABLE 19. COMPOSITIONS AND C.I.P.W. NORMS OF TWENTY DOLERITE SAMPLES FROM THE WEELI WOLLI FORMATION

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
	20751	20755	20759	20762	20765	20771	20775	20779	20783	20787	20792	20796	20800	29304	29307	29311	29315	29319	29323	29325	Average of Column 1–20
SiO_2	56·1	60·6	52·7	55·1	54·3	49·6	51·1	50·6	57·5	50·7	51·0	50·2	50·2	48·1	49·1	51·3	50·1	50·9	50·5	50·5	52·3
Al_2O_3	14·6	13·6	15·7	14·6	14·8	13·8	12·2	12·8	10·8	14·3	14·1	13·9	14·6	16·3	14·8	14·2	14·5	13·6	13·2	13·4	14·0
Fe_2O_3	3·1	3·0	3·5	2·8	3·6	7·6	3·4	5·5	5·3	3·7	4·3	3·5	4·1	7·1	5·1	4·3	4·8	3·6	4·1	2·8	4·3
FeO*	6·19	4·99	7·10	6·70	6·63	10·46	9·62	9·40	8·72	10·09	8·68	9·29	7·41	7·35	9·01	9·39	9·15	9·06	10·03	10·18	8·47
MgO	3·6	3·0	5·0	5·4	4·8	5·0	4·2	3·6	1·9	4·3	4·6	4·6	5·0	3·7	5·1	4·6	4·6	4·6	5·2	5·2	4·4
CaO	4·74	4·28	5·28	5·16	4·46	3·31	7·08	7·16	3·57	5·05	6·98	7·04	9·12	6·49	4·21	5·61	5·36	6·78	5·17	4·37	5·56
Na_2O*	3·25	2·92	4·25	3·23	2·90	3·56	1·46	2·59	2·89	3·12	3·55	3·26	2·22	3·10	3·81	2·68	3·35	3·02	1·78	0·35	2·86
K_2O	3·9	4·2	2·3	2·9	3·5	1·4	5·4	3·0	2·2	2·5	1·1	1·1	2·6	0·7	0·9	1·7	0·9	2·2	3·3	7·1	2·7
H_2O^+*	2·59	1·96	3·37	3·21	3·46	3·93	3·21	3·45	3·33	4·05	3·54	3·71	3·21	4·60	4·57	4·04	4·08	2·55	3·91	3·69	3·72
H_2O^-*	0·08	0·13	0·12	0·08	0·11	0·11	0·15	0·26	0·35	0·06	0·05	0·06	0·11	0·72	0·86	0·26	0·61	0·16	0·31	0·21	0·24
CO_2*	0·00	0·00	0·00	0·32	0·23	0·00	0·46	0·30	0·92	0·14	0·20	0·54	0·08	0·00	0·00	0·00	0·17	0·23	0·26	0·00	0·32
TiO_2	0·58	0·55	0·56	0·49	0·49	0·45	1·26	1·50	1·45	1·25	1·08	1·10	0·93	1·18	1·22	1·29	1·30	1·25	1·25	0·16	0·97
P_2O_5	0·10	0·09	0·06	0·06	0·06	0·11	0·14	0·18	0·17	0·13	0·13	0·10	0·12	0·13	0·11	0·16	0·11	0·16	0·15	0·21	0·12
MnO	0·15	0·12	0·17	0·16	0·17	0·18	0·20	0·24	0·27	0·22	0·19	0·28	0·46	0·11	0·10	0·19	0·14	0·20	0·22	0·21	0·20
Total	98·9	99·5	100·2	100·2	99·5	99·5	99·9	100·5	99·5	99·7	99·5	98·6	100·2	99·6	98·9	99·7	99·3	100·0	99·3	99·4	99·6

C.I.P.W. Norms

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Q	5·36	13·42	....	4·28	4·90	3·74	0·45	3·58	20·40	1·47	3·19	3·31	1·14	6·25	2·51	6·61	5·17	1·76	4·91	....
C	....	....	....	....	....	0·70	....	....	....	....	....	....	....	....	0·21	....	....	....	....	....
Or	23·03	24·78	13·84	17·12	20·72	8·14	32·11	17·73	13·12	14·72	6·35	6·60	15·41	4·27	5·23	9·89	5·45	12·94	19·27	41·88
Ab	27·48	24·67	36·00	27·31	24·51	30·09	12·33	21·94	24·45	26·38	30·02	27·57	18·76	26·21	32·21	22·70	28·34	25·51	15·10	2·96
An	13·71	11·75	16·76	16·79	16·94	15·68	10·59	14·51	10·05	17·70	19·38	19·87	22·26	28·36	20·15	21·63	21·85	17·14	18·33	13·98
Di	7·56	7·31	7·40	5·23	2·72	....	17·25	14·94	0·61	4·69	10·86	9·09	17·79	2·42	....	4·31	2·41	11·66	3·91	5·54
Wo	3·83	3·72	3·77	2·67	1·39	....	8·64	7·50	0·30	2·35	5·49	4·57	9·06	1·24	....	2·17	1·22	5·86	1·97	2·78
En	1·95	1·99	2·06	1·50	0·77	....	3·84	3·39	0·10	1·03	2·75	2·12	4·95	0·72	....	1·05	0·61	2·72	0·95	1·29
Fs	1·78	1·60	1·57	1·06	0·56	....	4·77	4·05	0·21	1·31	2·62	2·40	3·78	0·46	....	1·09	0·58	3·08	0·99	1·47
Hy	13·32	9·79	10·90	20·37	19·27	24·97	15·10	12·28	14·26	22·24	17·12	19·76	13·38	23·93	23·22	21·12	21·30	18·75	24·23	22·80
En	6·97	5·43	6·20	11·93	11·15	12·47	6·73	5·60	4·74	9·77	8·76	9·27	7·59	18·49	12·68	10·34	10·93	8·79	11·88	10·67
Fs	6·35	4·36	4·70	8·44	8·12	12·50	8·37	6·68	9·52	12·47	8·36	10·49	5·79	5·44	10·54	10·78	10·37	9·96	12·35	12·13
Ol	....	....	5·53	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	1·46
Fo	....	....	3·01	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	0·68
Fa	....	....	2·52	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	0·78
Mt	4·46	4·41	5·11	4·04	5·26	11·08	4·95	7·91	7·73	5·41	6·18	5·06	5·90	10·30	7·35	6·31	6·99	5·28	6·01	4·07
Il	1·11	1·05	1·06	0·93	0·94	0·85	2·39	2·84	2·75	2·37	2·06	2·09	1·77	2·23	2·31	2·54	2·46	2·38	2·38	2·48
Ap	0·23	0·22	0·14	0·14	0·15	0·26	0·34	0·43	0·41	0·30	0·31	0·24	0·28	0·31	0·26	0·37	0·27	0·37	0·36	0·38
Cc	....	....	....	0·73	0·52	....	1·03	0·68	2·09	0·32	0·45	1·23	0·18	....	....	....	0·39	0·52	0·59	....

* Analysis by chemical methods, remainder by X.R.F.

Analysts : Government Chemical Laboratories : N. March (X.R.F. analyses), G. Bialecki and R. Hogg (analyses by chemical methods).

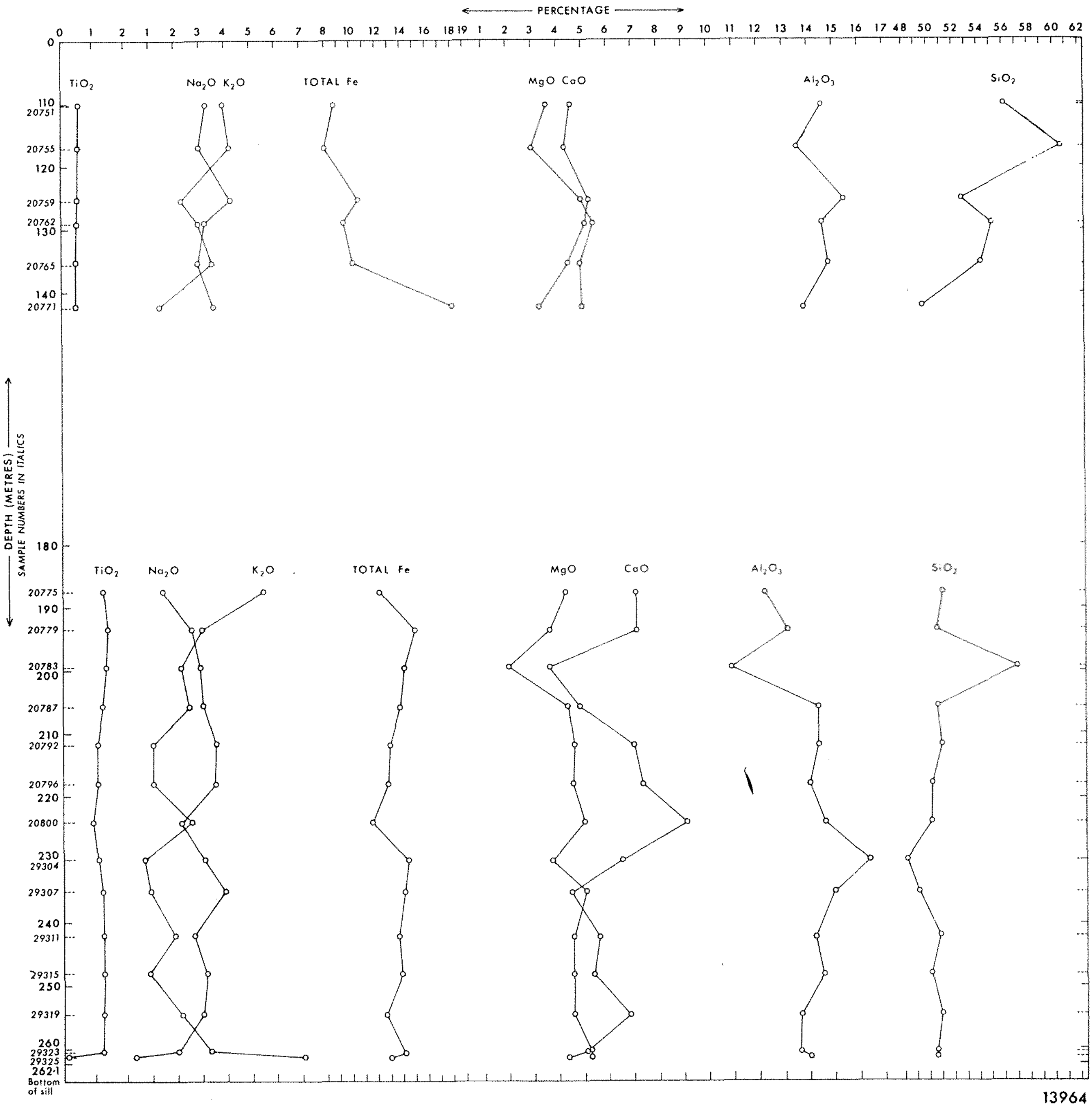


Figure 56. Variation of selected elements with position in sill : lower two dolerite sills intersected in DDH WW1.

RUBIDIUM-STRONTIUM DATA

Experimental procedures

About 100 g of each sample was reduced to –200 mesh using a jaw crusher and a Tema mill. Approximately 0.2 g of powder was then accurately weighed and taken into solution in a HF-$HC10_4$ mixture in a teflon dish. This solution was converted to the chloride form with 2.5M HC1. After again taking to dryness the residue was redissolved in 1M HC1 and centrifuged. The supernate was transferred to a quartz ion-exchange column contraining 2 g of Dowex 50W-X8, 200-400 mesh cation-exchange resin. Strontium was eluted using 2.5M HC1 and, after being taken to near dryness, each sample was loaded on the side filaments of a conventional rhenium triple filament assembly, ready for mass spectrometric analysis.

Blank determinations using the isotope dilution technique showed that the Rb and Sr contamination introduced by the chemical processing was less than 10^{-9} g and 10^{-8} g respectively. Full details of the isotope dilution technique used in this laboratory are given by de Laeter and Abercrombie (1970).

Isotopic analyses were carried out on a 30.5 cm radius, 90° magnetic sector, solid source mass spectrometer equipped with an electron multiplier. Previously outgassed rhenium filaments were used throughout the analyses. No evidence of Sr contamination from the ion source or filaments was ever observed.

A 1μg sample of $SrCl_2$ produced an ion-beam of approximate strength 10^{-11} amps for many hours of operation. The resulting signals were amplified in a vibrating reed electrometer with a 10^8 ohm input resistor. A voltage to frequency converter, followed by an electronic counter, allowed digital presentation of the data, which was fed on-line to a small digital computer. The amplifying system was periodically checked for linearity and speed of response.

Mass 85 was monitored on a sensitive scale at intervals during the analysis in order to correct the measured 87 peak for Rb contribution. The isobaric contribution of Rb^{87} to the Sr^{87} ion-beam was always less than 0.01 per cent before data were collected.

The isotopic peaks were scanned magnetically from mass 86 to 88 and then back again, this operation constituting one sweep. Approximately 40 sweeps were taken for each sample.

Replicate analyses of the NBS 987 Sr standard were made to give a mean value of Sr^{87}/Sr^{86} of 0.7105 normalised to a Sr^{88}/Sr^{86} value of 8.3752. The Sr^{87}/Sr^{86} values listed in Table 20 have been normalised to a Sr^{88}/Sr^{86} value of 8.3752. A value of 1.39 x 10^{-11}/year was used for the decay constant of Rb^{87}.

X-ray fluorescence was used to select rocks with favourable Rb/Sr ratios for mass spectrometric analyses, and also to determine precise values of the Rb/Sr ratio for the selected samples. A Siemen's SRS-1 fluorescence spectrometer equipped with a molybdenum tube, a lithium fluoride (200) crystal and a scintillation detector was used. The method of Norrish and Chappell (1967) was used to determine the Rb/Sr ratio in the samples.

Results

The measured Rb/Sr and Sr^{87}/Sr^{86} ratios, as well as the Rb^{87}/Sr^{86} ratios calculated from these, are given in Table 20. The errors accompanying the ratios are given at the 95 per cent confidence level. The data are also plotted in Figure 57, together with the isochrons the status of which is discussed below.

TABLE 20. RUBIDIUM-STRONTIUM DATA FOR 12 DOLERITE SAMPLES.

Sample No. *	Rb/Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
^{1}29304	0·107 ± 0·002	0·31 ± 0·006	0·7305 ± 0·0007
^{1}29311	0·439 ± 0·007	1·27 ± 0·02	0·7588 ± 0·0007
^{2}29323	0·72 ± 0·01	2·10 ± 0·03	0·7697 ± 0·0007
^{2}20787	0·89 ± 0·01	2·59 ± 0·03	0·7767 ± 0·0007
^{1}20779	0·94 ± 0·01	2·75 ± 0·04	0·8086 ± 0·0008
^{1}20751	1·01 ± 0·01	2·94 ± 0·04	0·8208 ± 0·0007
^{2}20762	1·14 ± 0·02	3·33 ± 0·05	0·8186 ± 0·0007
^{1}20755	1·68 ± 0·03	4·95 ± 0·09	0·8842 ± 0·0008
^{3}20783	1·91 ± 0·02	5·57 ± 0·06	0·8162 ± 0·0007
^{2}29325	4·0 ± 0·07	11·9 ± 0·2	1·0075 ± 0·0010
^{1}20775	4·06 ± 0·04	12·2 ± 0·12	1·1023 ± 0·0007
^{2}20777	4·2 ± 0·07	12·5 ± 0·2	1·0084 ± 0·0009

*Note : Superscript 1 before Sample Number indicates inclusion in older isochron. Superscript 2 indicates inclusion in younger isochron. Superscript 3 indicates sample not used for isochron computation.

DISCUSSION

Bulk composition and vertical compositional variation of the sills

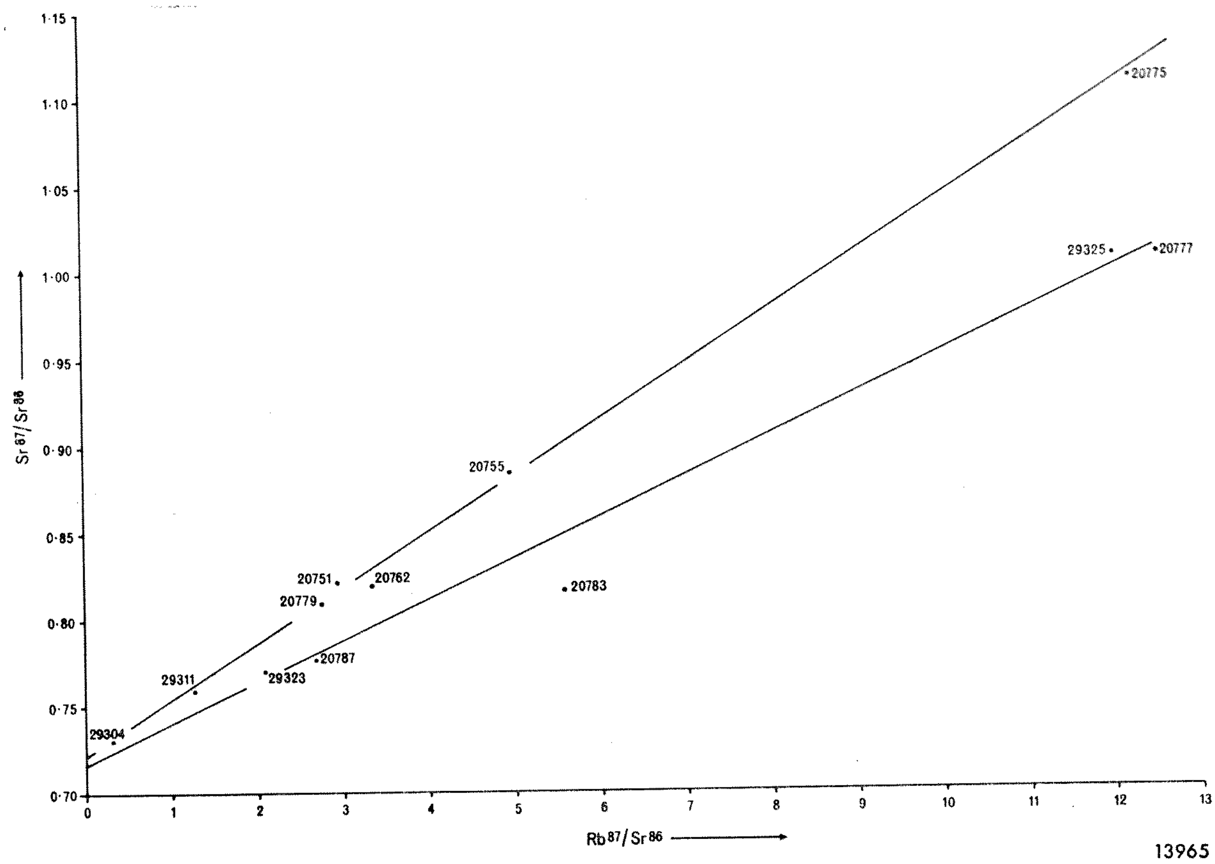
The rocks of the two sills with which this paper deals have the typically dark green granular macroscopic appearance of dolerites. In thin section they appear to have crystallised originally as clinopyroxene-feldspar-opaque rocks with the usual texture of dolerites; and finally, the apparent replacement relationship of the K-feldspar and the abundance of secondary Ca-rich minerals associated with the existing albite, jointly suggest that the original feldspar was largely the calcic plagioclase to be expected in normal dolerites.

