GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1970

1971

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EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

Minister: The Hon. A. F. Griffith, M.L.C.

Under Secretary: I. R. Berry

Director, Geological Survey: J. H. Lord.

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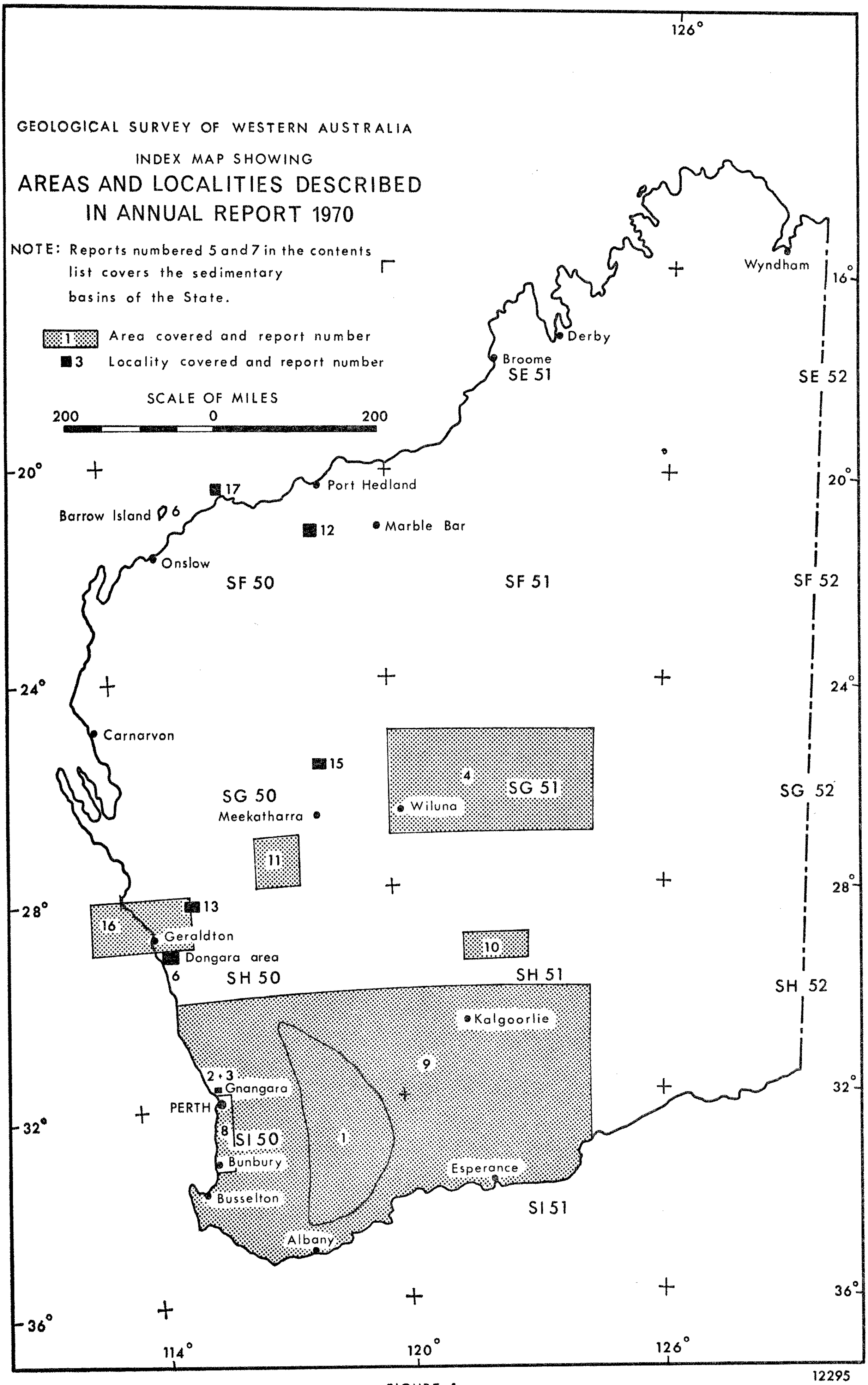
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
INDEX MAP SHOWING
AREAS AND LOCALITIES DESCRIBED
IN ANNUAL REPORT 1970
NOTE: Reports numbered 5 and 7 in the contents list covers the sedimentary basins of the State.
1 Area covered and report number
3 Locality covered and report number
SCALE OF MILES
200 0 200
Wyndham
Derby
Broome
SE 51
SE 52
Port Hedland
Marble Bar
17
Barrow Island 6
12
Onslow
SF 50
SF 51
SF 52
Carnarvon
15
4
SG 51
Wiluna
SG 50
Meekatharra
SG 52
11
13
16
Geraldton
Dongara area
6
10
SH 50
SH 51
SH 52
Kalgoorlie
9
2+3
Gnangara
PERTH
8
SI 50
1
Bunbury
Busselton
Esperance
SI 51
Albany
126°
16°
20°
24°
28°
32°
36°
114°
120°
12295
FIGURE 1

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1970

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1970

The 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, together with some of the reports on investigations made for departmental purposes.

INTRODUCTION

The mineral exploration boom continued throughout 1970, with new companies continually joining in the search for new mineral deposits.

There was renewed activity in the search for, or rather the proving of, iron ore deposits, particularly in the Hamersley Range iron province. Detailed drilling programmes were commenced and in some cases are still continuing on such deposits as Rhodes Ridge, Koodaiderie, McCamey's Monster, Marillana and Mount Gibson. Further mines are expected to be developed on some of these deposits.

Bauxite attracted considerable attention, and Western Aluminium (Alcoa) commenced the establishement of an additional alumina plant at Pinjarra, its plant at Kwinana having reached its maximum production size of 1·2 million tons of alumina per year. The Amax alumina project in the Kimberley is in its final planning stage before the commencement of construction. Alwest, in conjunction with Broken Hill Proprietary, and Hanwright, in conjunction with Pacminex, are carrying out feasibility studies for the establishment of alumina plants near Bunbury and to the north of Perth respectively. A number of other companies are searching for suitable deposits.

The mining of nickel ore continued at Kambalda, Scotia and Nepean. Development work in preparation for mining is being done at Mount Windarra (Poseidon), Carr Boyd, Spargoville (Selection Trust), Widgiemooltha (3 miles northwest, Inco and B.H.P.), Redross and Wannaway (Anaconda and C.R.A.). Nickel mineralisation warranting further investigation has been reported from many localities; in particular, Mount Clifford, Siberia, Pyke Hill, Mount Monger, Trough Wells and Mount Keith.

Those engaged in oil exploration had another disappointing year. Most of the exploration was concentrated off-shore with no significant results. Plans were announced for the development and piping of gas from Dongara to Perth. There should be more search on-shore again under the new Act and with ground becoming available.

The exploration boom is attracting attention to minerals other than those mentioned above. There has been a revival of interest in mineral sands and many new companies have become involved. Most were investigating the possibility of locating and operating large lower grade deposits. This has resulted in the location of some additional high and low-grade deposits. The investigations have been carried beyond the Bunbury-Busselton area around the coastal areas. A promising deposit containing rutile has been found near Eneabba. One company, Norseman Titanium, has announced its intention of establishing a new plant and mine near Capel, while several other companies are carrying out detailed feasibility studies.