TABLE 21. SELECTED AVERAGE ANALYSES REFERRED TO IN DISCUSSION.

	1	2	3	4	5	6	7
SiO_2	52·5	50·6	51·2	47·0	54·7	50·0	50·8
Al_2O_3	14·1	15·3	15·1	15·8	14·2	14·7	12·8
Fe_2O_3	4·3	2·4	2·3	3·3	4·7	4·7	3·1
FeO	8·5	8·9	8·9	7·9	9·2	8·5	9·9
MgO	4·4	6·4	6·4	7·1	3·7	4·6	4·7
CaO	5·6	10·1	10·1	10·1	0·1	6·6	5·7
Na_2O	2·9	2·4	2·2	3·2	0·1	3·1	0·9
K_2O	2·7	0·9	0·9	1·4	10·0	1·4	6·3
H_2O+	3·7	1·0	0·9	1·0	2·6	4·0	3·5
TiO_2	1·0	1·5	1·5	2·5	0·5	0·1	0·7
P_2O_5	0·1	0·26	0·20	0·50	0·1	1·1	0·2
MnO	0·2	0·18	0·19	0·16	0·1	0·1	0·2
Total Fe	9·6	8·6	8·5	8·4	10·4	9·9	9·9

1. Average of 20 analyses reported in Table 19 of this paper (recalculated to 100 per cent on dry basis).
2. Average of 417 dolerites (Manson, 1967).
3. Average of 331 tholeiitic dolerites (Manson, 1967).
4. Average of 84 alkalic dolerites (Manson, 1967).
5. Potassic shales of Brockman Iron Formation (average of columns 1 and 3 of Table 15 in Trendall and Blockley 1970).
6. Average of 6 innermost samples of lower sill (columns 11-16 of Table 19).
7. Average of 2 outermost samples of lower sill (columns 7 and 20 of Table 19).

Despite these features, columns 1-4 of Table 21 leave no doubt that the average composition of both sills differs markedly from that of average dolerite. Notably it has excess K_2O and deficient CaO, but shows significant enrichments in SiO_2, Fe_2O_3 and Na_2O and a deficiency in MgO. We accept the circumstantial evidence already given



13965

Figure 57. Isochron of data of Table 20. The two isochrons are those of Table 22.

that the magma was essentially doleritic, and attribute at least part of these chemical disparities to contamination.

The Weeli Wolli Formation parted preferentially along shale horizons to receive these sills. Although none of these shales have yet been analysed some shales of the immediately underlying Brockman Iron Formation are known to have an unusually high K_2O content. Reference to Table 21 indicates firstly that, provided the oxidation state of the iron is disregarded, all major components except Al_2O_3 of the marginal dolerite of the lower sill (column 7) are intermediate between such shale (column 5) and average alkalic dolerite (column 4); and secondly that, in respect to both alkali content and proportions, the inner, and presumably less contaminated part of the same sill (column 6) has a very different composition, close to that of average alkalic dolerite. This inner material remains deficient in both CaO and MgO compared with alkalic dolerite, and we suggest, but cannot quantitatively demonstrate, that the carbonate axinite in veins which transect the core may account for the bulk of this deficiency. The occurrence of axinite appears to support the possibility of assimilation of shale; some shales of the Brockman Iron Formation have abundant tourmaline as a source of boron (Trendall and Blockley, 1970, p. 115). The inner dolerite of the sill is also somewhat richer in total Fe and SiO_2, and this may well be due to a smaller proportion of digested BIF.

Marginal contamination by BIF may also be the explanation for the high Fe and SiO_2 contents of sample 20771, the lowest sample from the upper sill. If this is accepted then the only asymmetry suggestive of consistent vertical compositional zoning in either sill is otherwise explained. Figure 56 clearly indicates the general lack of compositional layering in both sills, and this is consistent with the homogeneity of both mineral composition and texture.

We conclude that both sills probably result from the intrusion of rather alkali-rich basic magma which was at least marginally contaminated by the adjacent sediments, and which crystallized sufficiently quickly for negligible differentiation to take place. One interpretation of the Rb-Sr data, referred to later, suggests that even the internal dolerite of the sills is contaminated, but it does not seem that this can be argued from the major element compositions alone.

Post-emplacement alteration

We have already suggested that pre-emplacement modification of the magma took place by digestion of material from the intruded sedimentary rocks. We have further noted that the principal primary minerals have been altered to a greater or lesser extent after crystallization: the pyroxene mainly to amphibole, and the calcic plagioclase to albite and epidote. If the potassium in K_2O-rich samples is derived by assimilation of shale we must assume that both this initial breakdown of calcic plagioclase and the further replacement of albite by K-feldspar followed the initial crystallization almost instantaneously. It may be that in the replacement of albite by K-feldspar the additional potassium was concentrated in interstitial glass so that it was available during a late stage of the first cooling of the sills.

Although these dolerites are thus assumed to have acquired much of their present mineral composition by early deuteric processes, the ferrostilpnomelane seems likely to have a different status. Stilpnomelane is a common constituent of much of the BIF of the Hamersley Group. Trendall and Blockley (1970, p. 294) summarised the evidence for the thermal history of the group and concluded from evidence then available that no part of the Brockman Iron Formation immediately below the Weeli Wolli Formation had reached a temperature above 160°C. But Becker's (1971) later oxygen isotope work led him to conclude that the lowest member of the Brockman Iron Formation had experienced a temperature between 250° and 300°C. Since ferrostilpnomelane has not been reported as a result of deuteric processes, but is a common product of low-grade regional metamorphism, it seems more likely that this mineral in the dolerites was produced by a later low-grade pervasive metamorphism, as suggested by Ayres (1972) for the Brockman Iron Formation. This is consistent with its textural occurrence.

Interpretation of Rb-Sr data

It is immediately clear that the data of Table 20 and Figure 57 have a sufficiently wide scatter to make the calculation of a single meaningful isochron completely impossible; nor can this be achieved by the arbitrary omission of one or two points.

In the fourteen years since the isochron concept for whole-rock Rb-Sr geochronology was conceived, a wide range of refined statistical techniques has been evolved for the evaluation of the value and error limits of both the slope, and Y intercept of an isochron defined by a set of approximately colinear points (analyses) to which the concept applies. However, in the treatment of an array of widely scattered points from a group of samples collected from a single rock body, a good deal of judgement must be applied if the best working hypothesis to explain the scatter is to be developed. In dealing with such an array, the first step is subjective visual construction of the fewest straight lines that pass as close as possible to as many points as possible; the second step is assessment of the geological credibility of the ages represented by these lines; and the final stage is intuitive integration of these two steps until least internal conflict within the total evidence is achieved. The succeeding discussion presents the product of such a process.

The five points of Figure 57 with Rb^{87}/Sr^{86} greater than 4 are so disposed that a minimum of three lines is needed to include all of them. A line of greatest slope is required by samples 20755 and 20775; and samples 20762, 20751, 20779, 29311 and 29304 fall fairly close to this line. Samples 29325 and 20777 may be assumed to lie reasonably close to a single line of less steep slope passing between them and extending down to include at least 20787 and 29323, and possibly also 29304 and 29311. Sample 20783 cannot be accommodated by either of these lines, and can only lie on a line of least slope which may again include 29304, or 29311, 29323 and 20787, or all of these latter four analyses. The possible significance of each of these lines is examined in reverse order.

Lines of least slope including 20783, and any combination of the four possible points suggested above, would represent ages between approximately 900 and 1200 m.y. It is true that the samples 20783, 20787, 29323, 29311 and 29304 are a sequential set of five samples through the greater part of the thickness of the lower sill (Fig. 53); however, these five points are by no means precisely colinear, and we appeal to the evident departure of 20783 from the consistent compositional trends expressed by samples above and below (Fig. 56) to support the alternative view that it has genuinely been affected by a late event, possibly related to the development of the Bangemall Basin farther south. We do not suggest that the anomalous composition was acquired at the time of this event, but that it possibly caused a distinctive mineralogy, not evident optically, which was selectively sensitive to thermal up-dating. We thus regard sample 20783 as unique and anomalous and can offer no satisfactory explanation for its isotopic composition.

Of the remaining points of Figure 57, the two which appear to have equal potential for contributing to either of the two steeper lines were arbitrarily allocated to the older isochron, and both were computed using the programme of McIntyre and others (1966). The first (older) set thus included 29304, 29311, 20779, 20751, 20762, 20755 and 20775; the second (younger) set included 29323, 20787, 29325 and 20777. The results appear in Table 22.

TABLE 22. ISOCHRONS COMPUTED FROM SELECTED DATA OF TABLE 20.

Samples	Age	Initial Ratio Sr^{87}/Sr^{86}
Older Group : 20775, 20755, 20762, 20751, 20779, 29311, 29304	2222 ± 116	0·7219 ± 0·0084
Younger group : 29325, 20777, 20787, 29323	1689 ± 222	0·7174 ± 0·0140

For both isochrons the mean square of the weighted deviates was 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 Sr^{87}/Sr^{86} ratio of each set was homogeneous, and that all the samples of that set were subsequently closed to Rb and Sr, therefore do not hold. The programme has then examined each set of data for geological variation and indicated that the distribution of the residuals suggests that the rocks within the older isochron have the same age but different initial Sr^{87}/Sr^{86} ratios. The programme also suggests that the distribution of the residuals for the younger set of data is a combination of experimental and geological variation proportional to and independent of the Rb^{87}/Sr^{86} ratios.

Although we accept the two ages of Table 22 as useful for the purposes of discussion, the arbitrary allocation of the two samples with lowest Rb^{87}/Sr^{86} to the upper isochron means that no genetic significance can be attached to the computed initial Sr^{87}/Sr^{86} values.

Trendall and de Laeter (1972) reported an age of 1 720 ± 25 m.y. from beds of porcelanite, believed to represent tuff, within the Joffre Member of the Brockman Iron Formation, which lies immediately and conformably below the Weeli Wolli Formation. In the discussion of that result they summarised (ibid, Table 4) the Rb-Sr data then available from rock units for whose time relationship to the Joffre Member there was geological evidence. They concluded that acceptance of 1 720 m.y. as the time of an event which terminated free isotope mobility within the Joffre Member, some 300-400 m.y. after its deposition, led to a satisfactory integration of all available geological and geochronological evidence.

We see the younger isochron of Table 22 as supporting evidence for a significant regional event in the Hamersley Basin area at about 1 700 m.y. which strengthens part of Trendall and de Laeter's (1972) conclusions. This event we now envisage to have involved local igneous activity (the Boolaloo Granodiorite), tectonism, de-watering of Hamersley Group sediments, and probably the general low-grade metamorphism of the Hamersley Group already referred to in this discussion. Three of the four points contributing to this isochron are close to the margin of the lower sill, so that the implied up-dating could credibly be related to the likely zone of high stress between the more competent dolerite and less competent shale during folding. However 20787 lies well within the sill, and is separated from the margin by samples (20775, 20779) which preserve an older age. Acceptance of our present explanation of this isochron thus involves acceptance of irregular distribution of up-dating within the sill.

The older of the two isochrons appears to be capable of two explanations, which may most clearly be separated by initially restating the isochron hypothesis in its most commonly applied form: colinearity of a set of points is consistent with the hypothesis that, at a time represented by the slope of the line (isochron) the Sr^{87}/Sr^{86} ratio throughout the rock body from which the analysed samples were collected had the uniform value represented by the ordinate intercept. The existence of a uniform Sr^{87}/Sr^{86} value is normally taken to be possible, in rock bodies with inhomogenous Rb/Sr, only in a small number of special situations in their life. Such situations are usually conceived of as their existence as magma in the case of igneous rocks; equilibration with ambiant water, in the case of sedimentary rocks; and for metamorphic rocks, their metamorphism. In the sills under discussion a standard interpretation of the oldest isochron would suppose it to represent the age of intrusion and crystallization of the dolerite.

This interpretation requires that, at that time, strontium was isotopically equilibrated throughout each sill. However we have supposed, earlier in this discussion, that potassium now present in the marginal dolerite was substantially contributed by assimilated shale, and the interpretation would therefore require that while radiogenic strontium from the shale diffused to equilibrium throughout the sill, potassium remained locally restricted. The alternative concept is to suppose that radiogenic strontium derived from ingested potassic shale had not greater mobility than potassium, and this supposition forms the basis for the second explanation of the older isochron.

If the uncontaminated doleritic magma had, as would be expected, a low (say < 0.5) Rb/Sr ratio, and it intruded slightly older potassic shales of much higher Rb/Sr, then individually isochemical mixtures of dolerite and shale would fall within a very narrow zone approximating a depositional age isochron of the shale. We believe this to be the best interpretation of the status of the older isochron of Figure 57 and Table 22; it represents a depositional age of about 2 200 m.y. for the invaded shale. With the exception only of 20762, all the points which contribute to it with Rb^{87}/Sr^{86} above 1.5 are of samples close to sill margins, whose K_2O contents (Table 19) additionally lead to suspicion of contamination.

It follows that the age of dolerite intrusion must be sought in uncontaminated dolerite. Samples 29304 and 29311 come from the inner part of the lower sill, and have K_2O contents of only 0.7 and 1.7 per cent respectively. A line joining them represents an age of 2 090 m.y. but, perhaps more significantly, these two points are very closely colinear with 20762, whose position in the sill has already been noted as anomalous if it is to be interpreted as a contaminated rock. Although these data are admitted to be inadequate, we conclude that they suggest an age of about 2 100 m.y. as the intrusive age of the dolerite.

More data are nevertheless required before these suggestions can be accepted as other than tentative. A serious problem remaining from them, for example, is that if samples 29304, 29311 and 20762 are accepted as inner uncontaminated samples which define an age of intrusion, then the initial Sr^{87}/Sr^{86} ratio involved, in excess of 0.72, certainly cannot be that of a magma derived directly from the mantle. The petrogenetic problems involved cannot be effectively pursued until more data are available.

Integration of Rb-Sr interpretation with regional geochronology

In their earlier summary Trendall and de Laeter (1972) were able to achieve a satisfactory integration of all available geochronological and geological evidence from the Hamersley Basin. The interpretations discussed above, although tentative, introduce new difficulties which now make this impossible.

The relevant data are displayed in summary in Figure 58. In that Figure the stratigraphic positions of samples used in published Rb-Sr age determinations are shown in the central column, while the equivalent numbers appear, with vertical error bars where appropriate, to the right of the column in relation to a time scale in millions of years. The numbers of the 14 determinations are arranged, as far as possible, in the time sequence suggested by the geological evidence, so that any departure from upward numbered sequence on the time scale represents an anomaly to be explained; in most instances of non-sequence there is a simple explanation, but in some there is not.

Working upwards through the numbered determinations, No. 4 is out of sequence because the 2 940 m.y. age is that of detrital muscovite from the underlying Archaean rocks rather than that

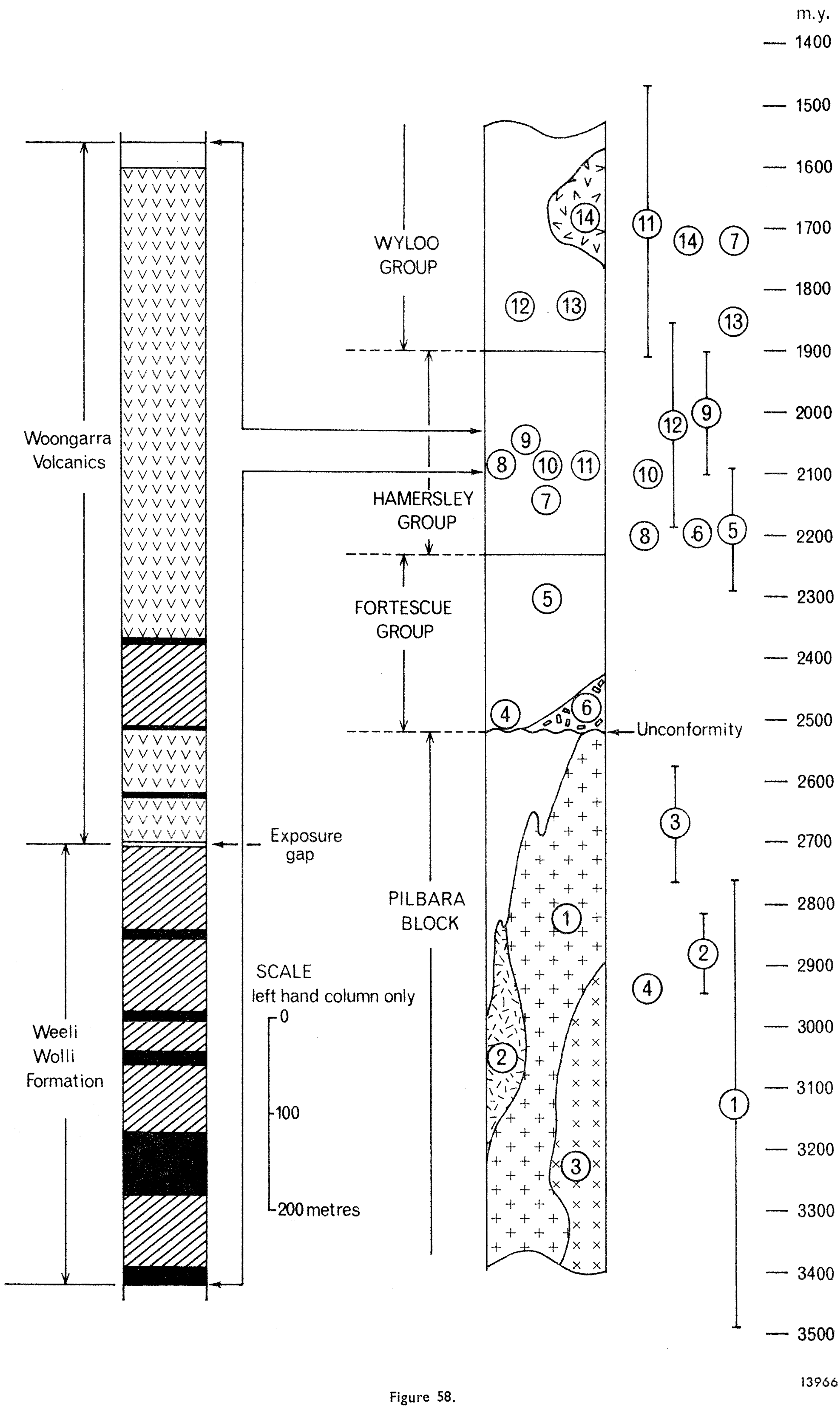

m.y.
1400
1500
1600
1700
1800
1900
2000
2100
2200
2300
2400
2500
2600
2700
2800
2900
3000
3100
3200
3300
3400
3500
Woongarra Volcanics
Weeli Wolli Formation
Exposure gap
SCALE
left hand column only
0
100
200 metres
WYLOO GROUP
HAMERSLEY GROUP
FORTESCUE GROUP
PILBARA BLOCK
Unconformity
13966

Figure 58.

of deposition of the Cliff Springs Formation. Nos. 5, 6 and 8 appear coeval. There is no difficulty in explaining this, because No. 6 certainly represents an intrusive age, and No. 5 probably, also does. No. 7 appears much later than any of these three, and is believed to represent a late up-dating, as already discussed; No. 11 appears out of sequence because of the same up-dating event. So far all non-sequences can be simply accounted for, and the first real difficulty occurs in the reverse order of Nos. 9 and 10. Before discussing this fully it is necessary to record briefly some results of continuing work by one of us (A.F.T.) on the Hamersley Group which are not yet published.

There are three main points to note:

(1) The dolerite sill which Trendall and Blockley (1970 p. 92) thought to occur within the Woongarra Volcanics is now known to be present consistently over much of the outcrop area; it is believed to be, in effect, a representative, in the overlying formation, of the dolerite sills of the Weeli Wolli Formation.

(2) The occurrence reported by Trendall and Blockley (1970, p. 91) of a xenolith of the overlying Woongarra Volcanics in dolerite of the Weeli Wolli Formation has been closely re-examined, and found to be in error.

(3) Careful study of the upper margin of the Woongarra Volcanics indicates that its acid igneous rocks are, on the balance of evidence, more likely to be intrusive than extrusive.

The third point destroys what has come to be accepted as the most reliable internal evidence for the depositional age of the rocks of the Hamersley Basin (No. 9): instead, this age of $2\,000 \pm 100$ m.y. sets only a minimum age for the sediments into which the acid sills were intruded. Taken together the three points place the acid igneous sills of the Woongarra Volcanics and the dolerite sills of the Weeli Wolli Formation as spatially overlapping sets of intrusions for whose relative age there is no present evidence. Nos. 9 and 10 of Figure 58 are thus no longer anomalous, and the age (No. 8—2 200 m.y.) here interpreted by us as the depositional age of the Weeli Wolli Formation becomes the most reliable, and the only direct determination of depositional age in either the Fortescue Group or the Hamersley Group.

Clearly this situation is unsatisfactory, and further work is planned to place more definite time constraints on Hamersley Basin evolution.

FIGURE 58 (opposite)

Summary of selected geochronological data from the Hamersley Group and unconformably underlying Archaean rocks.

The circled numbers in the central diagrammatic stratigraphic column correspond with those placed against a scale of years to the right. A key to numbers follows in which the information relevant to each number is given in the sequence : age (m.y.) ; points on isochron (WR = whole rock, L = leached or residual fraction, M = separated mineral, n.a. = information not available) ; rock body ; reference. All the listed ages were obtained by the Rb-Sr method.

1. $3\,125 \pm 366$; 7 WR ; older granite of Pilbara Block ; de Laeter and Blockley, 1972.
2. $2\,880 \pm 66$; 6 WR ; Copper Hills Porphyry ; de Laeter and Trendall, 1970.
3. $2\,670 \pm 95$; 6 WR ; younger (tin) granite of Pilbara Block ; de Laeter and Blockley, 1972.
4. 2 940 ; 1 M ; muscovite from basal Cliffs Springs Formation of Fortescue Group ; Compston and Arriens, 1968.
5. $2\,190 \pm 100$; n.a. ; interbedded layers of acid igneous rocks in Fortescue Group ; Compston and Arriens, 1968.
6. $2\,196 \pm 26$; 6 WR ; granophyre intruded along basal unconformity of Fortescue Group ; de Laeter and Trendall, 1971.
7. $1\,720 \pm 25$; 5 WR, 2 L ; porcelanite (tuff) of Joffre Member of Brockman Iron Formation in Hamersley Group ; Trendall and de Laeter, 1972.
8. 2 200 ; 4 WR ; marginally contaminated dolerite of Weeli Wolli Formation to give inherited depositional age of shale ; this paper.
9. $2\,000 \pm 100$; 48 WR ; Woongarra Volcanics ; Compston and Arriens, 1968.
10. 2 100 ; 3 WR ; central uncontaminated part of dolerite of Weeli Wolli Formation, thought to give age of intrusion ; this paper.
11. $1\,689 \pm 222$; 4 WR ; up-dating of some parts of dolerite of Weeli Wolli Formation ; this paper.
12. $2\,020 \pm 165$; n.a. ; layered acid igneous rocks interbedded in the Wyloo Group ; Compston and Arriens, 1968.
13. 1 850 ; 1 WR ; Wyloo Group tuffaceous siltstone ; Leggo and others, 1965.
14. 1 720 ; 2 WR, 2 M ; Boolaloo Granodiorite (intrudes Wyloo Group) ; Leggo and others, 1965.

The different forms of ornamentation in the central column distinguish different bodies of igneous rock which are clearly identified by the numbers. All sedimentary and metasedimentary rocks are left blank. In the left-hand column, which is a scale summary of the lithology of the Weeli Wolli Formation and the Woongarra Volcanics near Woongarra Pool (Trendall and Blockley, 1970) the ornamentation follows that of Figure 53, with the addition of v = fine-grained rhyolite or dacite, formerly believed to be extrusive, but now more likely to be intrusive ; solid black includes tuff as well as BIF and shale. See text for further discussion.

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THE AGE OF A GRANITE NEAR MOUNT CROFTON, PATERSON RANGE SHEET

by A. F. Trendall

ABSTRACT

Eight Rb-Sr isotopic analyses were carried out on whole-rock samples from a small granitic body that intrudes gently folded low-grade metasedimentary rocks, possibly correlative with the Bangemall Group, near Mount Crofton (21° 33′ S; 121° 27′ E). Seven analyses of six samples of coarse biotite granite, and one of a finer vein, define a 614 ± 42 m.y. isochron with $R_i = 0.709\,3 \pm 0.007\,3$. With the addition of data from the eighth sample, a cross-cutting low-strontium aplite with a much higher Rb-Sr ratio, the resultant isochron becomes 594 ± 2 m.y., with $R_i = 0.712\,2 \pm 0.002\,5$. This slight apparent difference may be genuine. The age of crystallization of the granite is in any case close to 600 m.y. This age, at about the Precambrian-Cambrian boundary, is consistent with it geological relationships. Unpublished data of Compston from two previous whole-rock analyses of granite unconformably overlain by Lower Ordovician sandstone at a depth of 2 015 m in a petroleum exploration well 240 km north-northwest of Mount Crofton lie on the same isochron; it seems likely that an extensive igneous province of this age developed along the western edge of the Canning Basin immediately before initial deposition. This may have a direct tectonic relationship with igneous and metamorphic activity in the south-western part of the Yilgarn Block.

INTRODUCTION

The most recent published account of the geology of the Paterson Range 1 : 250 000 Sheet area is that of Wells (1959). Although Blockley (1974) notes that much of the granite outcrop shown by Wells is in fact occupied by sedimentary rocks, granite does crop out east and southeast of Mount Crofton (21° 33′ S, 121° 27′ E). Coarse biotite granite is well exposed in several bare rounded hills rising a few tens of metres above the sandy plain over an area of about 40 km². Wells (1959, p. 5 and map) described this granite as cutting Lower Proterozoic rocks, which Blockley (1974) likens to the Bangemall Group.

In November, 1973, Newmont Pty. Ltd. supplied seven large unweathered samples from this granite for isotopic age determination. This paper reports Rb-Sr isotopic results from these samples, provides a brief description of the material, and discusses the geological significance of the results.

MATERIAL USED

Six of the seven samples received (30557-58-59-60-61-62) were collected from a low granite hill centred 1.5 km east of Mount Crofton. The sampling points form an irregular array with an average separation distance of about 30 m, and a maximum distance of 130 m. The location coordinates for the group are 21° 33′ S , 121° 58′ E. The seventh sample (30555-56) was taken from a separate hill, 6.5 km east-southeast of Mount Crofton, at 21° 35′ S , 122° 00′ 30″ E; it bears two numbers because the granite forming the bulk of the sample (30555) was cut by a vein 2 cm wide which was analysed separately (30556).

The granite in the vicinity of the sample locations is remarkably uniform in appearance. On broken surfaces vaguely defined elongate areas of rather patchily coloured pink to red feldspar up to 20 mm long are randomly arranged within an interstitial mixture of similar feldspar, equant grains of dark glassy quartz 2-5 mm across, and random black biotite flakes whose longest dimensions are of the same order. Although the feldspar areas give the rock a coarse appearance it is only rarely that a cleavage face of feldspar wider than 10 mm can be seen, and most feldspar cleavage faces on broken surfaces of the granite are less than 5 mm across. No macroscopically defined planar or linear direction, defined either by variations of mineral content or by mineral orientation, was observed; the rock appears quite massive and homogeneous.

The following generalised description of the petrography of the coarse granite applies to thin sections cut from samples 30555 and 30558-30562 inclusive.

Quartz and feldspar are the main constituents of the rock, and form approximately 30 and 60 per cent by volume respectively, with biotite and other constituents making up the remainder. The main feldspar is an alkali variety with highly irregular extinction, probably a cryptoperthite. The irregularity is expressed in a variety of ways ranging from vague general strain, through various microperthitic textures, to annealed crack networks of cataclastic appearance. Several optically distinct individuals up to 5 mm across make each of the feldspar areas macroscopically apparent, and it appears that these areas are relics of large early ternary feldspar phenocrysts which were extensively modified during cooling. Optically imperfect simple twinning is often present. Most individuals are cloudy with undetermined "dust", and this cloudiness usually has an irregular distribution which follows the irregularities of the extinction pattern. Much clearer subhedral oligoclase grains, up to 2 mm across but mostly much smaller, occur either singly or in aggregates, and may be enclosed within or marginal to the alkali feldspar. The oligoclase is distinguished by its strain-free extinction, lamellar twinning, and often by albite rims which are occasionally myrmekitic.

Quartz forms an irregular continuous mosaic of clear and intensely strained anhedral grains up to 5 mm across. Biotite forms subhedral flakes, scattered in clusters. It is conspicuously pleochroic, from pale straw to very dark brown. Chloritisation is rare, but thin goethitic veinlets in and around the biotite may reflect weathering. Very minor amounts of sphene, green amphibole, apatite, and opaque minerals are usually associated with the biotite.

The 2 cm thick vein of 30556 consists in thin section of separate grains, or clusters of grains, of all the minerals of the adjacent granite, up to 5 mm across, set in an even-grained polyhedral mosaic of quartz, albite, and microcline, in which most grains are between 0.05 and 0.1 mm in diameter. The edges are quite sharply defined, and the marginal textures imply that the vein originated by fracturing and small-scale stoping from the granite constituents.

The aplite sample received, 30557, consisted of a compact pale pinkish brown sugary-textured rock in which more coarsely crystalline bands show feldspar cleavage faces up to about 4 mm across. In thin section the finer parts closely resemble the matrix part of the vein 30556. An even-grained polyhedral mosaic of average grain diameter of about 0.1 mm is composed of quartz, albite, and an alkali feldspar which resembles a cryptoperthite rather than microcline. Fluorite is also present. In one part of the thin section these same constituents form a coarser aggregate resembling the granite, except that a bladed texture and an abundance of vermiform quartz in both feldspars combine to give a pegmatoid appearance. This is consistent with the field occurrence of the aplite. Subsequent observation showed that the sample was collected from a vein about 60 cm thick striking approximately north and dipping westward at about 15 degrees. While the lower part of the vein is of aplitic appearance the uppermost 5-10 cm consists of a coarse pegmatoid edge in which each crystal is several centimetres across. The vein thus resembles closely the layered aplite dykes from the Yilgarn Block described by Doepel (1970).

EXPERIMENTAL PROCEDURES

All instruments and methods used are the same as those described by de Laeter and others (1974), except as noted below.

The Sr^{87}/Sr^{86} values of Table 23 were normalised to a Sr^{88}/Sr^{86} value of 8.365 to give a mean value of 0.710 3 for replicate analyses of NBS 987 standard. The resultant age difference of about 0.13 per cent is not large enough to affect comparison with other ages reported from the Western Australian Institute of Technology laboratory where the more usual 8.375 2 normalising value has now been adopted. Most Sr^{87}/Sr^{86} values of Table 23 result from three runs each made up of ten sweeps; errors quoted for these values relate to reproducibility between runs, and do not derive from within-run variation.

For accurate X.R.F.S. determination of the Rb/Sr ratio a pre-set count of 2×10^5 was used for each peak and two associated background values, and for all samples except 30557 the peak-to-background ratio was such that better than ± 1 per cent precision was obtained. For 30557 the low Sr peak necessitated a total of five passes in each of which the Sr values (peak and two backgrounds) were measured twice.

RESULTS

The measured Rb/Sr (X.R.F.S.) and Sr^{87}/Sr^{86} ratios appear in Table 23, together with the calculated Rb^{87}/Sr^{86} values. All errors are at the 95 per cent confidence level. The data are also plotted in Figure 59 together with a theoretical 600 m.y. isochron with an R_i of 0.70, as an aid to visual assessment.

TABLE 24. COMPUTED ISOCHRONS FROM DIFFERENT COMBINATIONS OF ANALYTICAL RESULTS

Combination	Age (m.y.)	R_i (Sr^{87}/Sr^{86})	Model*
1	614 ± 47	0·7093 ± 0·0073	3
2	611 ± 24	0·7105 ± 0·0037	4
3	594 ± 2	0·7122 ± 0·0025	3
4	594 ± 1	0·7131 ± 0·0016	3

* Except for Combination 4, this column shows the preferred Model of the programme of McIntyre and others (1966). In summary, a programme choice of Model 3 means that a smaller increase to the assigned experimental errors is involved by an assumption that departure from a perfect fit is due to variations of R_i between coeval samples than by an assumption that it is due to variations in age between samples of the same R_i (Model 2). Model 4 is a compromise between Models 2 and 3. For Combination 4 the programme found no preference between a Model 2 and a Model 3 isochron, and the Model 3 result is here inserted for ease of comparison with Combination 3.

Combination 3 includes all the analyses; that is, it represents Combination 1 with the addition of the aplite 30557. Combination 4 includes all the analyses except the visually anomalous 30561; it represents Combination 2 plus the aplite 30557.

INTERPRETATION OF RESULTS

Age of the granite

From Table 23 it is clear that the 2 cm thick cross-cutting vein 30556 does not differ significantly in its Rb and Sr data from its enclosing granite 30555, whereas the thicker cross-cutting aplite 30557 differs substantially. The geological and chronological relationship between granite and aplite are critical to the interpretation of the results. If, for reasons of geological judgement, it is postulated that the emplacement of both the parent granite body and the aplite (30557) took place over a geologically very short interval (less than a million years) then the figure of 594 m.y. of Table 24 may be accepted as a point more closely fixed within the wider age ranges of Combinations 1 and 2, and thus as a highly accurate date for this essentially single event. But the data presented do not invalidate the alternative hypothesis that the main granite was emplaced at about 612 m.y., about the mean of Combinations 1 and 2, and that the aplite was intruded substantially later. In this latter case the pooling of 30557 with the granite analyses would not be valid

TABLE 23. ANALYTICAL DATA FOR EIGHT WHOLE-ROCK SAMPLES FROM THE GRANITE NEAR MOUNT CROFTON

Sample No.	Rb (ppm)	Sr (ppm)	Rb/Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
30560	247	108	2·27 ± 0·02	6·59 ± 0·07	0·766 6 ± 0·001 3
30559	239	99	2·34 ± 0·02	6·80 ± 0·07	0·767 4 ± 0·002 7
30558	295	95	3·10 ± 0·03	9·02 ± 0·09	0·789 1 ± 0·000 4
30562	279	86	3·15 ± 0·03	9·17 ± 0·09	0·788 9 ± 0·000 2
30561	276	80	3·35 ± 0·03	9·74 ± 0·1	0·788 1 ± 0·001 7
30555	276	50	5·39 ± 0·05	15·8 ± 0·2	0·844 3 ± 0·000 6
30556	276	50	5·63 ± 0·06	16·5 ± 0·2	0·851 8 ± 0·001 1
30557	414	9	63·4 ± 1·8	215 ± 6	2·495 ± 0·003

Note: The Rb and Sr concentrations are preliminary results from loose powder samples, and have an accuracy of about ± 5 per cent. The Rb/Sr ratios are from accurate measurements of these ratios on compressed pellets; they do not correspond exactly with the ratios that would be derived from the separate Rb and Sr values shown.