Exploration has been directed towards the discovery of many other minerals, in particular copper, silver-lead-zinc, uranium, diamonds, platinum and coal.

Three lectures followed by field excursions were arranged during 1970. The first was on the Geraldton 1 : 250,000 sheet, which involves both Precambrian and Phanerozoic geology and attracted about 90 persons. The second was on the Norseman 1 : 250,000 sheet, which attracted about 100, and the third was a repeat of the Kurnalpi 1 : 250,000 which attracted about 120. The attendances again illustrated that there is a keen demand for the results of geological mapping before publication. It is hoped to arrange further lectures during 1971.

ACCOMMODATION

The move to Mineral House from the seven substandard buildings previously occupied took place in May, 1970. The staff and laboratories are now housed in first class accommodation which is appreciated by all concerned.

The new library lay-out is proving to be of great value to the public, who can now pursue their literature searches in comfort. The small geological museum is also attracting considerable interest.

Further additions to our core stores are being proposed for the next financial year. This is required to cope with the material being lodged with the Survey and collected during the current exploration boom.

STAFF

The Branch suffered severe setbacks this year due to the resignations of senior staff as well as junior staff, the majority of whom resigned to accept more lucrative positions in private enterprise. Many of the senior officers leaving had contributed greatly to the development of the Survey, in particular Messrs. L. E. de la Hunty, J. Sofoulis and R. R. Connolly, all of whom had over 20 years' service. Also Drs. P. E. Playford and R. C. Horwitz, both of whom were in charge of Divisions, had, by their own ability and example, made a major contribution to the geology of this State and to the development of the Survey.

During the year the number of professional vacancies rose to 19. However by the end of the year it appeared as if most of the positions will be filled during 1971. Nearly all new staff are being recruited from overseas, in particular the United Kingdom, and so will lack local experience.

There were also many changes in the clerical and general staff. It is also difficult to recruit suitable staff in these fields.

The establishment of the Branch at the end of 1970 was 51 professional, 7 clerical and 16 general officers.

PROFESSIONAL

Appointments

Name	Position	Effective Date
Thom, R., B.Sc. (Hons.)	Geologist, Level 1	5/1/70
Thom, J., B.Sc. (Hons.)	Geologist, Level 1 (Temp.)	19/1/70
Clure, V., B.Sc. (Hons.)	Geologist, Level 1 (Temp.)	29/6/70
Carter, J., B.Sc. (Hons.)	Geologist, Level 3	7/9/70
Marcos, G., B.Sc.	Geologist, Level 1 (Temp.)	7/10/70
Toledo, M., B.Sc. (Hons.)	Geologist, Level 1	19/10/70
Barnes, R., B.Sc. (Hons.)	Geologist, Level 1	23/11/70

Resignations

Ryan McMahon, M.	Geologist, Level 1	27/1/70
Boyer, D. D.	Geologist, Level 1	2/4/70
Playford, P. E.	Supervising Geologist, Level 5	10/4/70
Horwitz, R. C.	Supervising Geologist, Level 5	10/4/70
Barnett, J. G.	Geologist, Level 1	10/4/70
Newton-Smith, J.	Geologist, Level 1	22/5/70
Whincup, P.	Geologist, Level 2	22/5/70
Connolly, R. R.	Geologist, Level 2	29/5/70
de la Hunty, L. E.	Supervising Geologist, Level 5	4/6/70
Sofoulis, J.	Senior Geologist, Level 3	4/6/70
Williams, X. K.	Geochemist, Level 3	22/6/70
Brown, W.	Geologist, Level 1	10/7/70
Doepel, J. J. G.	Geologist, Level 1	18/9/70
Pippet, A. H.	Production Geologist, Level 4	30/10/70

Promotions

Sanders, C. C.	Geologist, Level 2	19/12/69
Bestow, T. T.....	Supervising Geologist, Level 5	14/1/70
Gordon, F. R.	Supervising Geologist, Level 5	14/1/70
Low, G. H.	Senior Geologist, Level 3	18/3/70
Blockley, J. G.	Senior Geologist, Level 3	1/7/70
Daniels, J. L.	Supervising Geologist, Level 5	15/7/70
Williams, I. R.	Senior Geologist, Level 3	12/8/70
Muhling, P. C.	Geologist, Level 2	16/10/70
Baxter, J. L.	Geologist, Level 2	20/11/70

CLERICAL AND GENERAL

Appointments

Watt, J.	Geophysical Assistant	3/4/70
D'Silva, A.	Clerk (Temp.)	15/6/70
Jeffrey, S.	Geological Assistant	29/6/70

Transfers In

Dunham, J.	Typist	2/2/70
Williams, G.	Laboratory Assistant	15/6/70
Allison, L.	Library Assistant	15/7/70
Hewitt, P.	Clerk	10/8/70
Bradshaw, B.	Clerk	7/12/70

Resignations

Birch, S.	Typist	30/1/70
Schellpeper, S. H. W.	Geophysical Assistant	5/2/70
Squires, G.	Laboratory Assistant	6/3/70
Leeder, K. A.....	Geological Assistant	13/3/70
Bruce, R.	Library Assistant	22/5/70
Mitchell, P.	Clerk (Temp.)	29/5/70
Smith, P.	Clerk	20/8/70
Gayski, A.	Laboratory Assistant	18/9/70
Jeffrey, S.	Geological Assistant	16/10/70
Allison, L.	Library Assistant	31/12/70

Transfers Out

Dunham, J.	Typist	3/11/70
Jennings, D.	Clerk	10/12/70

OPERATIONS

HYDROLOGY AND ENGINEERING GEOLOGY DIVISION

E. P. O'Driscoll (Chief Hydrogeologist), F. R. Gordon, T. T. Bestow (Supervising Geologists), K. Berliat (Senior Geologist), A. D. Allen, C. C. Sanders, B. R. Paterson, W. A. Davidson, J. A. Bunting, G. W. A. Marcos, R. Barnes and A. S. Harley.

Hydrology

The Government-assisted scheme of exploratory drilling for water in the drought-affected areas was completed in July. Some further drought relief work has been carried out in the last 3 months of the year in the Fitzgerald and Chillinup areas, where a limited programme of drilling has resulted in the discovery of new sources of supply on public reserves.

Drilling for the Metropolitan Water Board has continued in the Gnangara area, where another 68 boreholes have been sunk for pump testing or observation. A large programme of test pumping has been carried out in order to determine bore yields and aquifer characteristics.

An investigation into the groundwater potential of the De Grey-Shaw-Strelley river system has continued with a view to establishing additional water sources for the expanding needs of Port Hedland. Further refraction seismic and also resistivity surveys have been carried out on new section lines. An additional 30 boreholes have been drilled, about half of which have been test pumped. The large volume of data is in process of evaluation.

Although there has been no deep exploratory drilling in the Perth Basin this year, the collection of hydrographic data pertaining to the Pinjarra area has continued and this will be of considerable value in the later assessment of the infiltration conditions in this part of the Basin.

Water level recorders are being installed on strategically sited observation boreholes in all areas subject to long term investigation. The network of stations will provide valuable data for the assessment of water resources. The first water balance study based on such data was completed during the year.

Modifications to the Department's formation testing equipment have greatly improved its reliability in use which, together with the application of more sophisticated means of interpretation, has facilitated the derivation of more hydrologic data from tests. Four completely successful formation tests were run during the year on bores drilled for the Public Works Department. One of these was later developed for production and the results substantially confirmed predictions made by formation tests.

During the winter break in the drought assistance programme, it was possible to complete 21 boresite inspections for private landholders which, owing to staff shortages, had been outstanding since before the inception of drought relief in 1969. However, as the shortage of staff has continued, it has not proved possible to re-institute the inspection service.

Engineering Geology

The most important work of the year was the compilation of a Bulletin which is nearing completion, on the Meckering Earthquake. The earthquake was a remarkable scientific event but probaby the most significant aspect was the information it provided on earthquake mechanism and hazards in the State.

The stripping of the foundation area of the South Dandalup dam site enabled a study to be made of the relationship of the upper parts of the granite weathering profile to the bed rock types as shown in drilling.

Dam sites in the Upper Helena Valley and in the Darkin Valley were mapped as part of the feasibility study for the augmentation of the Goldfields Water Supply. Detailed studies at the Upper Helena site included the location and logging of six diamond drill holes and the logging of a centre line trench and numerous test pits in the foundation area and in proposed borrow locations.

Geological assistance was given to the consultant geologist, Mr. Peter Burgess, at the Ord River Main Dam. The successful completion of the foundation excavation of the dam and emplacement of the lower part of the dam and core, marks the virtual completion of a project with which the Geological Survey has been involved for over 10 years.

SEDIMENTARY (OIL) DIVISION

R. N. Cope, G. H. Low (Senior Geologists) and D. C. Lowry.

Details of exploration and production activities of companies were collated and appraised. Studies of the economic potential of Barrow Island oilfield and the Dongara gasfield were up-dated.

The surface mapping of the Perth Basin is being compiled and the assembly of the sub-surface information has commenced.

The manuscripts for a bulletin on the " Geology of the Western Australian part of the Eucla Basin " and the Phanerozoic stratigraphy for the " Geology of Western Australia " were completed and edited ready for publication.

A deep drilling programme for coal was carried out on the Collie Mineral Field where two areas were investigated as recommended in a report by Messrs. Menzies and Hanrahan. Reports on the projects are being prepared.

A reconnaissance was made of the Officer Basin in preparation for a regional survey commencing in 1971. This will be a joint project with the Commonwealth Bureau of Mineral Resources.

REGIONAL GEOLOGY DIVISION

J. L. Daniels (Supervising Geologist), I. R. Williams (Senior Geologist), P. C. Muhling, C. F. Gower and R. Thom.

Eastern Goldfields area

Geological mapping was completed on the Edjudina 1 : 250,000 Sheet area and compilation is in progress.

Compilation and drawing is continuing with the following 1 : 250,000 Sheet areas: Norseman, Zanthus, Balladonia, Malcolm, Esperance, Mondrain Island and Cape Arid.

Murchison area

Regional mapping of Yalgoo and the compilation of Murgoo sheet is continuing.

Blackstone-Warburton Area

A Bulletin on the geology of the Blackstone-Warburton area has been compiled and is being prepared for printing. The drawing of the Scott 1 : 250,000 sheet was finalised.

General

Compilation of a new State Geological Map is almost complete.

Some officers within the section have contributed several chapters to the Survey's Bulletin on the Geology of Western Australia.

In collaboration with the Engineering Geology section a study has been made of the drainage patterns of much of the western part of the State. This forms part of a larger study by the Engineering Geology section on the Meckering Earthquake.

The progress of geological mapping at 1 : 250,000 scale at the end of 1970 is shown in Figure 2.

MINERAL RESOURCES DIVISION

J. G. Blockley, J. D. Carter (Senior Geologists) and J. L. Baxter.

The study of the tin deposits throughout the State was continued. All field inspections and studies have been completed and the results are now being compiled ready for publication.

The suspected carbonatite occurrences near Mount Fraser were mapped in detail and a geochemical survey carried out. The results have been compiled.

A senior geologist (J. Carter) commenced the study, assessment and filing of geological information supplied to the Department with respect to exploration results on mining temenents.

The known reserves of ilmenite in the State were assessed by examining all deposits, which had been tested in the southwest area and scrutinising each company's estimates.

COMMON SERVICES DIVISION

Petrology—(J. D. Lewis and R. Peers)

During 1970 the Petrology Section provided services to all Divisions of the Geological Survey. Twenty-four written reports were made and petrological advice given to many geologists by personal discussion. Some identifications were made and advice given to the general public on specimens submitted.

Despite the disruption caused by moving to new accommodation, a record number of nearly 1,500 thin sections was prepared by the laboratory staff.

As there were no new regional mapping projects started this year no visits were made to field parties. Mr. Lewis spent 5 weeks during April and May investigating intrusive carbonate rocks near Meekatharra in conjunction with the geochemical investigations. In September Miss Peers made an extensive collecting trip in the Geraldton area in order to provide petrological data for the Northampton Block.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