The ages and intial ratios computed using the programme of McIntyre and others (1966) for various combinations of data appear in Table 24. Combination 1 of that Table includes all the analyses except 30557: that is, it includes all the massive granite samples and the thin vein 30556, but excludes the cross-cutting aplite 30557. Combination 2 is similar, but excludes also 30561 purely on the grounds that, from the plot of Figure 59 and from the computed results of Combination 1, it appears to depart farther than the remaining samples from a more closely colinear set of points; such anomalous departures below Rb-Sr isochrons are commonly and credibly attributed to weathering effects, but in this instance the granite of 30561 shows neither more nor less evidence of these than other samples. The result for Combination 2 confirms this impression, but does not greatly affect the preferred age.

for the computation of an isochron and the 594 m.y. so derived would be meaningless, since it would become necessary to assume an R_i to derive an age from the single analysis of 30557. If the aplitic liquid differentiated from the crystallizing granite magma at 612 m.y. with its present ratio of Rb to common Sr, and with its Sr^{87}/Sr^{86} equal to that of the granite (as would be expected), then the analytical data provide no criterion for the selection of an R_i related to the age of aplite intrusion. Provided that the aplitic liquid remained chemically closed and undifferentiated after its formation, the isochron hypothesis does not distinguish between its intrusion and crystallization at any time between 612 m.y. and the present; in fact, under the postulated conditions, the aplite analysis should reinforce the 612 m.y. isochron, whatever its time of emplacement. It follows that any interpretation involving a real younger age for the aplite must suppose that the aplite acquired

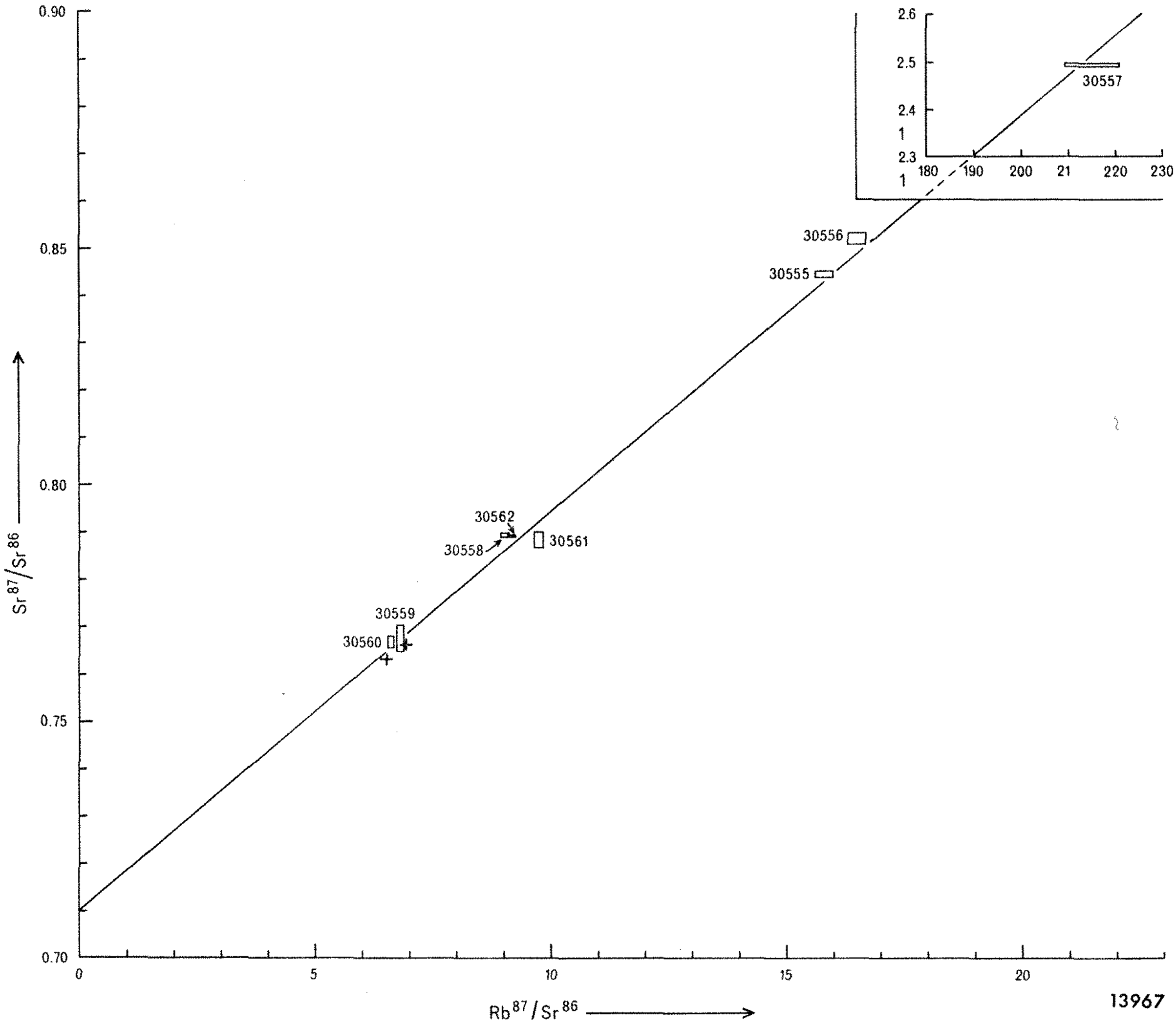

Figure 59. Isochron diagram including eight samples from the granite near Mount Crofton (rectangles with sides proportional to analytical error) and two granite samples from Samphire Marsh No.1 (crosses: analyses by Compston). See Tables 24 and 25 for data. *The line plotted is a reference isochron representing an age of 600 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0·71.*

its chemical identity, and in particular its high Rb/Sr ratio, significantly later than the emplacement of the analysed granite which it cuts. It is difficult in this case to suggest any mechanism not involving differentiation from granite close to the same, later, crystallization age. It is possible that such a granite existed (and exists) at some lower level from which the aplite ascended transgressively, and that the granite sampled at the level of the present land surface represents an earlier product of a "front" of crystallization which descended through the (unknown) vertical extent of the magma over a short period. For an estimate of the duration of this period let:

A^A = age of aplite differentiation, intrusion, and crystallization

R_i^A = initial Sr^{87}/Sr^{86} ratio of the aplite

t = interval between the crystallization of the upper (analysed) part of the granite, and that of the lower part from which the aplite differentiated

$\frac{Rb^{87}}{Sr^{86}}$ = the mean Rb^{87}/Sr^{86} ratio of the entire granite body

λ = decay constant of Rb^{87}

and accept the following data and approximations from Tables 23 and 24:

Age of crystallization of analysed part of granite = 612 m.y.

Initial Sr^{87}/Sr^{86} (at 612 m.y.) of granite = 0.71

Present Sr^{87}/Sr^{86} ratio of aplite (30557) = 2.495

Present Rb^{87}/Sr^{86} of aplite = 215

Then $R_i^A = 0.71 + \frac{Rb^{87}}{Sr^{86}} \lambda t$ .... (1)

and also $t = 612 - A^A$

$$= 612 - \frac{\mathrm{Ln}\left\{\frac{2.495 - R_i^A}{215} + 1\right\}}{\lambda} \quad (2)$$

If, for present purposes, Rb^{87}/Sr^{86} be taken as the mean of all samples of Table 23 except 30557 (10.5), and also as time-invariant, then solution of equations 1 and 2 gives values for t of 18 m.y. and R_i^A = 0.7126, so that A^A = 594 m.y. It is thus not surprising, in this model, that the aplite sample regresses convincingly with the granite samples, in spite of the invalidity of the process, since its real but different age lies within the uncertainty limits of the granite isochron.

In summary, the data presented in Tables 23 and 24 are consistent with either of two separate geological models. In the first of these the granite and the aplite are both 594 m.y. old; in the second the granite is about 612 m.y. old and the aplite about 594 m.y. old. Additional data from separated minerals may discriminate between these two models; meanwhile the likely age of the granite from whole-rock analyses is best expressed as "about 600 m.y".

Origin of the granite

The age and initial Sr^{87}/Sr^{86} of the granite, accepted for the purpose of further discussion as 600 m.y. and 0.71 respectively, together indicate, firstly, that the granite was not emplaced as a direct isochemical mantle differentiate, and secondly, that if the whole of the granite is material with a prior crustal history then that history was quite short. If 10.5 is again accepted as a mean Rb^{87}/Sr^{86} value for the whole granite, then an interval of the order of only 30-60 m.y. is derived for wide assumed limits of 0.702-0.706 for possible mantle Sr^{87}/Sr^{86} at about that time (Faure and Powell, 1972, p. 132).

An isochemical anatectic derivation from an underlying eastward extension of the Archaean Pilbara Block cannot be invoked for this granite; neither can such a derivation be convincingly contrived by reasonable models involving open chemistry. An anatectic origin from lower levels of the adjacent metasediments is also excluded if:

(1) melting is envisaged as isochemical as far as Rb and Sr are concerned, and

(2) the sediments are taken to have the same age of the Bangemall Group, and this is accepted as 1 000 m.y. (Compston and Arriens, 1968; but see also Jackson, 1973), and

(3) the sediments were in isotopic equilibrium with sea water at that time, and this is accepted to have had an Sr^{87}/Sr^{86} ratio of 0.708 3 (Faure and Powell, 1972, p. 134).

Although all these assumptions are reasonable, some may be invalid.

The simplest and most credible genetic model which accommodates the reported data is that the granite magma differentiated from a mantle source with Sr^{87}/Sr^{86} of about 0.704, no more than about 20 m.y. before its emplacement. In addition, the elevation of its initial Sr^{87}/Sr^{86} prior to crystallization was achieved jointly by internal radiogenic increase of Sr^{87} and partly by assimilation of older crustal material of high Sr^{87}/Sr^{86} ratio during the course of its ascent.

REGIONAL GEOLOGICAL SIGNIFICANCE

The granite age reported here indicates igneous activity at the western margin of the Phanerozoic Canning Basin a comparatively short time before its initiation during the Ordovician. In the Paterson Range area no sedimentary rocks older than Permian overlie granite unconformably. However, granite encountered at a depth of 2 015 m in a stratigraphic petroleum exploration well, Samphire Marsh No. 1 (19° 31′ 08″ S, 121° 10′51″ E), 240 km north-northwest of Mount Crofton is overlain unconformably by Lower Ordovician sandstone (Johnstone, 1961). Two whole-rock Rb-Sr analyses of this granite were carried out by Compston, and the results were reported, in a personal communication to Johnstone (1961) to indicate "an age not older than 700 million years and not younger than 500 million years".

Although Compston's result was published by Johnstone (1961, footnote p. 8), it was not included in a subsequent compilation of geochronological data by White (1962), a review of Precambrian rocks encountered in deep Phanerozoic basin drilling by Peers and Trendall (1968), or a review of Australian Precambrian geochronology by Compston and Arriens (1968); Peers and Trendall (1968) even suggested the desirability of such work being done. It seems possible that the results created little interest partly because they did not relate clearly to other geochronological data available; and partly because a K-Ar age of 580 m.y. from the same granite, reported in the same footnote by Johnstone (1961), was mentioned both by White (1962) and by Peers and Trendall (1968) and was accepted as the reflection of Ordovician weathering. It seems to have become tacitly accepted that Compston's Rb-Sr results were also probably related to weathering, rather than that they represented a true age for the granite.

TABLE 25. ANALYTICAL DATA FROM CORE 12, SAMPHIRE MARSH No. 1*

Sample	Rb (ppm)	common Sr (ppm)	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
A	197	87·6	6·51	0·763
B	202	84·7	6·91	0·766

* Data of W. Compston, A.N.U. No. G.A. 198.

The analytical results obtained by Compston appear in Table 25, and are plotted in Figure 59, from which it is apparent that their regression with the Mount Crofton samples would have little effect on the computed age. The data of Figure 59 could be explained as the result of weathering only if radiogenic strontium had been completely extracted from these rocks 600 m.y. ago; the samples appear completely fresh, and so far as is known weathering is an ineffective mechanism for the up-dating of granite (Worden and Compston, 1973). A re-examination of the granite from Samphire Marsh No. 1 shows it to be closely similar to that at Mount Crofton in both macroscopic and microscopic appearance, although a highly altered amphibole is more abundant than biotite in the thin section used by Peers and Trendall (1968). It is concluded that co-genetic granite magma may have been generated during a late Precambrian or early Cambrian period of igneous activity over a wide area along the western side of the Canning Basin.

There is insufficient evidence to assess the likely thickness of overlying cover when these granites were intruded, but it seems unlikely that this could have been less than a kilometre. Vertical uplift and erosion of at least this magnitude is therefore indicated during the 120 m.y. between intrusion and the Early Ordovician. Possibly the eroded material was transported to the (present) southeast, where continuous deposition through uppermost Precambrian into the Cambrian took place in the subsiding Amadeus Basin (Wells and others, 1970).

It is not possible to allocate an exact stratigraphic age to the granite at Mount Crofton at present. Firstly, because separate mineral analyses are needed to reduce the limits of uncertainty; secondly, because there is no international agreement on a biostratigraphic definition of the base of the Cambrian (Daily, 1972); and thirdly, because isotopic dating of any lowest Cambrian strata leaves substantial doubt concerning the possible error in the approximate 600 m.y. age currently accepted for the base (Lambert, 1971).

The igneous activity reported here at about 600 m.y. at the northeast extremity of the Western Australia Precambrian Shield, may well correspond in regional tectonic terms with the long-known up-dating and metamorphism in the southwestern part. Extensive areas of Archaean rocks along the western margin of the Yilgarn Block had their radiogenic strontium redistributed between their constituent minerals at about this time, and granulites of the Leeuwin Block register a 670 m.y. metamorphism (Compston and Arriens, 1968). A metamorphic event at about 600 m.y. has also been detected by P. J. Leggo in central Australia (Harding, 1966). It may be that igneous and metamorphic events of about this age are more widely distributed along the borders of the Phanerozoic basins than has so far been appreciated, and that they may provide a clue to the geological events which preceded the initiation of the basins. This is an area of ignorance to which Peers and Trendall (1968) drew attention.

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DEVONIAN SPORES FROM THE GOGO FORMATION, CANNING BASIN

by K. Grey

ABSTRACT

Cuttings from Noonkanbah No. 1 borehole, drilled in the Gogo Formation of the Canning Basin, yielded spores of a late Middle to early Late Devonian age. Identifications to generic level are listed, and a comparison made with Devonian assemblages known from other areas in Australia.

INTRODUCTION.

The Gogo Formation was described by Playford and Lowry (1966) as an inter-reef deposit which inter-tongues with the fore-reef facies repesented by the Sadler Limestone. It comprises a sequence of shale and siltstone with thin beds of limestone and abundant calcareous nodules. Exposures of the Gogo Formation are poor, but it is present in the Bugle Gap, Emanuel Range and Pillara Range areas. Drilling by the B.M.R. West Canning Basin Field Party in 1972 penetrated sediments of this formation in Nookanbah No. 1 borehole. Cuttings from this borehole have yielded a diverse microflora containing several new species. This is the first published record of spores from the Gogo Formation.

LOCATION AND BOREHOLE DATA

The B.M.R. Noonkanbah No. 1 borehole was sited near Sadler Ridge and Longs Well Creek; Noonkanbah 1 : 250 000 sheet, SE/51-12; 18° 34′ 13″ S, 125° 58′ 16″ E (Fig. 60). The hole reached a total depth of 155.4 m, and five cores were cut at approximately 30 m intervals. Cuttings and one quarter of all cores are stored at the Geological Survey of Western Australia. The hole was drilled entirely within the Gogo Formation and penetrated calcareous mudstone and interlaminated limestone of the inter-reef sediments. Further details are given by Druce and Radke (1973).

PREVIOUS PALAEONTOLOGICAL STUDIES

A diverse fauna has been described from the Gogo Formation. This includes ammonoids (Glenister, 1958), conodonts (Glenister and Klapper, 1966; Seddon, 1970), brachiopods (Veevers, 1959), and radiolaria, siliceous sponge spicules and ostracods (Glenister and Crespin, 1959). Crustacean and fish remains are also common (Playford and Lowry, 1966; Brunton and others, 1969; Rolfe, 1966). Of these, ammonoids, conodonts and crustaceans have proved most useful for age determination, and they indicate an early Late Devonian age (Frasnian do 1 α to do 1 β). Roberts and others (1972) stated that there was no palaeontological evidence to support an extension of the Gogo Formation into the Givetian, although both Playford and Lowry (1966), and Glenister and Klapper (1966), had considered this a possibility on stratigraphic grounds.

PALYNOLOGY

Cuttings from depths of 33 m, 96 m, 130 m and 147 m were examined for palynomorphs. Specimens from 33 m and 96 m showed a poor degree of preservation. Spores from 130 m were slightly less corroded and those from 147 m were fairly well preserved. All four samples contained similar palynormorphs; the absence of certain forms in the shallower samples is probably a result of weathering. Investigation of the microflora has so far been of a preliminary nature, and no attempt is made in this report to deal with the

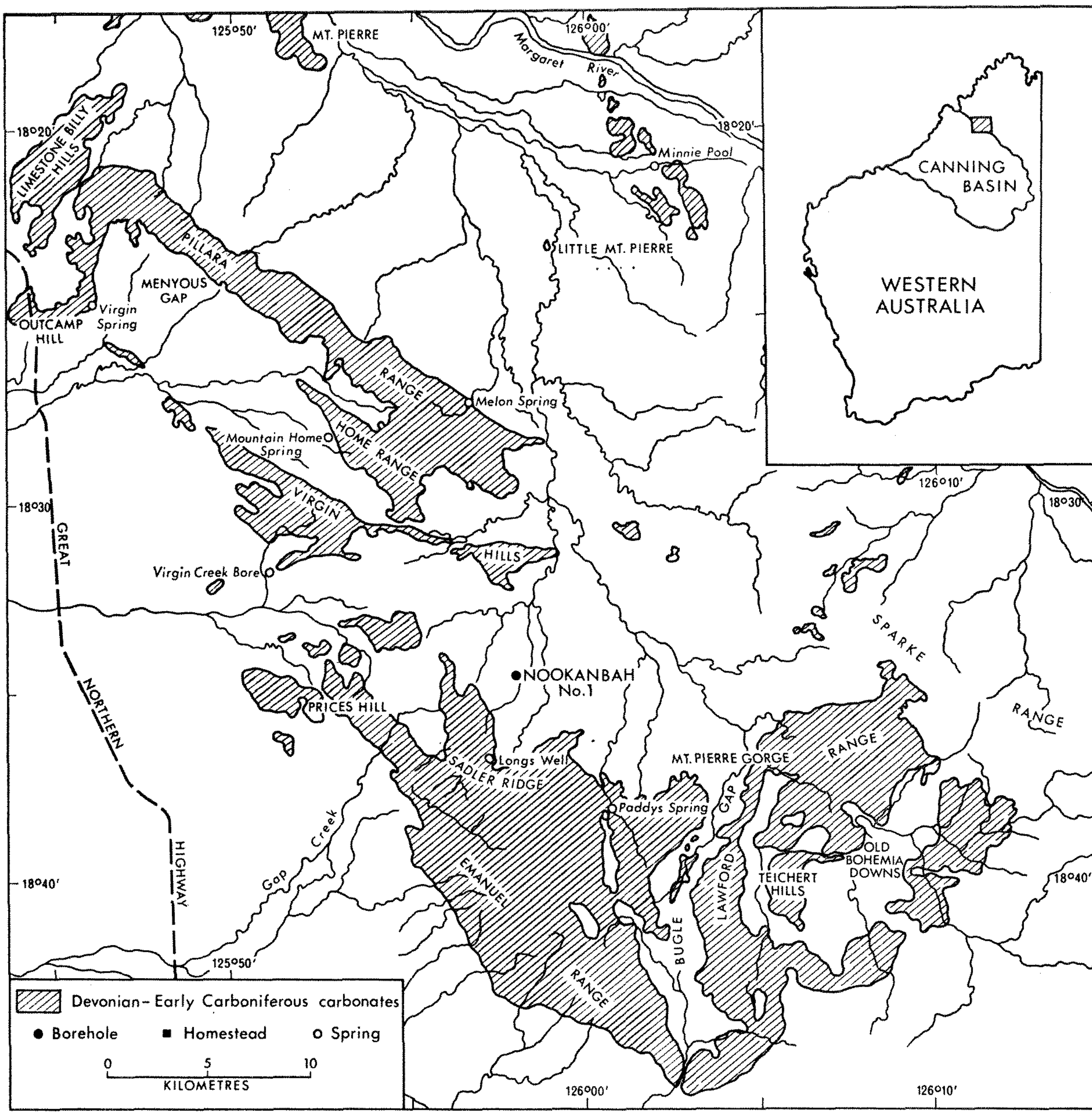

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Figure 60. Emanuel Range area, showing location of Noonkanbah No. 1 borehole.

detailed systematics of the assemblage. The list of genera given below (Table 26) is incomplete, as some specimens still have to be identified. Some of the more important forms are shown in Figure 61.