1:250,000 OR 4 MILE GEOLOGICAL MAPPING

1970

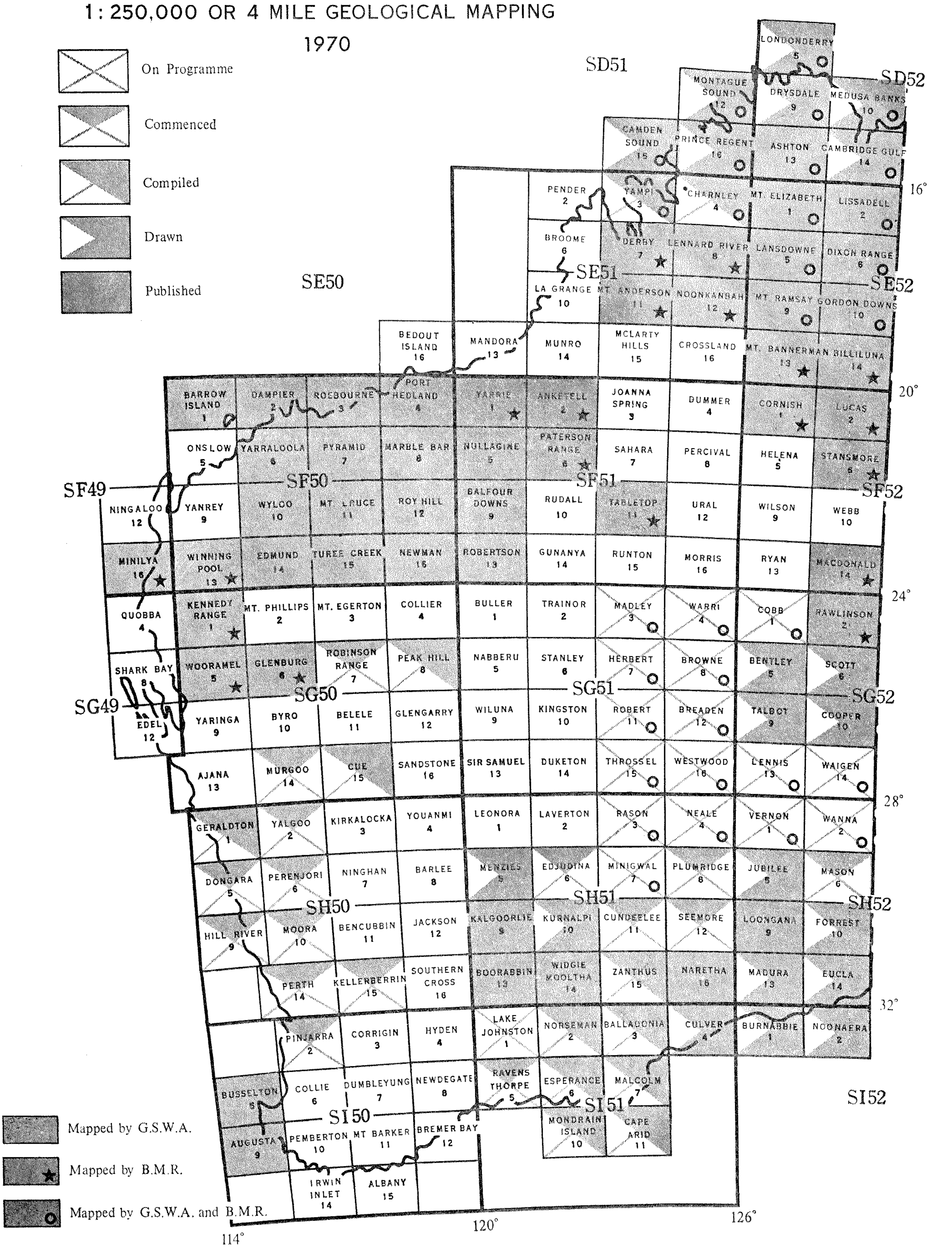

Fig. 2.

12296

The liaison with the Physics Department of the Western Australian Institute of Technology on geochronology continued and further reports on the results appear in this Annual Report.

As in previous years, chemical and mineralogical work carried out at the Government Chemical Laboratories has materially assisted many of the projects dealt with.

Palaeontology—(B. S. Ingram and J. Backhouse)

Much of the year has been devoted to routine palynological examination of bore samples for the Hydrology Division. This can be seen in the summary below of the 39 file reports prepared during 1970 (note : palynology and micropalaeontology sometimes attempted on the same samples).

Division requesting report	Field of Palaeontology		
	Macropalaeontology	Micropalaeontology	Palynology
Hydrology/Engineering	....	4	31
Sedimentary/Oil	....	....	1
Regional/Mineral Res.	1	....	1
Outside organisations	....	1	5

Both the palynological and the foraminiferal projects on the Ginginup corehole material are continuing, as is the benthonic foraminiferal study of the Plantagenet Group near Esperance. Some time has been spent assisting in arranging palaeontological displays for the Museum.

Mr. Backhouse was seconded to the Sedimentary Division for several months to assist in the supervision of the drilling in the Collie Basin.

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

There was a marked decrease in well-logging activities during 1970 as indicated by comparison with the 1969 statistics (in parenthesis). Forty-one (107) logging operations were carried out on 38 (103) individual bores to give a total of 31,760 (67,150) of footage recorded. Point resistivity and gamma-ray logs, run in a series of exploratory coal bores in the Collie Basin, materially assisted the project by providing accurate seam thicknesses in intervals of poor core recovery and by inter-bore correlations.

Normal laboratory services were maintained and 470 field determinations of water salinity made.

Geophysical surveys for underground water in the Pilbara, using seismic refraction and resistivity techniques, occupied 19 weeks' field work. The Port Hedland township supply project was continued and a locality near Roebourne was investigated. In all 40·4 line miles (68·3 km) of refraction shooting and 29 line miles (49 km) of resistivity profiling were completed and these results are being processed.

An experimental survey was made in the Pilbara to evaluate the efficacy of the gravity method to define high-grade hematite bodies beneath a cover of lower grade material. Whilst interesting anomalies were obtained, the low density contrast between the hematite and overlying goethitic canga and the ambiguities inherent in gravity interpretations coupled with severe terrain effects precluded reliable delineation of the ore bodies.

Geochemistry—(vacant).

A detailed geochemical survey using the mobile field laboratory was made on the Mount Fraser area, Peak Hill Goldfield where carbonatites were thought to occur.

A paper was prepared on the use of selenium as an indicator for mineralisation.

Since the resignation of Miss Williams no geochemical surveys have been attempted.

Technical Information—(J. Thom, V. Clure, M. Toledo and S. M. Fawcett).

This section has been called on in recent years to carry a heavy burden of work answering inquiries and providing advice arising from the mineral exploration boom. In order to cope with such activity quickly and efficiently, a great depth of local geological knowledge is required which can be only acquired by long experience in the section. Staff resignations, in particular that of Mr. R. R. Connolly, have left the section with no experienced officers. It will take some time before new staff can give a similar quick service again.

The section, in particular the library, has greatly improved facilities and conditions as a result of the move to Mineral House.

The library continues to be used extensively, especially by consultants and company geologists for reference. Loans to staff numbered 2,614 and to others 626 during 1970.

Requisitions raised on Surveys and Mapping Branch for drafting services and photography totalled 696. A larger portion of the copying of out-of-print publications is directed to other services.

Twenty-two records and one Information Pamphlet were prepared and issued during the year. Considerable time was spent in the preparation of manuscripts and proof-reading, as can be gauged from the Publications and Records listed later.

The new Geological Museum was established in Mineral House. While all showcase displays were ready for the official opening of the building, the displays in the drawers are still being developed.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

The geological and geophysical projects carried out by the Bureau of Mineral Resources included the following :—

1. Compilation of 1 : 250,000 geological sheets and bulletins on the Kimberley Division as a joint project with the Survey.
2. Continuation of the conodonts in the Bugle Gap area of the Canning Basin in conjunction with the Survey's studies.
3. Aeromagnetic and radiometric survey of Wiluna, Glengarry and Kingston 1 : 250,000 sheets at 1-mile spacings.
4. Continuation of the helicopter gravity survey of the State.
5. Preliminary survey for the proposed geological mapping of the Officer Basin in conjunction with this Survey.

PROGRAMME FOR 1971

HYDROLOGY AND ENGINEERING DIVISION

A. *Hydrology*

1. Continuation of the hydrological survey of the Perth Basin including deep drilling.
2. Hydrogeological investigations and/or exploratory drilling for groundwater in the following areas :—
   (a) Lake Gnangara extending to Yanchep-Pinjar area.

(b) Wiluna district—further drilling and pump testing.

(c) Pilbara area—further investigations on the de Grey river system and Harding River.

(d) Gascoyne—further drilling and assessment.

(e) Agaton area—additional bores with test pumping.

(f) Bunbury area—deep drilling.

(g) Town water supplies for following centres: Capel, Carnamah, Coolup, Leeman, Still Bay, Green Head, Esperance, Albany, Wedge Island, Cervantes and Ledge Point.

3. Hydrogeological Investigation for Metropolitan Water Board:—

   (a) Gnangara—development and test pumping.

   (b) Gwellup—logging and supervision of shallow and deep drilling.

   (c) Balcatta—logging of deep bores.

   (d) Commencement of a major regional study of Metropolitan area.

4. Kimberley—hydrological assistance to pastoralists.

   (a) Bore site selection as required.

   (b) Completion of compilation of hydrogeological mapping in conjunction with the Bureau of Mineral Resources.

5. Continuation of bore census work in selected areas.

6. Miscellaneous investigations as requested by Government departments and public.

B. *Engineering Geology*

1. South Dandalup Dam Site—progressive mapping of abutments, floor and trenches as required.

2. North Dandalup Dam Site—further mapping.

3. Harris River Dam Site—reconnaissance mapping and probable drilling.

4. Geological mapping of railway cuttings on standard gauge Perth-Northam.

5. Other investigations as requested by Government departments if staff is available.

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 1 : 250,000 geological map sheets of the Perth Basin.

4. Continuation of the subsurface study of the Perth Basin and the preparation of the Bulletin.

5. Commencement of the field work on the Officer Basin study in conjunction with the Bureau of Mineral Resources.

6. Completion of reports on drilling for coal on the Collie Mineral Field.

REGIONAL GEOLOGY DIVISION

1. Compilation of new State Geological map 1 : 2,500,000.

2. Compilation of the Edjudina and Murgoo 1 : 250,000 maps.

3. Commencement of field mapping of the Lake Johnston and Ravensthorpe 1 : 250,000 sheets.

4. Commencement of a re-assessment of the regional geology of the Eastern Goldfields (Menzies-Edjudina sheets to south coast).

MINERAL RESOURCES DIVISION

1. Continuation of the mineral survey of the Yalgoo and Murchison Goldfields.

2. Completion of a mineral resources bulletin on the tin deposits of Western Australia.

3. Continuation of a survey of the mineral sands resources of the State.

4. Miscellaneous investigations as required and dependent on the availability of staff.

PUBLICATIONS AND RECORDS

Issued during 1970

Annual Report 1969.

Publications catalogue 1970.

Bulletin 119: The iron formations of the Precambrian Hamersley Group, Western Australia with special reference to associated crocidolite.

Geological map of Ashton 1 : 250,000 sheet (SD/52–13 International Grid) with explanatory notes.

Geological map of Kalgoorlie 1 : 250,000 sheet (SH/51–9 International Grid) with explanatory notes.

Geological map of Loongana 1 : 250,000 sheet (SH/52–9 International Grid) with explanatory notes.

Geological map of Mount Elizabeth 1 : 250,000 sheet (SE/52–1 International Grid) with explanatory notes.

Geological map of Naretha 1 : 250,000 sheet (SH/51–16 International Grid) with explanatory notes.

Geological map of Wyloo 1 : 250,000 sheet (SF/50–10 International Grid) with explanatory notes.

In press

Bulletin 121—Devonian corals from the Canning Basin, Western Australia.

Bulletin 122—The geology of the Western Australian part of the Eucla Basin.

Geological maps 1 : 50,000, Perth Metropolitan area (4 sheets).

Geological map of Bentley 1 : 250,000 sheet (SG/52–5 International Grid) with explanatory notes.

Geological map of Cooper 1 : 250,000 sheet (SG/52–10 International Grid) with explanatory notes.

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

Geological map of Eucla/Noonaera 1 : 250,000 sheet (SH/52–14 International Grid) with explanatory notes.

Geological map of Madura/Burnabbie 1 : 250,000 sheet (SH/52–13 International Grid) with explanatory notes.

Geological map of Scott 1 : 250,000 sheet (SG/52–6 International Grid) with explanatory notes.

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

In preparation

Bulletin 123—Geology of the Blackstone Area, Western Australia.

Bulletin The Meckering Earthquake.

Mineral Resources Bulletin 9—Lead, zinc and silver deposits of Western Australia.

Geological maps 1 : 250,000 with explanatory notes, the field work having been completed: Peak Hill, Edjudina, Esperance, Murgoo.

Geological map 1 : 2,500,000 Western Australia.
Special publication, The Geology of Western Australia.

Records produced

1970/1 Explanatory notes on the Kurnalpi 1 : 250,000 geological sheet, by I. Williams.
1920/2 The geology and geochemistry of a cupriferous area at Yalgoo Goldfield, W.A., by J. Sofoulis and X. Williams.
1970/3 Explanatory notes on the Menzies 1 : 250,000 geological sheet, by M. Kriewaldt.
1970/4 Geochemical prospecting for copper, lead and zinc on the Northampton Mineral Field, by X. Williams.
1970/5 Explanatory notes on the Geraldton 1 : 250,000 geological sheet, by R. Horwitz, P. Playford, J. Baxter and R. Peers.
1970/6 Iron deposits of the Robinson Ranges, Peak Hill Goldfields W.A., by J. Sofoulis.
1970/7 Explanatory notes on the Cue 1 : 250,000 geological sheet, by L. de la Hunty.
1970/8 Geochemical survey of the Mount Frazer area, W.A., by X. Williams.
1970/9 Explanatory notes on the Norseman 1 : 250,000 geological sheet, by J. Doepel.
1970/10 Explanatory notes on the Zanthus 1 : 250,000 geological sheet, by J. Doepel and D. Lowry.
1970/11 Explanatory notes on the Balladonia 1 : 250,000 geological sheet, by J. Doepel and D. Lowry.
1970/12 Explanatory notes on the Malcolm 1 : 250,000 geological sheet, by J. Doepel.
1970/13 Selenium as a guide to mineral exploration, by X. Williams.
1970/14 Engineering geology reconnaissance of the Upper Helena and Darkin River Damsites, by P. Whincup (confidential).
1970/15 Gas reserves—Dongara, Yardarino and Mondarra, by A. Pippet (confidential).
1970/16 Gas Reserves, Barrow Island, by A. Pippet (confidential).
1970/17 Explanatory Notes on the Scott 1 : 250,000 geological sheet, by J. Daniels.
1970/18 The aquifer characteristics and yield of the Gnangara sand beds—1970 pump test series, by T. Bestow (restricted).
1970/19 Port Hedland water supply, geophysical investigations. Progress report 1970 (May), by I. Nowak (restricted).
1970/20 The ilmenite resources between Waroona and Augusta, W.A. 1970, by J. Baxter (confidential).
1970/21 The water balance in the North Gnangara area, by T. Bestow
1970/22 The Badja Granite, Yalgoo 1 : 250,000 geological sheet, by P. Muhling.

1st February, 1971.

J. H. LORD,
Director.

FINAL REPORT ON THE UNDERGROUND WATER INVESTIGATION FOR DROUGHT RELIEF 1969/70 IN WESTERN AUSTRALIA

by J. H. Lord

INTRODUCTION

The 1969 drought and the arrangements made by the Western Australian Government to assist in the search for underground water in the areas affected were outlined in the 1969 Annual Report of this Survey (Lord, 1970). The described methods of search were continued into 1970 until the end of the drought.

The serious drought situation was fortunately changed suddenly in February, 1970, when an unusual tropical cyclone, code-named "Glenis", traversed the eastern portion of the wheat belt. This brought drought-breaking rains, which filled many dams and relieved the water shortage in most of the drought areas, except the far southern areas. The emergency measures reduced quickly as areas were completed, until only two groups were operating, one in the far south and one in the Mount Marshall-Koorda Area. The last group completed its drilling programme in July, 1970.

INSPECTIONS

The procedure previously adopted was continued. Seven districts had been completed or were in progress at the end of 1969. As additional staff became available new areas for the scheme were selected by the Farm Water Supply Advisory Committee (F.W.S.A.C.). In all, inspections followed by drilling were carried out in 13 areas as shown on Plate 1.