TABLE 26. DISTRIBUTION OF SPORE GENERA NOONKANBAH No. 1 BOREHOLE

Genera	Depth in metres 147 m *F8481	130 m *F8480	96 m *F8479	33 m *F8478
Acinosporites sp.	x			x
Ancyrospora sp. A	x	x	x	x
Ancyrospora spp.	x			x
Apiculatasporites sp.	x			x
Apiculiretusispora sp.	x			
?*Archaeoperrisaccus* sp.	x			
Auroraspora sp.	x	x		x
Calamospora spp.	x	x	x	x
Convolutispora sp.	x	x	x	x
Cyclogranisporites sp.	x			x
Cymbosporites sp.	x	x	x	x
Dibolisporites sp.	x	x		x
?*Grandispora* sp.	x			x
Geminospora sp.	x			
Hymenozonotriletes sp.	x			
Hystricosporites sp.	x	x		
Latosporites sp.	x			
Leiotriletes spp.	x			
Lophozonotriletes sp.	x		x	x
?*Perotriletes* sp.	x			x
Punctatisporites sp.	x			
Reticulatisporites sp.	x			
Retusotriletes spp.	x			
Rhabdosporites sp.	x	x		x
Samarisporites spp.	x	x	x	x
Stenozonotriletes sp.	x	x		
Verrucosisporites sp.	x	x		x

* G.S.W.A. registered fossil number. x = present.

The assemblage is characterized by the presence of large camerate spores, and by forms with either grapnel-tipped spines or biform ornament. Spores with radial ribbing, usually common in Devonian assemblages, were not observed. *Cymbosporites* sp. is abundant in all four samples and shows a wide variation in ornament. *Ancyrospora* and *Samarisporites* are common throughout the assemblage, but are more abundant in the two lower samples. Specimens of *Verrucosisporites* and *Convolutispora* are present in fairly large numbers in the sample from 147 m, but are less frequent in the other samples. *Dibolisporites*, a significant form in three of the samples, was not observed in the sample from 96 m, although it may be present as a corroded form.

AGE OF THE ASSEMBLAGE

Only generalized assertions can be made about the age of the assemblage at this time. Examination of core material, and a detailed study of the systematics will probably enable a more precise dating to be made. The general aspect of the microflora suggests a Middle to Late Devonian age. Grapnel-tipped ornament is a common feature of Middle Devonian spores, and is less frequent in the Late Devonian. Other groups, such as the verrucate spores, range into the Carboniferous. It is therefore very difficult to be precise with regard to age, using only generic information. *Ancyrospora* sp. A shows close affinities to,

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and is probably conspecific with *Ancyrospora parva* de Jersey which is regarded as ranging through the Givetian and the Frasnian (de Jersey, 1966). It thus seems likely that the assemblage from the Gogo Formation is of Givetian or Frasnian age.

COMPARISON WITH OTHER DEVONIAN ASSEMBLAGES FROM AUSTRALIA

Very few papers dealing with Devonian assemblages from Australia have been published. Balme and Hassell (1962) described Famennian spores from the Fairfield Formation of the Canning Basin. Several genera are common to both the Fairfield Formation and to the older Gogo Formation although differences occur at specific level. This similarity suggests that a diverse, but evolving flora was well established in the Canning Basin during Middle to Late Devonian times. The single Frasnian assemblage from the Sadler Limestone examined by Balme and Hassell contained a restricted microflora composed of spores of the *Punctatisporites* type and is probably facies controlled.

Balme (1960) described two Frasnian, possibly Givetian, assemblages from the Gneudna Formation of the Carnarvon Basin. The Gneudna Formation occupies a similar stratigraphic position to the Gogo Formation, but the spore assemblages from the two formations show surprisingly little similarity. The Gneudna assemblages, unlike the assemblage from the Gogo Formation, are poor in species. The specimens of *Radiaspora* and *Chomotriletes,* figured by Balme, are absent from the Gogo assemblage. *Geminospora lemurata* Balme, the most abundant species in the Gneudna assemblages, was not observed in material from the Gogo Formation. Balme commented on the dissimilarity between the assemblages from the Gneudna Formation and those from the Fairfield Formation (Balme and Hassell, 1962), and suggested that the marked diffence between the two had a genuine biostratigraphical significance. In view of the wide differences between the Gneudna and the Gogo microfloras, it now seems possible that a biogeographical factor may have caused some of the differences between the floras of the two basins during Middle and Late Devonian times.

Middle Devonian assemblages from the Etonvale Formation in the Adavale Basin of Queensland have been described by de Jersey (1966). He compared the Adavale material with the assemblages described by Balme (1960), Balme and Hassell (1962) and the then unpublished work of Hodgson on the Amadeus Basin. He concluded that the Adavale assemblages were older than those from Western Australia and the Amadeus Basin. The material from the Gogo Formation has several genera in common with the Adavale assemblages, particularly in the presence of *Ancyrospora* sp. A, which is probably equivalent to *Ancyrospora parva* de Jersey. *Geminospora lemurata,* occurring only in the higher part of the Adavale assemblages, was not recorded from the Gogo Formation. This suggests that a detailed comparison of species present may reveal a correlation between the Gogo Formation and part of the Etonvale Formation of the Adavale Basin.

Hodgson (1968) described an assemblage from the Pertnjara Formation of the Amadeus Basin of late Middle or early Late Devonian age. This assemblage also contains the genus *Ancyrospora.* Hodgson referred some of his specimens to *Ancyrospora* cf. *A. simplex* Guennel, but de Jersey (1966) regarded Hodgson's specimens as conspecific with *A. parva.* The samples from the Pertnjara Formation of the Amadeus Basin contain *Geminospora lemurata* and *Radiaspora darensis,* neither of which has been observed in the Gogo assemblage.

CONCLUSIONS

Until further work is done on the Gogo microfloras comparison with other Australian assemblages remains uncertain, but would tend to suggest that the assemblage is slightly older than those from the Gneudna Formation and Pertnjara Formation and younger than assemblages from the lower part of the Etonvale Formation in the Adavale Basin. A correlation between the Gogo assemblage and the upper part of the Etonvale Formation may be possible after detailed identification of core material. Comparison with overseas assemblages has also been deferred until more information has been obtained on the species present in the Gogo Formation.

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FIGURE 61 (opposite)

Photomicrographs of Devonian spores.

Magnification of all specimens x 500. G.S.W.A. Fossil registration numbers follow figure descriptions. Coordinates on Leitz Ortholux microscope number 587962 are given in brackets.

a. *Acinosporites* sp., F8481/1 (30·3 x 96·9)
b. *Ancyrospora* sp. A., F8481/1 (31·0 x 103·2)
c. *Ancyrospora* sp., F8481/1 (37·1 x 100·9)
d. *Auroraspora* sp., F8481/1 (39·4 x 111·9)
e. *Convolutispora* sp., F8481/1 (42·3 x 110·8)
f. *Cyclogranisporites* sp., F8481/1 (35·2 x 110·1)
g. *Cymbosporites* sp., F8481/1 (34·3 x 110·9)
h. *Dibolisporites* sp., F8481/1 (32·3 x 110·0)
i. *Hystricosporites* sp., F8481/2 (34·7 x 109·3)
j. *Latosporites* sp., F8481/1 (33·5 x 106·0)
k. *Lophozonotriletes* sp., F8481/1 (39·4 x 106·0)
l. *Retusotriletes* sp., F8481/2 (28·8 x 102·5)
m. *Rhabdosporites* sp., F8481/1 (33·7 x 110·0)
n. *Stenozonotriletes* sp., F8481/1 (43·2 x 98·4)
o. *Verrucosisporites* sp., F8481/1 (43·3 x 108·8)
p. *Samarisporites* sp., F8481/1 (35·2 x 100·7) proximal view
q. *Samarisporites* sp., F8481/1 (35·2 x 100·7) distal view

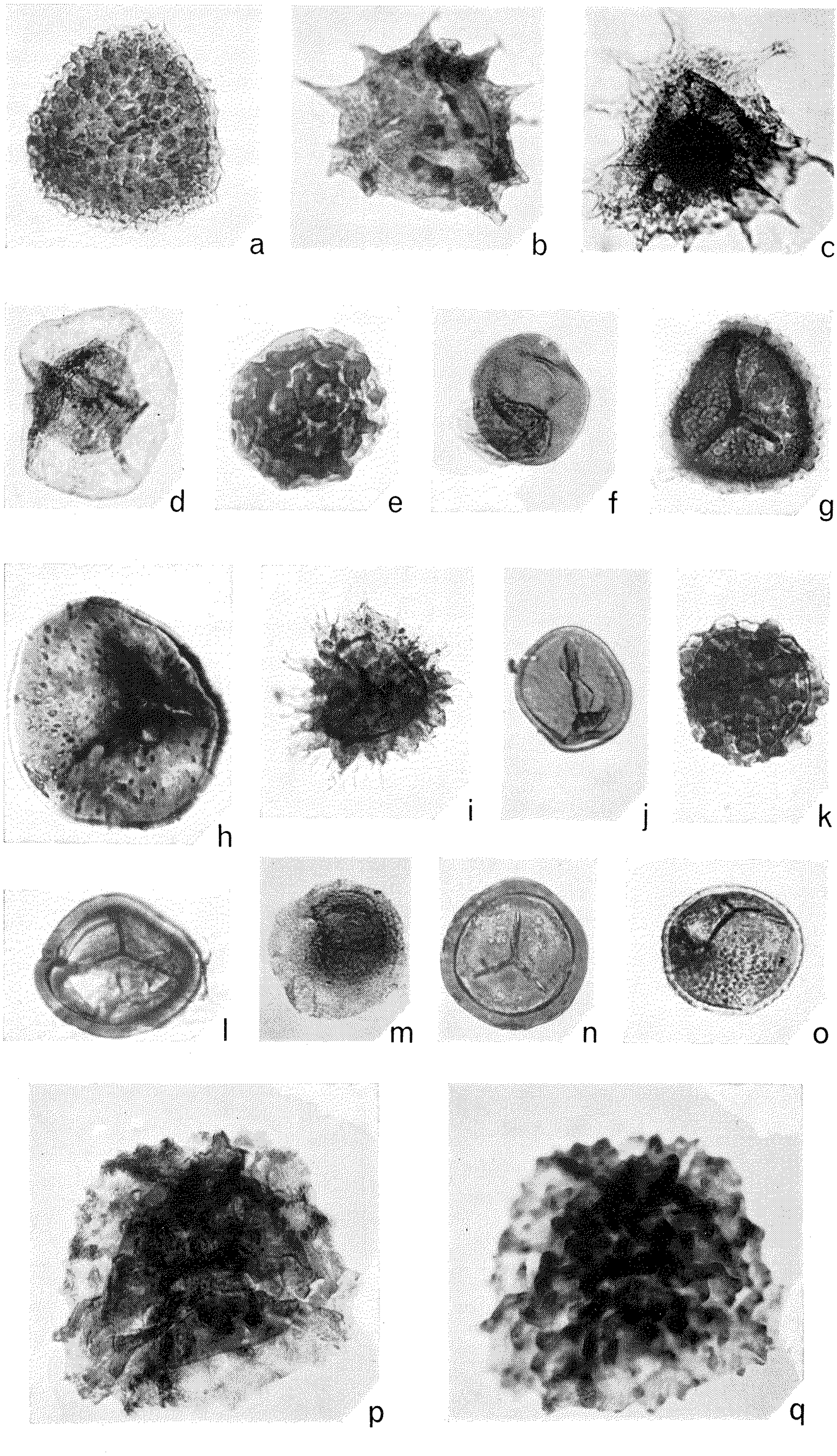

Figure 61.

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STRATIGRAPHIC PALYNOLGY OF THE WATHEROO LINE BOREHOLES, PERTH BASIN

by J. Backhouse

ABSTRACT

Four biostratigraphic zones are recognized in the Upper Jurassic and Lower Cretaceous of the Yarragadee Formation in the Watheroo Line boreholes in the Perth Basin, some 210 km north of Perth, Western Australia. These are in ascending order, the *Dampieri, Baculatisporites, Cicatricosisporites* and *Concavus* Zones. The zonation is compared with the zonations of Balme (1964) and Ingram (1967a), and also with zonations proposed in Eastern Australia.

INTRODUCTION

The Watheroo Line boreholes (referred to as W.L. boreholes in this report) are located between Watheroo and Jurien Bay in the Perth Basin, approximately 210 km north of Perth. Drilling started in 1967 and by 1968 boreholes W.L. 1 to W.L. 4 and the Agaton boreholes 7 and 19 were completed. Drilling recommenced in 1971 and by the end of 1972 W.L. 5 to W.L. 12 had been drilled (Fig. 62).

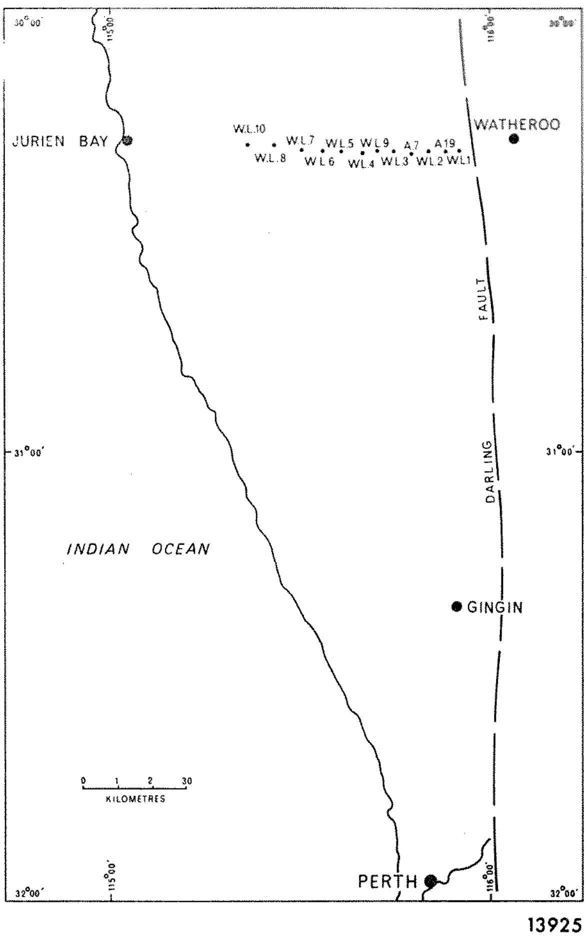


Figure 62. Location of Watheroo Line boreholes.

This report is concerned with the palynology of samples taken in the Yarragadee Formation in boreholes W.L. 1 to W.L. 10 and Agaton 7 and 19, as shown in Figure 63. The Yarragadee Formation was not encountered in the boreholes W.L. 11 and W.L. 12 which intersected Lower Jurassic and Triassic sediments respectively. Very poor assemblages of spores and pollen were obtained after preparing samples from W.L. 8 and results from this borehole are excluded.

Samples were taken from conventional cores except those from W.L. 7, 8 and 10 which were from sidewall cores.

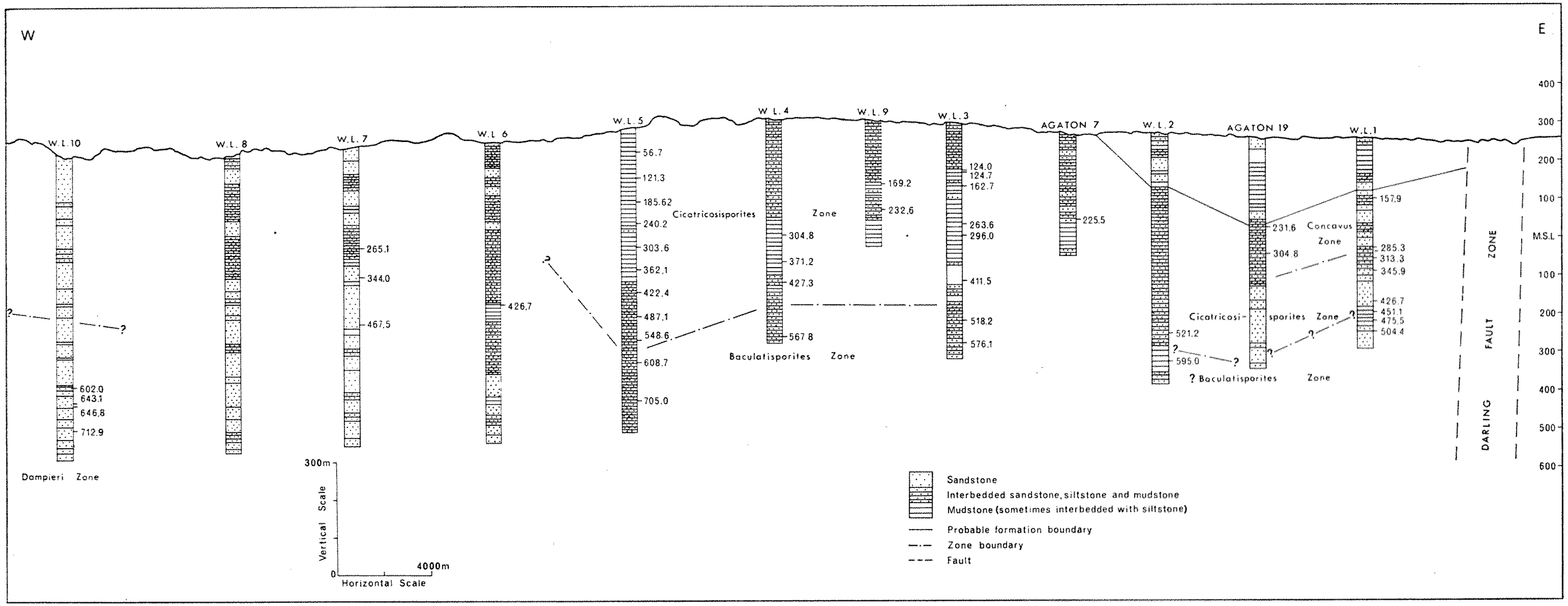
All samples were originally prepared by a procedure which involved maceration in Schultze solution. Later the samples were processed again by a method which did not use a strong oxidizing agent, although some samples were treated with concentrated nitric acid for up to ten minutes. It was noticed that the number of *Baculatisporites* spp. was much higher in preparations where Schultze solution was not used. It was concluded that Schultze solution selectively destroys these forms and this results in a biased spore count. The data given in Table 27 are from preparations made without using Schultze solution.