After the cyclone, water supplies were adequate in most areas, except the far south in the Stirling and Ravensthorpe areas, where new areas were nominated by the F.W.S.A.C. and commitments in previously selected areas were met.

During the drought relief work a total of 575 private properties and 253 Government reserves were inspected, and drilling was recommended on 521 and 162 respectively (see Table 1). It should be remembered that the inspecting geologists were instructed to recommend drilling even if there was only a remote chance of locating water.

DRILLING

The drilling was continued along the lines described in the 1969 report. The Mayhew 1000 drills proved to be the faster and more adaptable for this type of work and are recommended for any such work in the future.

During the programme 220,781 feet (67,294m) of drilling was carried out. In addition, 1,663 feet (506·9m) were drilled in the Tunney area after a group of local property owners had employed a consulting geologist to make an inspection and choose sites on the properties concerned.

The cost of this drilling averaged about \$1·14 per foot. When the cost of inspections and supervision of drilling by geologists and field assistants was included the final cost was slightly below \$1·50 per foot of drilling.

There has been criticism of the drilling methods used, but nobody has been able to suggest an alternative procedure which would have allowed so much drilling to be done in such a short period of time at a comparably low cost.

Of the holes which were considered successful in the sense that they were classed as " Wet-suitable supply " (10 per cent), a few have proved not to be so, either due to insufficient supply or higher salinity. The emergency methods used are the reason for this. It should be remembered that no one has tested the holes classified " Wet-insufficient supply " (13·5 per cent) of " Wet-saline supply " (17 per cent) and it could be that a similar small number of these holes might have been success holes if more time and money had been expended on their development. Any property owner with a hole

TABLE 1. RESUMÉ OF INSPECTIONS AND RESULTS—DROUGHT RELIEF PROJECT, 1969–1970

Areas	Mount Marshall-Koorda	Westonia	South Yilgarn	South Burra-coppin	Mount Walker	Kulin-Kondinin	Holt Rock	Lake Grace	North Stirling	South Stirling	Nyabing-Pingrup	Ongerup	Ravens-thorpe	Total
Inspections—														
Private Property	31	24	15	21	32	33	49	52	26	43	83	121	45	575
Government Reserves	2	7	....	1	2	14	53	79	4	9	75	5	2	253
Total	33	31	15	22	34	47	102	131	30	52	158	126	47	828
Drilling Recommended—														
Private Property	24	22	15	21	25	31	49	43	24	39	77	111	40	521
Government Reserves	1	6	....	1	2	7	37	40	4	8	49	5	2	162
Total	25	28	15	22	27	38	86	83	28	47	126	116	42	683
Drilled Successfully—														
Private Property	9	9	1	6	8	6	28	6	14	24	7	35	21	174
Government Reserves	....	2	....	1	1	2	12	4	2	5	8	1	1	39
Total	9	11	1	7	9	8	40	10	16	29	15	36	22	213
Drilled Unsuccessfully—														
Private Property	15	13	14	15	17	25	21	37	10	15	70	76	19	347
Government Reserves	1	4	....	....	1	5	25	36	2	3	41	4	1	123
Total	16	17	14	15	18	30	46	73	12	18	111	80	20	470

TABLE 2. RESUMÉ OF DRILLING RESULTS—DROUGHT RELIEF PROJECT, 1969–1970

Areas	Mount Marshall-Koorda	Westonia	South Yilgarn	South Burra-coppin	Mount Walker	Kulin-Kondinin	Holt Rock	Lake Grace	North Stirling	South Stirling	Nyabing-Pingrup	Ongerup	Ravens-thorpe	Total	Per cent.
No. of Holes Drilled—															
Dry	90	159	74	105	85	120	105	173	20	34	251	160	30	1,406	53·3
Wet—Insufficient Supply	41	76	23	32	15	14	24	11	9	28	25	38	20	356	13·5
Wet—Saline Supply	5	22	3	9	14	14	34	31	21	35	109	134	18	449	17·0
Wet—Suitable Supply	10	22	1	12	12	10	43	11	16	31	30	43	22	263	10·0
Abandoned	20	4	5	17	19	4	1	20	2	10	26	32	5	165	6·2
Total	166	283	106	175	145	162	207	246	68	138	441	407	95	2,639	....
Footage Drilled—															Ave. Depth
Dry	8,710	8,144	7,021	9,114	8,137	9,013	6,664	14,233	1,519	2,486	16,477	12,673	1,879	106,070	75·4
Wet—Insufficient Supply	4,751	5,528	2,671	3,231	1,411	1,963	2,448	1,550	873	3,232	1,722	4,187	2,177	35,744	100·4
Wet—Saline Supply	330	1,900	290	1,067	1,243	1,804	3,220	2,585	1,647	2,431	7,899	12,579	1,179	38,174	85·0
Wet—Suitable Supply	868	1,816	30	1,069	1,184	1,343	4,427	1,306	1,239	3,843	2,660	5,020	1,925	26,730	101·6
Abandoned	1,240	165	356	1,961	2,421	310	168	1,660	107	963	1,715	2,813	184	14,063	85·2
Total	15,899	17,553	10,368	16,442	14,396	14,433	16,927	21,334	5,385	12,955	30,473	37,272	7,344	220,781	83·7
Water Located—															
Suitable supplies in thousands of gallons/day	23·6	77·5	1·2	19·7	20·0	83·8	207·6	25·6	144·3	234·7	63·2	202·0	81·7	1,285·0	....

which was "wet" but in which the supply was not up to 1,000 gallons (4,500 litres) per hour or the salinity was only just in excess of the maximum may find that a close investigation is warranted.

The logs of all holes drilled have been filed and incorporated in the hydrological records of the Geological Survey.

RESULTS

When considering the results of this operation it must be remembered and emphasised that many of the areas inspected and drilled were considered geologically unfavourable for underground water.

Despite this, one in ten of the holes drilled as classified as successful under the conditions of the project, namely 1,000 gallons (4,500 litres) or more per day with a salinity of less than 11,000 ppm (see Table 2). This success ratio varied greatly with the areas, the poorest being the South Yilgarn with one success every 106 holes with the best being the North Stirling area, with one success in 4·2. The Holt Rock area had a success ratio of one in five which was surprisingly good, and shows that in future more reliance should be placed on underground water supplies in this district.

When the drilling results are considered in terms of private properties drilled they show that water was found on one in every three of the properties recommended for drilling and one in 4·1 of the Government reserves.

The quantity of water found was usually in the range 1,000 gallons (4,550 litres) to 5,000 gallons (22,700 litres) per day. In the Holt Rock area larger supplies were located, with one bore producing 17,000 gallons (77,300 litres) per day. To the south, in the Stirling area, the Plantagenet rocks produced better supplies, with several bores yielding over 20,000 gallons (100,000 litres) and one bore 43,000 gallons (195,500 litres) per day.

The 263 successful bores located during the whole operation were tested to produce a total of 1,285,000 gallons (5,387,000 litres) per day, or an average of 4,800 gallons (21,800 litres) per day in each bore.

During the drought period the Government carted over 16 million gallons (73 million litres) of water to central tanks and dams at the cost of almost one cent per gallon. To this should be added the cost of the farmer carting the water up to 20 miles (32·2 km) to his farm.

So provided it is developed and used, the water is worth at least $12,000 per day. This would save the Government about one million dollars during a three-month drought if water had to be carted instead.