Data for two samples prepared using Schultze solution are included in Table 27 for comparison.

PREVIOUS WORK

In 1957 Balme subdivided the Jurassic and Lower Cretaceous of Western Australia into broad zones which he called Microfloras I, IIa and IIb. In 1969 he renamed the microfloras after the most characteristic component of each assemblage. Microflora IIa was renamed the *Dampieri* Assemblage and Microflora IIb was called the *Microcachrydites* Assemblage.

Ingram (1967a) recognized three zones in the Yarragadee Formation in the Gingin Brook boreholes, which he named Zones A, B and C.



13926

Figure 63. Palynological correlation of Watheroo Line boreholes.

TABLE 27. DISTRIBUTION OF PALYNOMORPHS IN SAMPLES FROM WATHEROO LINE BOREHOLES 1 TO 10 AND AGATON 7 AND 19

PALYNOMORPHS	W.L.10				W.L.7			W.L.6	W.L.5											W.L.4				W.L.9		W.L.3									A.7	W.L.2		A.19		W.L.1								
	712.9	646.8	643.1	602.0	467.5	344.0	265.1	426.7	705.0	608.7	548.6	487.1	422.4	362.1	303.6	240.2	185.6	121.3	56.7	567.8	427.3	371.2	304.8	232.6	169.2	576.1	518.2	411.5	296.0	263.6	162.7	124.7	124.0	124.0 *	225.6	595.0	521.2	304.8	231.6	504.4	475.5	475.5 *	451.1	426.7	345.9	313.3	285.3	157.9
Aequitriradites acusus									1					1			2									4															1							
A. hispidus								p				1		9	3	1	3		3		2					5	1				1				1	1					4			1				
A. sp. cf. *A. verrucosus*																	1			1						2		3			2									1	3							
Araucariacites australis	94	88	65	74	7	12	11	13	21	16	21	27	34	26	17	15	14	8	8	13	17	10	17	2	7	27	16	23	21	3	3	7	9	5	16	10	13	14	10	11	6	19	17	24	32	20	23	16
Baculatisporites comaumensis	10	12	4	4	3	36	39	2	41	53	53	87	77	62	25	71	62	37	96	68	69	31	37	11	40	95	43	74	65	30	64	21	31		20	19	66	28	25	80	87	5	24	51	19	75	8	5
Ceratosporites equalis						1	10	6	5	2	2					3	4		2	2			1	2				4	2			p					1		6	2	2					1	1	
Cicatricosisporites australiensis													p		p						1		1		p			p	p		1						p							1				p
C. sp. cf. *C. ludbrooki*											p														1										1		p									p		
Classopollis classoides	10	9	18	20	1	4	4	7	1	2	2	3	2	1	4			1	1		1				1	1		1		3	2					1	1	31	41	1	3	3	21	1	54	10	13	27
Clavatipollenites hughesii											p																																					
Concavisporites infirmus																		2	1	1												1						p				1					p	1
C. jurienensis								1				1		3																2		5	p	3	1				1	p	1	1	1	1		p	p	
Contignisporites cooksonii					2				7			3	1	3	5	3		1	2	2	2	2	1		1	2	3	7	8	2	1	2	2	1	1	2	4			2	6	4	5	2			p	
C. multimuratus								2	8	1	3	3	5	4	3	1	2	1			1	3	1	3	1	3	1		6		1	p	2		4	2	2	1		1	3		2	3		6	p	
Cooksonites sp. cf. *C. variabilis*										1						1									1	1																						1
Coronatispora perforata								p	1						1			1											1										1	3								
C. telata					1					2												1			1							p	1		1	1	1			2	2	1	p		p		1	p
Cyathidites australis			1	3	1	2	3	4	7	5	3	8	8	13	1	6	9	3			6	4	1		5	6	3	8	3	1	7	1	7	16	11	1	11	4	p	3	11	3	2	3		15	1	2
C. concavus																		p					p									p	p	1	2		p	2	1				p	1			p	7
C. minor	4	10	17	14	1	14	21	12	16	13	17	14	8	16	9	16	20	20	13	19	16	17	17	9	13	12	14	26	10	17	14	17	19	19	22	7	16	20	17	36	30	21	20	31	20	33	13	8
Cycadopites nitidus		2	2	2			3	1	2	1				3	1			15	3				1			1	1		3	2	p	1			1	3		1	2	2	1	5	3	5	2		3	1
Densoisporites velatus										1					1							1															1				p	1	p					1
Dictyophyllidites sp.					1					p	3			1		1					1				2	1	1	3							6			p									p	
Dictyotosporites complex										1										1		1	1		p				p				3			1			p		p	1	p					1
Foveosporites canalis	1					1	1					2	2										2			1			1			1				1								2		1		
Foveotriletes parviretus						2	1		1														1										2						1							1		2
Gleicheniidites senonicus				p			1	3		2				1	p			2	1		1	1	1	2	p			1	2	3	1	1					3	3	1	p	1	2	1		2		1	5
Inaperturopollenites limbatus																																							p				p		p	p		5
I. turbatus								p																																								
Ischyosporites crateris								3	2		1	1			2	1		3	2	4		3		1	4	2	3			1		3	2		18	1	3	1			p	9	p	p		7	1	
Klukisporites scaberis		2		p				3	2	1			1				3	1			1	1			2	2	1	2	1	1	1		1		2	2					p	1	1	1		1		
Kuylisporites lunaris																																	p															
Laevigatosporites sp.															p												1				1				1								p	p			p	
Leptolepidites major								p	1	1								2			1				1																p	1	p		1			
L. verrucatus				3			1	3	1	1		1		1		1		1		3	1	1				1		1												3	3							
Lycopodiacidites sp.	1							1				1						p			1	2					3	1			p	1							p		p	3	p					p
Lycopodiumsporites austroclavatidites	1	8	6	6	1	9	11	13	12	7	8	7	7	5	6	1	2	5	4	6	4	5	3		2	1	6	5	3		1	p	1			1		1		8	2	3	7	2				1
L. circolumenus	2				2	2	1	3	1					2	p	1	2	p	3		6	1			4		1	3	2		p						2		1	2	1		1				p	
L. sp. cf. *L. eminulus*						1		p	1				1	2	1		1	3			1					1	1	1	2	2	1	1				2					2			2		1		
L. sp. cf. *L. nodosus*																																						p										p
Matonisporites crassiangulatus									1	2												1					1				p							p						1		p	p	1
M. cooksoni										1																																						p
M. sp.									1				1	p																											p	1	p					
Microcachryidites antarcticus					1	3	3	18	5	15	12	2	1	5	14	14	13	14	2	8	7	22	22	11	31		12	2	13	8	6	23	14	42	18	18	12	35	35	p	3	22	21	8	15	3	44	50
Microfoveolatosporis canaliculatus							1								1			1												1			p	1	2		3		1	p		3		1				p
Murospora florida				1			1	4	2		p						1				1	1			p														1				p	1		2	p	p
Neoraistrickia truncatus	1			6		5	2	2		2		2	3	1	3	8	3	13	12	3	10	8	1					2	2	3		3	4		1	1	3		3	10	2		3	2		1	2	
Nevesisporites vallatus							p				p																1								2	1								p				
N. sp.								p		1					1							4		4	p		1	1		1	p	9	2	23	4	6	3	p			1		p	p	1		2	
Pilosisporites notensis																												1		1	p				3													
Podocarpites sp.	1	2		2											1			1																														
Reticulatisporites pudens						p																															p		2		2		1					
Reticuloidosporites arcus																						1	1	1											1		5						3					
R. sp.											1				2							1		1							p		p	2									1				p	
Staplinisporites caminus	1			1			p							p																		1																
Stereisporites antiquasporites		2	4					p				1									2	1																1	6						1			
Trilobosporites purverulentus											p											p																						p				
Tripartina sp. cf. *T. variabilis*								p		1							1					1											p	1	3			1					p				p	
Zonalapollenites dampieri	20	16	20	9	2	1	4	5	7	3	4	4	4	2	3	3	3	3		3	3	1	1		3	6	5	7	2		p	p	4	2	2		2		1	2	1	12	4	6	2	3	2	p
Z. segmentatus																									1	1					p		4		1								1				p	
remanie forms					2		2	1	1				1	1	2	4	2	p	1	1	2					2	9		p												1	1	p	1				
bisaccate forms	50	39	48	44	14	22	59	83	36	32	28	17	33	17	46	24	32	39	17	15	18	38	44	12	37	6	41	6	23	24	8	67	36	53	30	21	20	36	36	1	8	46	45	22	34	10	65	54
Acritarchs																																																
Leiosphaeridia spp.			2			3		1	2	6	14		3		24		3	2	17	15	11	25	24		12			5		6	1	21	23	21	4	2	3	3	p			7	4	3	1		5	1
Veryhachium spp.										1	1				1								p																				p					
Incertae sedis																																																
Horologinella sp.															2																p	p						p									p	p
Other	4	10	13	11	4	6	21	9	14	26		15	8	21	22	24	17	18	12	36	14	12	22	12	27	17	29	12	29	10	17	20	28		20	12	24	18	8	30	13	23	12	23	16	9	15	10
Total	200	200	200	200	43	124	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	200	71	200	200	200	200	200	111	133	200	200	200	116	200	200	200	200	200	200	200	200	200	200	200	200	200

p Observed but not in actual count.

* Count of palynomorphs in a sample prepared using Shultze solution.

13927

ZONATION

Four biostratigraphic units named, in ascending order, *Dampieri* Zone, *Baculatisporites* Zone, *Cicatricosisporites* Zone and *Concavus* Zone can be recognized in the Yarragadee Formation in the Watheroo Line boreholes. The *Dampieri* Zone corresponds to Balme's (1964) *Dampieri* Assemblage and Ingram's (1967a) Zone A. The remaining three zones are new.

Table 28 shows the distribution of key species within the zones. Spore and pollen counts from each sample are set out in Table 27. Some of the important forms are shown in Figures 64 and 65.

TABLE 28. DISTRIBUTION OF KEY FORMS IN THE WATHEROO LINE ZONATION

Palynomorph	*Dampieri Zone*	*Baculatisporites Zone*	*Cicatricosisporites Zone*	*Concavus Zone*
Foveosporites canalis	—	—	—	
Klukisporites scaberis	—	—	—	
Leptolepidites verrucatus	—	—	—	
Staplinisporites caminus	—	—	—	
Araucariacites australis	—	—	—	—
Baculatisporites spp.	—	—	—	—
Classopollis classoides	—	—	—	—
Lycopodiumsporites austroclavatidites	—	—	—	—
L. circolumenus	—	—	—	—
Murospora florida	—	—	—	—
Zonalapollenites dampieri	—	—	—	—
Aequitriradites spp.		—	—	
Contignisporites spp.		—	—	—
Microcachryidites antarcticus		—	—	—
Nevesisporites spp.		—	—	—
Pilosisporites notensis			—	
Cicatricosisporites spp.			—	—
Cyathidites concavus			—	—
Inaperturopollenites limbatus			—	—

Dampieri Zone

The stratigraphically lowest zone, the *Dampieri* Zone, occurs only in W.L. 10. Only four samples from W.L. 10 yielded good assemblages of spores and pollen. The remaining samples had very sparse assemblages or were barren of palynomorphs.

Assemblages from this zone show high counts of *Araucariacites australis* Cookson and bisaccate forms, and relatively high counts of *Zonalapollenites dampieri* Balme and *Classopollis classoides* Pflug. Absent from this zone are *Aequitriradites, Cicatricosisporites* and *Contignisporites* but *Foveosporites canalis* Balme and *Murospora florida* (Balme) though rare, are recorded.

Baculatisporites Zone

The *Baculatisporites* Zone occurs in W.L. 7, W.L. 6, W.L. 5 below 548.6 m, W.L. 4 below 427.3 m and W.L. 3 below 411.5 m. It may also be represented by samples in W.L. 2 at 595.0 m, W.L. 1 at 495.5 m and 504.4 m (see Fig. 63).

An increase in the number of *Baculatisporites* spp. and a decrease of *A. australis* and *C. classoides* marks the base of the *Baculatisporites* Zone. In addition *Microcachryidites antarcticus* Cookson *Aequitriradites* spp., *Contignisporites* spp. and many other numerically less prominent forms appear.

A number of spores, which include forms assignable to *Baculatisporites comaumensis* (Cookson) and *Osmundacidites wellmanii* Couper, have been grouped under *Baculatisporites* spp. in Table 27 because of the difficulty in assigning many individual spores of this type to a particular species. These forms become very abundant in nearly all samples in the *Baculatisporites* and *Cicatricosisporites* Zones, comprising almost 50 per cent of the individual palynomorphs observed in some samples.

Cicatricosisporites Zone

All samples above the *Baculatisporites* Zone in boreholes W.L. 1 to 5 and Agaton 7 belong to the *Cicatricosisporites* Zone with the exception of the top two samples in W.L. 1.

Basically assemblages from this zone are similar to those of the *Baculatisporites* Zone. *Baculatisporites* spp. are still abundant and the numbers of other forms remain relatively unchanged. The first appearance of *Cicatricosisporites* marks the base of this zone. Other forms to appear at various levels in this zone are *Pilosisporites notensis* Cookson and Dettman, *Cyathidites concavus* (Bolkhovitina) and *Inaperturopollenites limbatus* Balme. *P. notensis* has been recorded from a small number of samples in W.L. 3 and Agaton 7, and although not a common species in the Yarragadee Formation it has been noted in the Otorowiri Siltstone Member (Ingram 1967b). *C. concavus* and *I. limbatus* are rare in this zone and become slightly more abundant in the overlying *Concavus* Zone.

An unusually large number of *C. classoides* is present in a few samples from the *Cicatricosisporites* Zone in W.L. 1 but throughout most of this zone it is rare.

Concavus Zone

The *Concavus* Zone occurs in the two samples from Agaton 19 and in W.L. 1 at 153.9 m and 285.3 m. It is characterized by the more frequent occurrence of *C. concavus* and *I. limbatus* and by the considerably higher count of *M. antarcticus* and *C. classoides*. *Baculatisporites* spp. decline in abundance but are still common. Several forms seem to disappear in this zone (see Table 28) but no new forms appear.

Remanie forms

Remanie forms occur frequently in the *Baculatisporites* and *Cicatricosisporites* Zones. No sample shows the abundance and diversity of remanie forms which Ingram (1967b) recorded from the Otorowiri Siltstone Member of the Yarragadee Formation farther north near Mingenew. Remanie forms were not recorded from the *Dampieri* or *Concavus* Zones, suggesting that little or no erosion of the nearby source rocks was taking place during those periods. The most common forms are *Parasaccites* spp., *Potoniesporites* spp., *Platysaccus* sp. and various striate bisaccate forms, indicating a Permian or Early Triassic age. *Veryhachium* is also probably a remanie form derived from the Early Triassic Kockatea Shale in which it is often abundant.

FIGURE 64 (opposite)

Photomicrographs of palynomorphs from the Watheroo Line boreholes.

Magnification of all specimens on Figure 64 and 65 x 500. G.S.W.A. fossil registration numbers follow figure description. Coordinates on Leitz Orthoplan microscope number 834965 are given in brackets.

a. *Aequitriradites acusus* (Balme), F8189/2 (50·1 x 107·4)
b. *Aequitriradites hispidus* Dettmann and Playford, F8190/3 (46·3 x 106·6)
c. *Cicatricosisporites australiensis* (Cookson), F6595/3 (47·2 x 109·9)
d. *Cicatricosisporites ludbrooki* Dettmann, F6495/3 (42·5 x 108·9)
e. *Classopollis classoides* Pflug, F6595/3 (45·3 x 100·2)
f. *Concavisporites jurienensis* Balme, F6595/3 (32·1 x 109·5)
g. *Concavisporites jurienensis* Balme, F666/2 (38·1 x 104·3)
h. *Cyadopites nitidus* (Balme), F7928/1 (40·7 x 97·5)
i. *Contignisporites multimuratus* Dettmann, F5591/5 (32·7 x 106·0)
j. *Coronatispora perforata* Dettmann, F8466/1 (42·5 x 103·0)
k. *Coronatispora telata* (Balme), F6660/1 (29·6 x 107·4)
l. *Cyathidites concavus* (Bolkhovitina), F6660/3 (26·7 x 104·5)
m. *Foveosporites canalis* Balme, F6595/3 (289 x 99·9)
n. *Foveotriletes parviretus* (Balme), F8200/4 (27·1 x 92·9)
o. *Laevigatosporites sp.*, F6669/1 (36·6 x 102·6)
p. *Inaperturopollenites limbatus* Balme, F6660/4 (47·3 x 110·5)
q. *Leptolepidites verrucatus* Couper, F8200/2 (38·6 x 99·7)
r. *Leptolepidites major* Couper, F6661/1 (37·3 x 106·1)
s. *Lycopodiumsporites circolumenus* Cookson and Dettmann, F6595/3 (35·3 x 101·7)

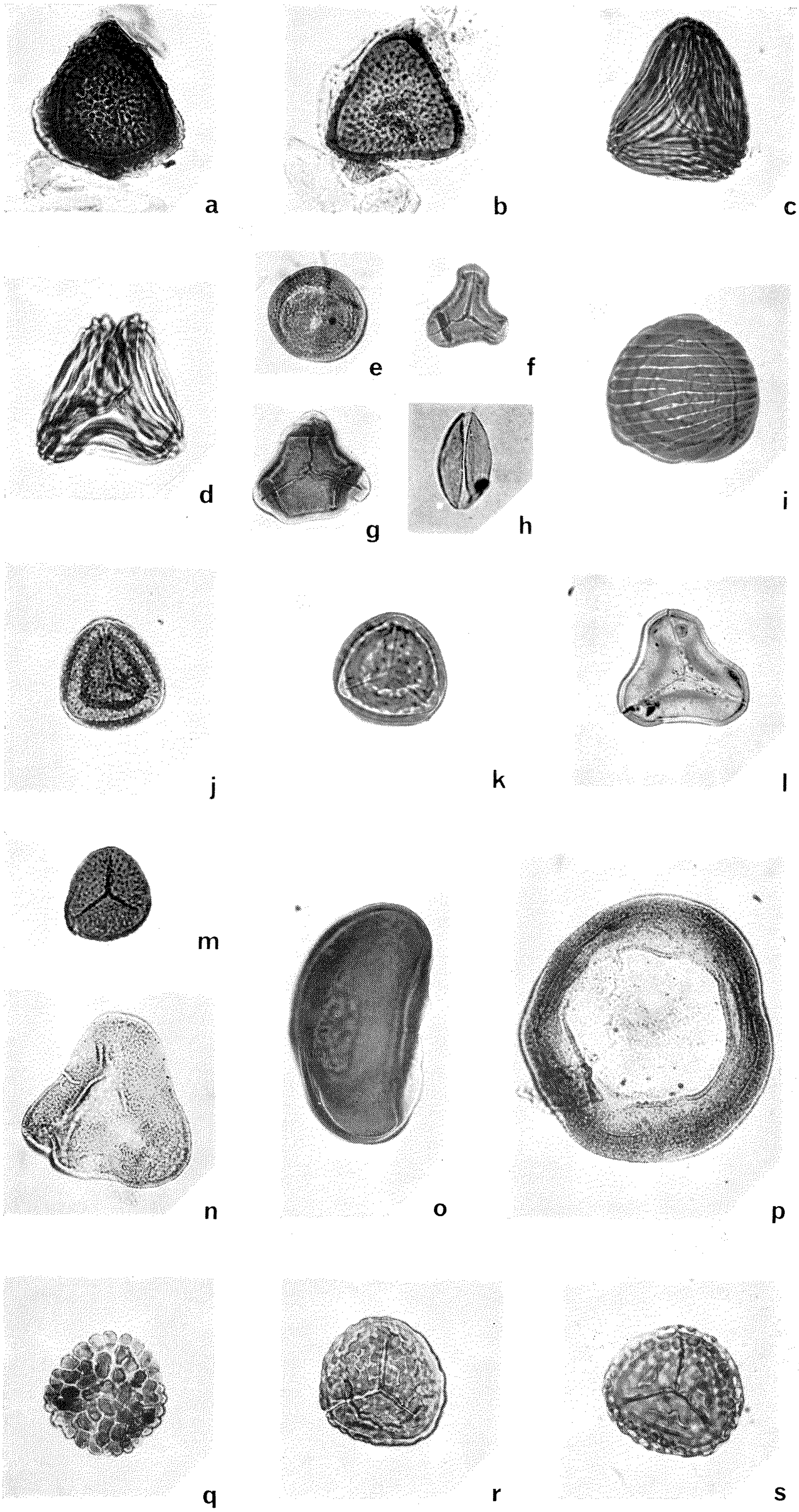


Figure 64.