CONCLUSIONS

While the methods used may be criticised they proved successful under the emergency circumstances. The results more than justified the expense incurred when considered in the long term.

The programme has clarified the underground water potential in many difficult areas and the results, which are incorporated in the records of the Geological Survey, will be of great assistance in the future.

In some areas, such as Holt Rock, North and South Stirling, and Ongerup, property owners should be encouraged to investigate their properties for stock supplies of underground water. The methods used for drought relief are recommended for such testing.

In other areas, such as South Yilgarn, South Burracoppin, Mount Walker, and Lake Grace, the search for underground water by individual farmers cannot be recommended as the chances of success are very remote.

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THE WATER BALANCE IN THE NORTH GNANGARA AREA

by T. T. Bestow

ABSTRACT

The seasonal groundwater level fluctuations which have been recorded in the North Gnangara area over the period 1967 to 1970, together with the aquifer characteristics derived from pump tests, have been used to derive a simple water balance. In the absence of any surface run-off it is estimated that only 7·3 per cent of the mean annual rainfall contributes to groundwater discharge and the remainder is lost be evaporation or is transpired by vegetation.

INTRODUCTION

Since 1964 an intensive hydrogeological investigation has been in progress in the general area east and southeast of Lake Gnangara, some 12 miles (19 km) north of Perth. A programme of controlled test pumping on 13 sites has recently been completed (Bestow, 1970) which, together with some earlier results (Morgan, 1964 ; Sanders, 1965) now gives an adequate picture of the general hydrogeology.

The Metropolitan Water Board propose to abstract groundwater from the " North Gnangara " area (Plate 2) for public supply. There is consequently a need to assess the current water balance before there is any disturbance by pumping.

RAINFALL

The area has a mediterranean type of climate, with a rainfall almost entirely confined to the winter months. This is evident from Plate 3, which is based on a station just north of the area under discussion. In 1967–1970, 88 to 94 per cent of the total annual rainfall occurred in the 7 months April to October and 70 to 85 per cent in the 5 months May to September. The mean annual rainfall for these 4 years is 31·40 inches (79·76 cm) which includes the drought year of 1969, when the total rainfall was only 19·08 inches (48·46 cm).

GROUNDWATER MOVEMENT

The form of the water table on the 5th October, 1970, is shown on Plate 2. From a maximum elevation of 184 feet (56·1 m) at bore 12, the water table declines towards the south and southwest. These are also the general directions of groundwater movement. The hydraulic gradient varies appreciably from place to place with a range of between 6 and 20 feet ($1 \cdot 1$ to $3 \cdot 8 \times 10^{-3}$ to one) per mile. It is particularly steep in the vicinity of the three surface discharges for groundwater: Lake Gnangara (evaporation), Emu Swamp (evaporation) and Bennett Brook (springs). Apart from the last, there is no surface runoff in the drilled area. The water table is generally not more than 16 feet (4·8 m) below the surface within the North Gnangara area, and the average depth during the early winter is about 6 feet (1·8 m).

SEASONAL FLUCTUATIONS IN WATER LEVEL

The water table changes in elevation in response to rainfall, but data are lacking on differences of magnitude over the area of study. However, in the absence of any marked areal variations in rainfall, the amount of any rise that occurs will probably be the same throughout the area, and any associated increase in the regional hydraulic gradients will be slight. On a regional scale, seasonal changes of gradient are of the order of 3 feet (1 m) over 12 miles (19 km) or say 0·25 feet ($4 \cdot 7 \times 10^{-5}$ to one) per mile over a whole year. As the range of gradients has been established as 6 to 20 feet ($1 \cdot 1 \times 10^{-3}$ to $3 \cdot 8 \times 10^{-3}$ to one) per mile, seasonal changes are about 4 per cent. However, more marked seasonal changes of gradient are probable near the three surface outlets. The springs feeding Bennett Brook show increased discharges as the water table gradient steepens during winter rainfall.

Water levels in bore No. 5 from February, 1967, have been plotted (Plate 3), which indicates that the water table levels lie in the range 11·9 to 13·5 feet (3·63 to 4·12 m) below the surface, between mid-April and mid-May. The maximum elevations, which occur between August and September, lie in the range 6·9 to 9·6 feet (2·10 to 2·93 m) below the ground. Shortly after reaching a maximum the hydrograph tends to follow a straight line recession until next seasonal rise takes place.

SALINITY PATTERN

The water samples collected during pump testing had a range of total dissolved solids of 220 to 520 ppm, between one-half and two-thirds being sodium chloride. This is a low salinity and a sensitive guide to movement, and the extent to which the concentration of dissolved salt increases is apparent from the contours of equal chloride concentration (Plate 2).

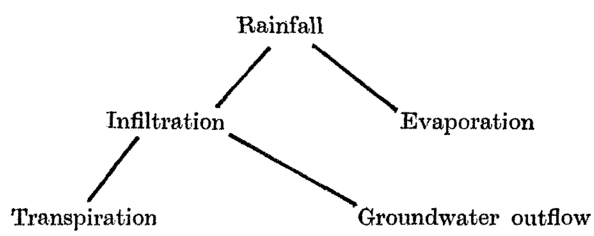
The chlorinity is least at bore 320, increasing towards the west, south and east. However, "troughs" of low chlorinity extend towards the three surface water outlets already referred to, corresponding to relatively high rates of groundwater movement in their directions. Conversely, relatively high chlorinities occur at bore 110 and west of Lake Gnangara.

THE WATER BALANCE MODEL

In the virtual absence of surface runoff, the hydrologic regime can be illustrated by a diagram, necessarily somewhat idealised because some components cannot be separated without more data.

Annual rainfall is divisible into two components, one which adds water to underground storage and another which does not. The latter includes direct evaporation, soil wetting and plant transpiration losses.

The infiltration of groundwater component is also divisible into a relatively small movement out of the area and a large transpiration loss.



Rainfall therefore contributes to four components, a composite and a simple component that may be directly derived from available data, and the remaining two by difference.

WATER BALANCE AT GNANGARA

The area analysed is between the 122 and 149–foot (37·2 and 45·4 m) water table contours (Sections A–A and B–B) bounded laterally by the curved lines A–B. This has a surface extent of 8·55 square miles (2,214 ha). Although a small part of the North Gnangara area near sites 130 and 140 is thus excluded, this is more than compensated for by the addition of an area west of site 200.

A further catchment area C–B–B of 2·71 square miles (702 ha), is also considered in the calculation.

Rainfall

Annual rainfall from 1967 to 1970 is in Table 1, together with the calculated input to the area A–B–B–A in millions of gallons. In the drought year 1969 this amounted to 2,420 million gallons ($11 \cdot 00 \times 10^6$ m^3), but the mean for the four years analysed is 3,980 million gallons ($18 \cdot 09 \times 10^6$ m^2).