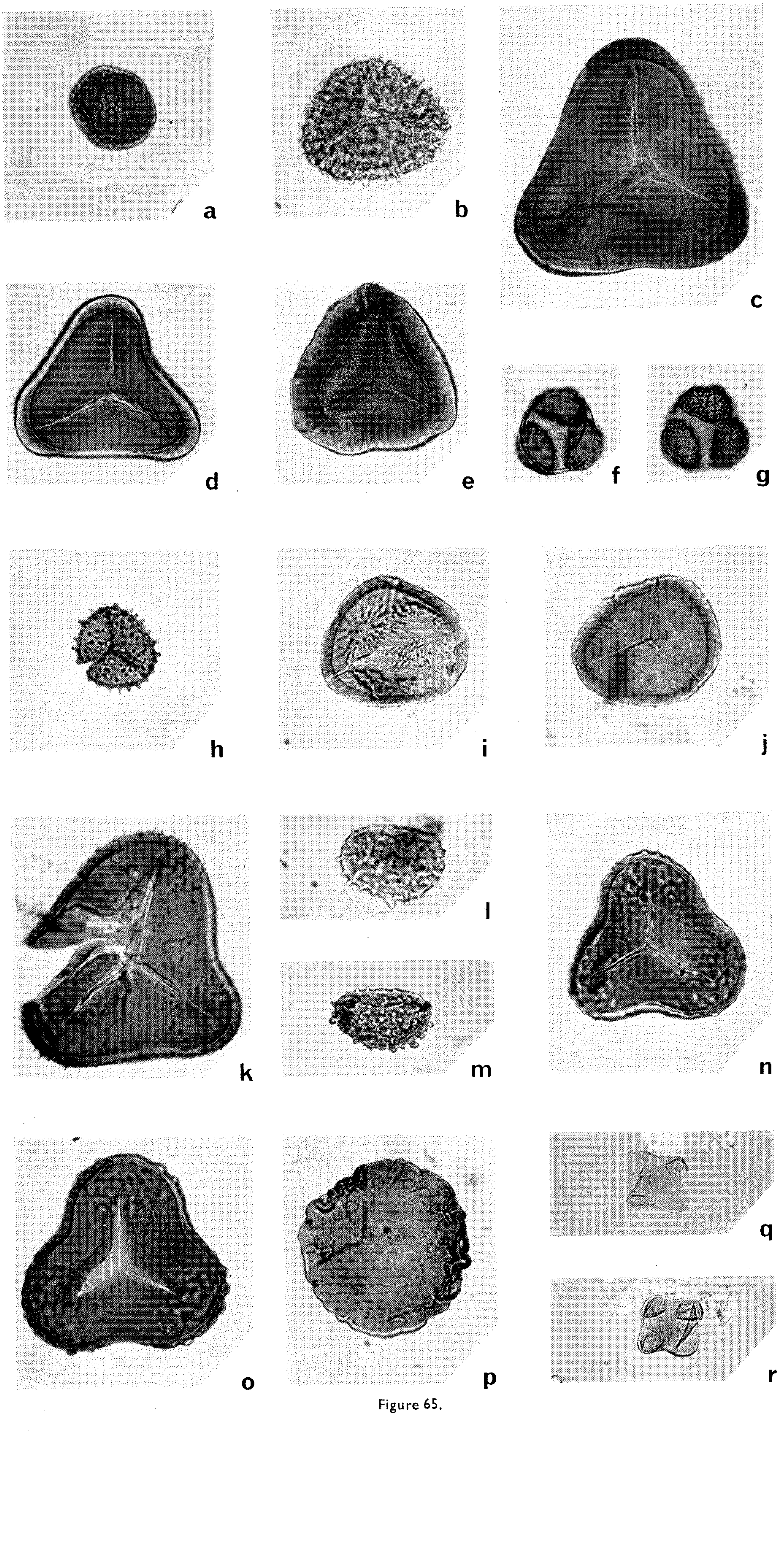


Figure 65.

TABLE 29. CORRELATION OF LATE JURASSIC AND EARLY CRETACEOUS ZONATIONS IN AUSTRALIA

Age	Balme 1964	Evans 1966a, b.	Ingram 1967	Dettmann and Playford 1969	This Paper
Cretaceous		Unit Kla	Zone C	*Dictyotosporites speciosus* Zone	*Concavus* Zone
	Microcachryidites Assemblage			- - - - - ? - - - - - *Crybelosporites stylosus* Zone - - - - - ? - - - - -	*Cicatricosisporites* Zone
- - - - - ? - - - - -			- - - - - ? - - - - -		
		Unit J5–6	Zone B		*Baculatisporites* Zone
		- - - - - ? - - - - -			
Jurassic	*Dampieri* Assemblage	Unit J4–5	Zone A		*Dampieri* Zone

COMPARISON WITH OTHER ZONATIONS

Table 29 indicates the correlation of the proposed zones with those of Balme (1964) and Ingram (1967a), and also the probable correlation with zonations in eastern Australia erected by Evans (1966a) and Dettmann and Playford (1969).

The correlation between the Watheroo Line zonation and that of Balme is fairly clear. Ingram's Zones B and C are more difficult to correlate with the Watheroo Line zonation. *M. florida* is recorded in the lowest zone in the Watheroo Line but is restricted to the highest zone (Zone C) in Ingram's Gingin Brook zonation.

Unit J5-6 of Evans is correlated wth the *Baculatisporites* Zone on the basis of the first appearance of *C. cooksonii.* However *Lycopodiumsporites circolumenus* Cookson and Dettmann and *M. florida,* which first appear in unit J5 in the Injune Creek Beds (Evans 1966a), occur in the *Dampieri* Zone in the Watheroo area. The base of Evans' Kla unit is established as the first appearance of *C. australiensis.* In the Watheroo Line zonation the first appearance of *Cicatricosisporites* is taken as the base of the *Cicatricosisporites* Zone. The presence of *M. florida* in the *Concavus* Zone indicates this zone also correlates with Evans' Kla unit. Evans (1966a, 1966b) suggests *C. australiensis* may occur in the Upper Jurassic in the Canning Basin and that unit Kla probably commences in the Jurassic. Allowing for the possible occurrence of *C. australiensis* in the Late Jurassic, the Jurassic-Cretaceous boundary probably occurs in the lower part of the *Cicatricosisporites* Zone.

If the *Crybelosporites stylosus* Zone of Dettmann and Playford (1969) is represented in the Watheroo area it must be within the *Cicatricosisporites* Zone, possibly in a thin section below the first occurrence of *P. notensis.* Forms comparable to *Cooksonites variabilis* Pocock and *Aequitriradites hispidus* Dettmann and Playford, occur in the *Baculatisporites* and *Cicatricosisporites* Zones, and overlap the range of *P. notensis* in W.L. 3 and Agaton 7. In Dettmann and Playford's zonation *A. hispidus* and *P. notensis* do not overlap and *C. variabilis* only appears at the top of the *Crybelosporites stylosus* Zone to which *A. hispidus* is restricted. These anomalies, and the absence of positively identified specimens of *Crybelosporites stylosus* Dettmann and *Dictyotosporites speciosus* Cookson and Dettmann, make Dettmann and Playford's zonation difficult to apply in the Watheroo Line boreholes.

FIGURE 65 (opposite)

Photomicrographs of palynomorphs from the Watheroo Line boreholes.

a. *Lycopodiumsporites* sp. cf. *L. eminulus* Dettmann, F6595/3 (44·5 x 99·4)
b. *Lycopodiumsporites* sp. cf. *L. nodosus* Dettmann, F6669/1 (42·3 x 109·2)
c. *Matonisporites* sp., F6666/2 (33·0 x 104·6)
d. *Matonisporites crassiangulatus* (Balme), F7928/1 (41·4 x 109·1)
e. *Murospora florida* (Balme), F6669/1 (34·2 x 105·4)
f.g. *Microcachryidites antarcticus* Cookson. Proximal and distal focii, F6660/2 (32·0 x 99·0)
h. *Neoraistrickia truncatus* (Cookson). F6595/3 (30·5 x 99·0)
i. *Nevesisporites vallatus* de Jersey and Paten, F6668/2 (39·5 x 111·9)
j. *Nevesisporites* sp., F6684/1 (37·7 x 104·1)
k. *Pilosisporites notensis* Cookson and Dettmann, F6686/1 (31·2 x 105·9)
l. *Reticuloidosporites* sp., F6665/1 (40·0 x 106·0)
m. *Reticuloidosporites* sp., F6666/2 (38·3 x 91·8)
n. *Trilobosporites purverulentus* (Verbitskaya), F6665/1 (44·0 x 101·7)
o. *Trilobosporites purverulentus* (Verbitskaya), F6665/2 (43·0 x 97·9)
p. *Zonalapollenties dampieri* Balme, F6595/3 (39·5 x 98·2)
q. *Horologinella* sp., F7928/1 (44·3 x 95·9)
r. *Horologinella* sp., F7928/1 (38·8 x 110·4)

CONCLUSIONS

This zonation has been applied only to the Watheroo Line boreholes in the Perth Basin. Further work may result in modification to the zonation and to the range of individual species. For example, study of further samples from the *Concavus* Zone may reveal species which, because of their rarity, were missed in the four samples examined from the Watheroo Line.

Further study of material from the Gingin Brook boreholes may show a closer correlation between the Yarragadee Formation in the Gingin Brook and Watheroo Line boreholes. Present drilling, on the Eneabba boreholes to the north of Watheroo, will provide additional information on the palynology of the Upper Jurassic and Lower Cretaceous in the Perth Basin.

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TRIASSIC CONCHOSTRACANS FROM THE KOCKATEA SHALE

by A. E. Cockbain

ABSTRACT

The well-known northern hemisphere conchostracan *Cyzicus minuta* is illustrated for the first time from the Early Triassic Kockatea Shale in the southern Carnarvon Basin. Conchostracans are also known from this formation in the Perth Basin and from the Blina Shale in the Canning Basin. All occurrences are in marine strata and probably represent specimens swept out to sea by floods.

INTRODUCTION

Conchostraca are small crustaceans with a translucent bivalved shell which is never strongly calcified and bears growth lines. Present day conchostracans live chiefly in impermanent ponds, but fossil forms are reported from fresh-water, brackish-water and marine environments. However, there is some debate as to whether conchostracans were ever truly marine or whether they lived in fresh and brackish waters and were carried into the sea by floods (Tasch, 1969).

In Western Australia, Triassic conchostracans have been recorded from the Blina Shale in the Canning Basin and from the Kockatea Shale in the Perth and Carnarvon Basins. Marine fossils have been found in both these formations. This paper will summarise these occurrences, describe and illustrate the Kockatea Shale conchostracan species for the first time, and comment on the significance of these fossils from Western Australia.

OCCURRENCE

Triassic conchostracans are known from the Blina Shale and from the Kockatea Shale (Fig. 66).

1. *Blina Shale.* Brunnschweiler (1954, 1957) recorded two species of *Cyzicus* from the Blina Shale under the names *Isaura* sp. cf. *I. minuta* and *I.* sp. cf. *I. ipsviciensis.* He pointed out (Brunnschweiler, 1954) that the bivalve *Carbonicola minutissima* described by Chapman and Parr in 1937 is a conchostracan (the first to be figured from Western Australia), and that Teichert (1950) had also recorded *"Estheria"* from the Blina Shale in Mayalls bore. Other records of conchostracans from this formation are given by Veevers and Wells (1961). The associated fauna includes *Lingula* and fish and amphibian remains. Brunnschweiler (1954) considered that the abundance of *Cyzicus* suggested a Late Triassic age for the Blina Shale. However, Lindner (*in* McWhae and others, 1958) thought that the formation might be Early Triassic and this has since been confirmed by Balme (1969) on palynological grounds.

2. *Kockatea Shale.* Conchostracans were first recorded from the Kockatea Shale by Dickins and McTavish (1963). The conchostracans, which were not identified, occur in cores 25 and 26 in B.M.R. (Beagle Ridge) No. 10 bore and are found in association with bivalves, ammonites and fish remains. The ammonites date the formation as Griesbachian (early Early Triassic) at this locality, but near Mount Minchin on the Northampton Block the lowest beds of the Kockatea Shale are Smithian (late Early Triassic, Playford and others, in press).

More recently, conchostracans have been found in the Kockatea Shale south of Kalbarri. This is the type region of the Wittecarra Formation (Johnstone and Playford *in* McWhae and others, 1958). This unit has been regarded as probably of Late Jurassic age on the basis of fossil leaves. Playford and others (in press) have re-interpreted the sequence at this locality as follows:

McWhae and others, 1958	Playford and others, (in press).
	Birdrong Sandstone
	UNCONFORMITY
Wittecarra Formation	Kockatea Shale
	Wittecarra Sandstone
UNCONFORMITY	UNCONFORMITY
Tumblagooda Sandstone	Tumblagoodoo Sandstone

The conchostracans come from the lower part of the Kockatea Shale in this section and are described below as *Cyzicus minuta.*

SYSTEMATIC PALAEONTOLOGY

Phylum ARTHROPODA

Superclass CRUSTACEA

Class BRANCHIOPODA

Subclass DIPLOSTRACA

Order CONCHOSTRACA

Suborder SPINICAUDATA

Superfamily CYZICOIDEA

Family CYZICIDAE

Cyzicus Audouin, 1837

1837 *Cyzicus* Audouin

1837 *Estheria* Rüppel (not *Estheria* Robineau-Desvoidy, 1830)

1841 *Isaura* Joly

The name *Estheria* by which these animals are widely known was originally given to a genus of Diptera. Brunnschweiler (1954) followed Bock (1953) in considering *Isaura* as the correct name for the genus. However, Dechaseaux (1953) and Tasch (1969) point out that the name *Cyzicus* has priority.

Cyzicus (Euestheria) minuta (von Zieten)
Figures 67 D and E.

1833 *Posidonia minuta* von Zieten: p. 72, pl. 54, fig. 5 (not seen).

1890 *Estheria minuta* (Alberti); Jones: p. 387, pl. 12, figs. 4-7.

?1907 *Estheria* sp. Etheridge Jr.: p. 11, pl. 8, fig. 11.

?1937 *Carbonicola minutissima* Chapman and Parr: p. 178, pl. 16, fig. 6.

1950 *Estheria (Euestheria) minuta* (Alberti); Defretin: p. 215, pl. 8, figs. 1-6, pl. 9, fig. 1, text fig. 1.

1953 *Isaura minuta* (Goldfuss); Bock: p.68, pl. 11, figs. 5-7.

1954 *Isaura* cf. *I. minuta* (Goldfuss); Brunnschweiler: p. 43.

1957 *Isaura* cf. *I. minuta* (Goldfuss); Brunnschweiler: p. 5.

1969 *Euestheria minuta* (von Zieten); Defretin-Lefranc: p. 127, pl. 1, figs. 3, 4 (with synonymy).

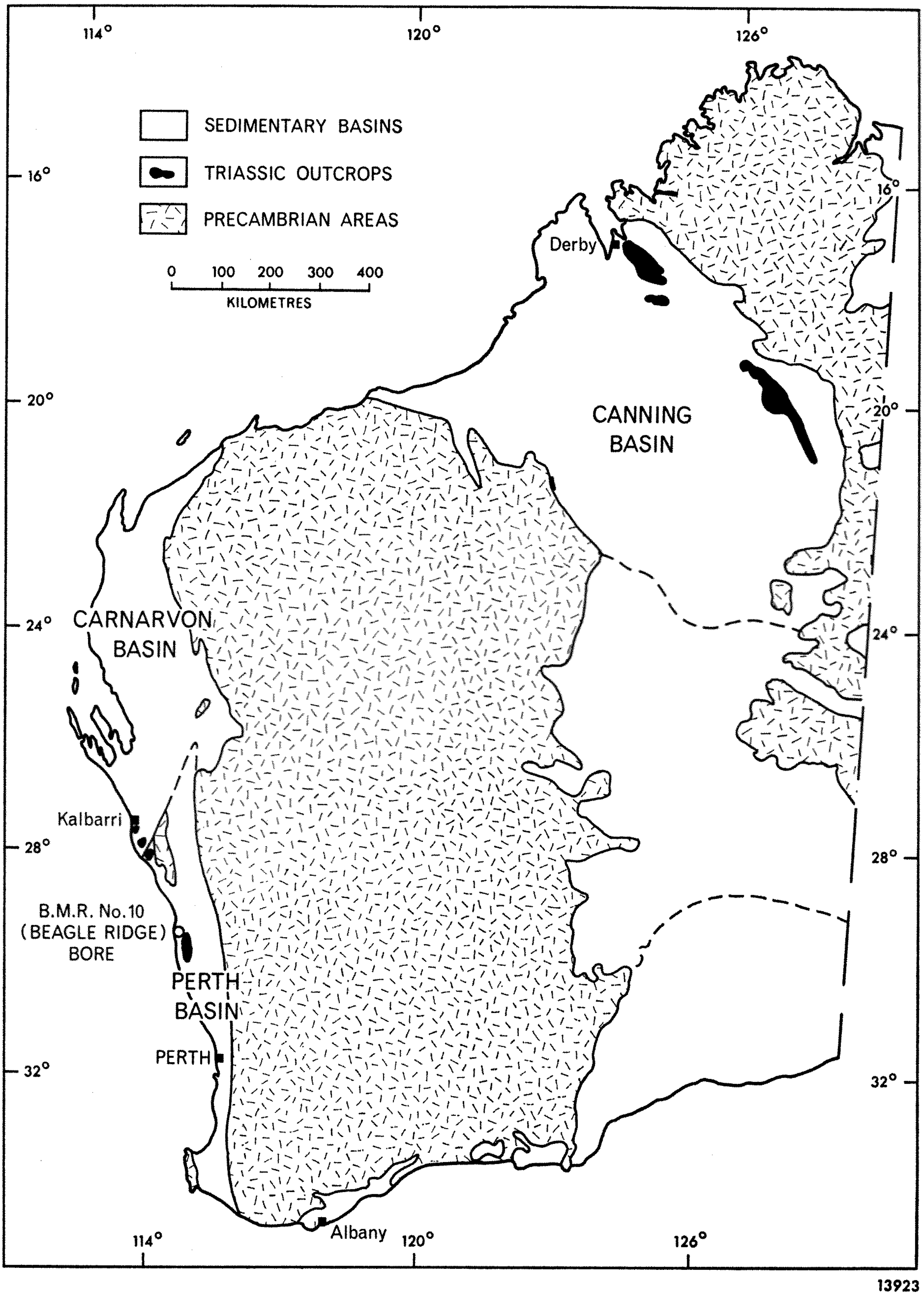

Figure 66. Location map of Blina and Kockatea Shales.

Material: G.S.W.A. registered number F8320, some 20 internal and external moulds preserved in a pale-grey to white siltstone; Kockatea Shale, 7.2 km south of Red Bluff, near Kalbarri, southern Carnarvon Basin.

Remarks: The specimens average about 3 mm in length. Growth lines are fairly well marked, but no trace of micro-ornament between growth lines is preserved. The material is identified as *Cyzicus minuta* on the basis of the size and general shape of the shells.

Distribution: The species occurs throughout the Triassic in Europe, but is most abundant in the late Middle Triassic Lettenkohle (Defretin, 1950). The Western Australian specimens come from the Early Triassic Kockatea Shale. The species also occurs in Greenland (Defretin-Lefranc, 1969), but is apparently absent from North America (Bock, 1953).

SIGNIFICANCE

The conchostracans from the Triassic of Western Australia are associated with a variety of fossils as summarised below:

lingulid brachiopods—1, 2, 3
marine bivalves—2
ammonites—2
fish and amphibian remains—1, 2
acritarchs—1, 2
spores and pollen—1, 2

(1) Blina Shale (Brunnschweiler, 1954, 1957)
(2) Kockatea Shale, B.M.R. No. 10 bore (Dickins and McTavish, 1963)
(3) Kockatea Shale, near Kalbarri (this paper)

The acritarchs, lingulid brachiopods, ammonites and bivalves suggest a marine environment, whilst the spores, pollen, amphibian remains and some of the fish remains are characteristic of fresh water or a continental environment. McKenzie (1961) postulated a quiet marine gulf with a large delta to account for the deposition of the Blina Shale and Balme (1969) suggested similar conditions for the Kockatea Shale. Under this hypothesis the non-marine faunal and floral elements could easily be carried into the sea during floods. The conchostracans may have been marine, but it is more likely that they too were swept into the sea by flood waters, a suggestion supported by the lack of articulated specimens of *Cyzicus minuta* in the Kalbarri material.

Tasch (1971) has endeavoured to use conchostracan fossils to indicate fresh and brackish-water dispersal routes across Gondwanaland. Such evidence must be applied with caution for as Tasch himself points out (1969), conchostracan eggs are very resistant and can be readily dispersed by wind and water. Modern conchostracans are cosmopolitan. The Western Australian Triassic conchostracan fauna contains one species (*C. minuta*) which is widespread in the northern hemisphere. This suggests that conchostracan species were cosmopolitan in the Triassic and that they must have been dispersed across wide stretches of land and sea with equal ease.

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FIGURE 67 (opposite)

A, B. *Cyclammina incisa* (Stache); Pallinup Siltstone, South Stirling; WAM 73·93; x 40

C. *Cyclammina incisa* (Stache); Pallinup Siltstone, South Stirling; WAM 73·93; equatorial section; x 40

D. *Cyzicus minuta* (von Zieten); Kockatea Shale, near Kalbarri; F8320; x 3

E. *Cyzicus minuta* (von Zieten); Kockatea Shale, near Kalbarri; F8230; x 10

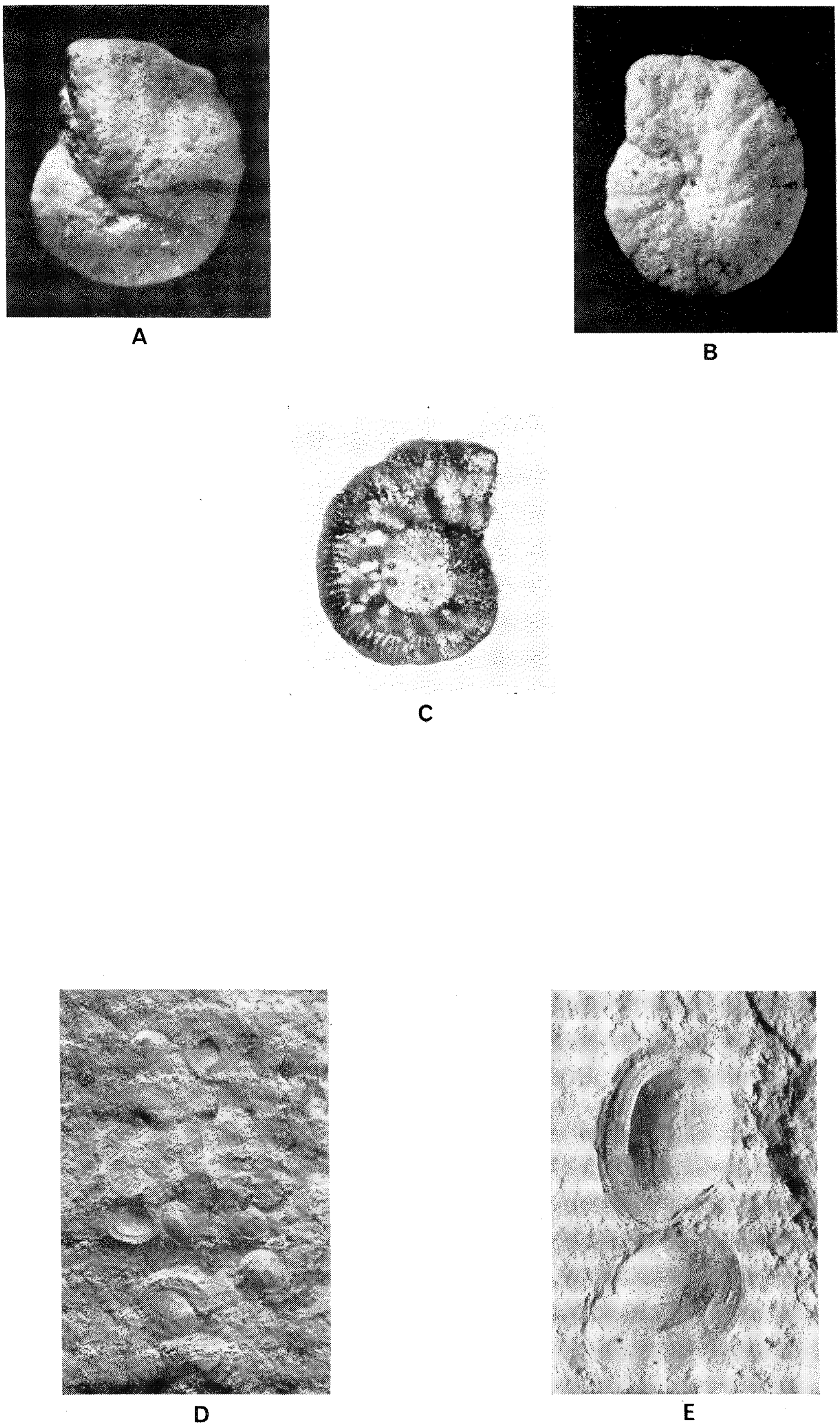

Figure 67.

THE FORAMINIFER CYCLAMMINA FROM THE PLANTAGENET GROUP

by A. E. Cockbain

ABSTRACT

Cyclammina incisa (Stache) is recorded from the Plantagenet Group for the first time. This Western Australian record, together with records from Victoria are from shallow water and support Robinson's (1970) suggestion that *Cyclammina* became confined to bathyal depths in the late Tertiary and had a shallower (? wider) depth range in the early Tertiary.

INTRODUCTION

A sample containing abundant foraminifers of the genus *Cyclammina* was forwarded to the Geological Survey by Mr. G. W. Kendrick of the Western Australian Museum. The sample came from a water bore on the property of P. M. and W. T. Grocock, Plantagenet location 5666, near South Stirling. The approximate co-ordinates are: Mount Barker 1 : 250 000 map Sheet, 615725: lat. 34° 36′ 00″ S, long. 118° 08′ 20″ E (see Fig. 68). The sample is a cuttings sample from 12-21 m depth and is given the Western Australian Museum registered number 73-93.

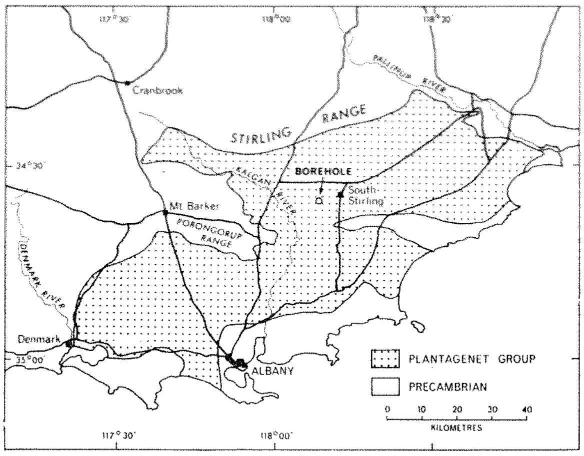

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Figure 68. Location of South Stirling borehole.

The foraminifers occur in a brown-grey, medium-grained sand which contains a few sponge spicules. This lithology is typical of the Pallinup Siltstone of the Plantagenet Group, from which the sample comes. All the foraminifers belong to the one species, and this is the first record of *Cyclammina* from the Plantagenet Group.

SYSTEMATIC PALAEONTOLOGY

Phylum PROTOZOA

Subphylum SARCODINA

Class RHIZOPODEA

Order FORAMINIFERIDA

Suborder TEXTULARIINA

Superfamily LITUOLACEA

Family LITUOLIDAE

Genus CYCLAMMINA Brady, 1879

Cyclammina incisa (Stache)
Figures 67 A, B and C.

1864 *Haplophragmium incisum* Stache: p. 165, pl. 21, fig. 1.

1864 *Haplophragmium maoricum* Stache: p. 166, pl. 21, fig. 2.

1930 *Cyclammina longicompressa* Chapman and Crespin: p. 97, pl. 5, figs. 3, 4.

1965 *Haplophragmoides* cf. *incisa* (Stache); Taylor: p. 150, figs. 2d, 3 (3a and 3b), 4 (4a and 4b).

1971 *Cyclammina incisa* (Stache); Hornibrook: p. 34, pl. 6, figs. 88-91, text fig. 9.

Remarks: Mr. Kendrick had picked out some 80 specimens of the species ranging in size from 1.1 mm to 2.7 mm in diameter. The number of chambers in the final whorl ranges from 11 to 15. No apertural pores were seen. The specimens vary somewhat in proportions, some being laterally compressed and others being fairly well rounded. Several specimens have more than the 11-12 chambers in the final whorl that is typical of *C. incisa*, but otherwise resemble that form; all are here considered to belong to the one species. A few specimens are distorted and thereby resemble *Cyclammina longicompressa* Chapman and Crespin, which, following Taylor (1965) I place in *C. incisa*.

There has been some doubt as to whether *incisa* is a *Cyclammina* (see Hornibrook, 1971). Taylor (1965) claimed that *incisa* (and other species usually assigned to *Cyclammina*) from the Paleocene and Eocene of Victoria should be placed in the genus *Haplophragmoides*. Ludbrook (1971) disputes this and supports the *Cyclammina* determination, as does Hornibrook (1971). If Taylor's (1965) figure 2d of *Haplophragmoides* cf. *incisa* is compared with Hornibrook's (1971) text figure 9 of *Cyclammina incisa* it will be seen that both are essentially the same and show the labyrinthic wall structure characteristic of *Cyclammina*. A thin section of a specimen from the Plantagenet Group (Fig. 67c) clearly shows the labyrinthic wall.

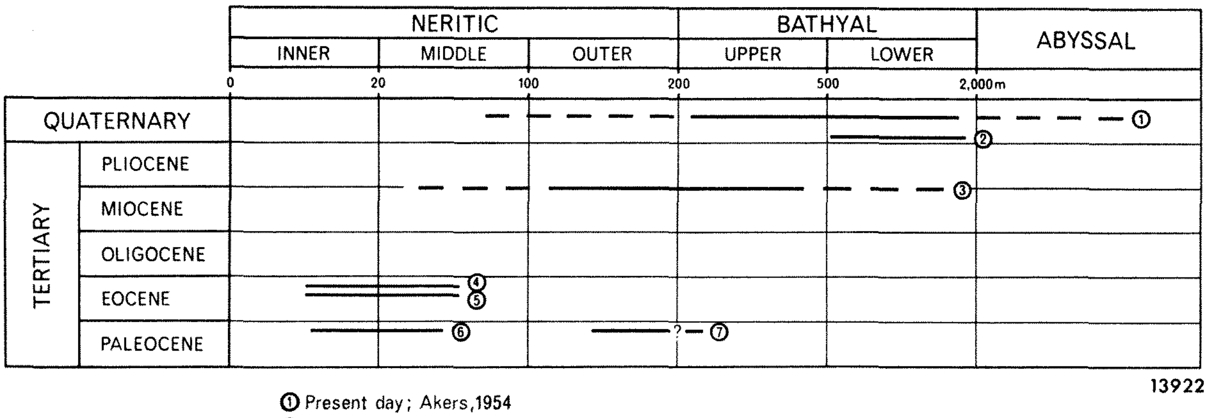
Distribution: In New Zealand *Cyclammina incisa* ranges through the Eocene and Oligocence with the upper limit uncertain (Hornibrook, 1971). Taylor (1965) records a similar range for the species in Victoria, and states that it is not associated with Paleocene and older faunas. In the Otway Basin Ludbrook (1971) has recorded the species from Cretaceous and Paleocene rocks, and in Western Australia *Cyclammina incisa* occurs in the type section of the King's Park Shale (Parr, 1938) which is now known to be of late Paleocene age (McGowran, 1964). The overall stratigraphic range of the species would seem to be at least Cretaceous to Oligocene.

DEPTH RANGE OF CYCLAMMINA

Since the work of Akers (1954) it has been generally considered that *Cyclammina* is a deep-water genus. Phleger (1960) states that it occurs in depths greater than 200 m whilst Bandy (1960) and Bandy and Arnal (1960) consider areanceous genera with labyrinthic walls (such as *Cyclammina*) to be characteristic of bathyal depths. Examination of Akers' (1954) data shows that the genus is found at depths between 80 m and 5 800 m. Only 7 per cent of the records are from waters shallower than 250 m and 86 per cent of the occurrences fall in the depth range 250 m to 2 500 m.

The Pallinup Siltstone is a shallow-water deposit. Fossil sponges from the formation suggest a water depth during deposition of between 20 and 200 m (de Laubenfels, 1953).

The borehole from which *Cyclammina incisa* is recorded is situated some 20 km south of the Stirling Range which was an island when the Pallinup Siltstone was deposited. It is probable that the species lived in water less than 50 m deep.



① Present day; Akers, 1954
② Gulf Coast; Robinson, 1970
③ Gulf Coast; Robinson, 1970
④ Pallinup Siltstone, Western Australia; this paper
⑤ Johanna River Sands and Demon Bluff Formation, Victoria; Taylor, 1965
⑥ Dilwyn Clay, Victoria; Taylor, 1965
⑦ Kings Park Shale, Western Australia; Parr, 1938

Figure 69. Depth distribution of the genus *Cyclammina* from the Cainozoic.

The Paleocene and Eocene *Cyclammina*-bearing sediments of Victoria are also shallow-water deposits—a fact that persuaded Taylor (1965) that the species belonged not to *Cyclammina* but to the shallow-water genus *Haplophragmoides*. Taylor (1965) considers the formations yielding *Cyclammina* (Dilwyn Clay, Johanna River Sands and Demons Bluff Formation) to be near-shore paralic sequences.

In view of the descrepancy between these early Tertiary shallow-water records of *Cyclammina* and the present day, predominantly deep-water depth range, Robinson's (1970) observations on Gulf Coast *Cyclammina* are pertinent. He concluded that the genus became restricted in its depth range to the upper bathyal and deeper zones during the late Pliocene. In the early Pliocene and late Miocene the genus extended into the neritic depth zone. Early Tertiary *Cyclammina* from Victoria and Western Australia also have a neritic depth distribution. Data on the depth distribution of *Cyclammina* in the Cainozoic are summarised in Figure 69.

It is suggested that early Tertiary *Cyclammina* in Australia lived in the neritic zone; possibly the genus ranged into the bathyal zone. During the late Tertiary, as Robinson (1970) documents, the genus became a predominantly bathyal form and at the present time is extremely uncommon in the neritic depth zone. The genus may have been forced out of the neritic zone by competition with other forms. *Cyclammina* seems to be a fairly tolerant genus. Present day forms have a rather wide temperature tolerance (12.1° C to 1.2° C according to Akers, 1954), and Boltovskoy (1963) remarks that the genus can survive low concentrations of oxygen. Wide variation in environmental factors is a characteristic feature of near-shore shallow waters and *Cyclammina* would have been preadapted for the lower temperatures of bathyal depths.

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INDEX

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