TABLE 1. ANNUAL WATER BALANCE

Year	Water Level in No. 5 Bore (feet below surface)		Total Annual Rainfall (1)		Infiltration (2)			Evaporation (3)			Transpiration (5)			Groundwater Outflow (4)	
	Maximum	Minimum	Inches	Million galls.	Inches	Million galls.	% of (1)	Inches	Million galls.	% of (1)	Inches	Million galls.	% of (1)	Million galls.	% of (1)
1967	6·9	12·5	37·15	4,710	20·30	2,575	54·6	16·85	2,125	45·4	18·14	2,302	48·8	273	5·8
1968	7·5	11·9	35·57	4,510	19·80	2,512	55·6	15·77	1,998	44·4	17·65	2,239	49·6	273	6·0
1969	9·6	12·0	19·15	2,430	13·68	1,735	71·4	5·47	695	28·6	11·52	1,462	60·2	273	11·2
1970	8·7	13·5	33·75	4,280	19·22	2,438	56·9	14·53	1,842	43·1	17·07	2,165	50·5	273	6·4
Mean	....	....	31·40	3,980	....	....	59·6	....	....	40·4	....	....	52·3	273	7·3

(1 inch = 2·54 cm ; 1 foot = 0·305 m ; 1 million gallons = 4,546 m^3)

Total Infiltration

Most of the rain falls during a fairly short period of time and the water table responds sharply. Rorabaugh (1960) has shown that following such recharge the water levels fall exponentially with time after a period of stabilisation.

Although affected by summer rainfall, the groundwater hydrographs for Gnangara No. 5 bore do follow a fairly straight line recession at the rate of 10 feet change of level in 437 to 470 days (1 m in 143 to 154 days). Each period of rainfall imposes further recharge on an existing curve of recession, the volume of such infiltration being calculable from the curve displacement, if the specific yield of the re-saturated aquifer is known.

So far no pump test at Gnangara has continued long enough to cause complete gravity drainage, and hence the ultimate specific yield has not been determined. However there is little doubt that in an essentially unconfined aquifer, a relatively large figure is probable, and is here assumed to be 0·3.

As each water level recession is exponential, the amount of the displacement between the two exponential lines is time dependent. This displacement is larger if measured in the middle of the period of recharge than at the end. The actual elevations and the times of occurrence of the maximum and minimum water levels depend on the rainfall distribution, and should not be used to assess total infiltration. However, the water table response will be substantially complete after 95 per cent of the rain has fallen ; and appropriate time to measure the water table rise caused by infiltration. For 1967 (Plate 2) this rise is taken to be 5·64 feet (1·72 m) near the end of October. By chance the difference between the measured minimum and maximum water levels is 5·6 feet (1·71 m) (Table 1), and for this recharge period the infiltration is taken to be $5 \cdot 64 \times 12 \times 0 \cdot 3$ or 20·3 inches (51·6 cm). The infiltration for the succeeding 3 years has been similarly derived. However the displacement between the recession curves before and after recharge is larger than the difference between the minimum and maximum water levels by up to 58 per cent (for 1969) for the reason mentioned.

During the recharge period, water levels follow successive small recession curves after each rainfall, and also some evapo-transpiration will be occurring. It is not possible to take full account of these influences, so that the derived figure of infiltration must be regarded as that part of the total infiltration remaining after that period.

As determined, the infiltration accounts for between 54·6 and 71·4 per cent of the annual rainfall and is greatest when the water table is low.

Evaporation

This is taken as the difference between total annual rainfall and the infiltration figure just described. It necessarily includes water taken up by wetting the soil profile or used directly by plants both during and partly subsequent to the recharge period.

For natural water level fluctuations evaporation is greatest when the water table is at its shallowest, and lies in the range 28·6 to 45·4 per cent of the total annual rainfall.

Groundwater Outflow

This may be defined as the contribution to groundwater discharge made by rainfall on the area, and is the difference between the total groundwater outflow and groundwater inflow from outside the area.

Two methods may be used to estimate the groundwater outflow : one is by the application of groundwater hydraulics to flow through aquifer sections and the other is by estimating this from the degree to which cyclic salt becomes concentrated during subsurface water movement.

(a) *Hydraulic Method.* The inflow may be derived by the application to section B–B of d'Arcy's law, which states that the quantity of water passing is proportional to the permeability, hydraulic gradient, and cross sectional area.

The mean of the transmissivities derived from the pump tests on bores 300, 310, 320, 330 and 340 is 20,400 gpd/ft (304 m^3/day/m) and the mean hydraulic gradient is 12·6 feet per mile ($2 \cdot 39 \times 10^{-3}$ to one) (measured at six equally spaced points). The section is 2·375 miles (3·821 km) long. Hence

$$Q = 20{,}400 \times \frac{12 \cdot 6}{5{,}280} \times 2 \cdot 375 \times 5{,}280$$
$$= 610{,}500 \text{ gallons } (2{,}776 \text{ m}^3) \text{ per day.}$$

Similarly the total groundwater discharge may be calculated. The mean of the transmissivities obtained at sites 100, 110, 120, 130, 140 and 200 is 14,100 gpd/ft (210 m^3/day/m) and the mean gradient 15·7 feet per mile ($2 \cdot 97 \times 10^{-3}$ to one).

Thus as the section A–A is 5·0 miles (8·02 km) long the discharge

$$Q = 14{,}100 \times \frac{15 \cdot 7}{5{,}280} \times 5 \cdot 0 \times 5{,}280$$
$$= 1{,}107{,}000 \text{ gallons } (5{,}032 \text{ m}^3) \text{ per day.}$$

The net groundwater discharge due to rainfall within the area under study is 1,107,000 minus 610,500 or 496,500 gallons (2,257 m^3) per day.

(b) *Chlorinity method.* The aquifer has been continually leached during Quaternary time, and it is virtually certain that all the original salt has been removed, the only source of salt now present in groundwater being from rainfall. Teakle (1937) determined the mean salt (NaCl) content of the rainfall at the Perth Observatory (5¼ miles (8.4 km) east of the shoreline) as being 27.2 ppm by titration. The chloride ion concentration is thus

$$\frac{27.2 \times 35.5}{58.5} = 16.5 \text{ ppm.}$$

All this salt is retained within the soil, aquifer material, and groundwater. Through evaporation and transpiration losses, the salt becomes progressively concentrated during groundwater movement. The mean chlorinity of the groundwater passing through the section A–A is 141 ppm, hence it may be inferred that the rainwater falling on the catchment has become concentrated in the ratio 16.5 : 141, so that only the fraction $\frac{16.5}{141}$ of the total annual rainfall remains as groundwater discharge from that catchment.

The area of the catchment commanded by section A–A is 8.55 + 2.71 or 11.26 square miles (2,916 ha), hence if the mean annual rainfall is 31.40 inches (79.76 cm) the mean daily discharge is :

$$\frac{11.26 \times 31.40 \times 14.8346 \times 10^6}{365} \times \frac{16.5}{141} = 1.681 \text{ million}$$

gallons (7,642 m^3).

However, it is necessary to deduct the groundwater inflow through the section B–B, in order to determine what proportion of the total groundwater discharge originates solely within the defined area A–B–B–A.

The mean chlorinity in this section is 84 ppm and as the catchment area is 2.71 square miles (702 ha), the daily inflow is:

$$\frac{2.71 \times 31.40 \times 14.8346 \times 10^6}{365} \times \frac{16.5}{84}$$ or 679,000 gallons (3,087 m^3) per day.

The net groundwater discharge by this method is 1,681,000 minus 679,000 or 1,002,000 gallons (4,555 m^3) per day.

The mean of the discharges determined by the two methods is 749,000 gallons (3,405 m^3) per day or 273 million gallons (1.24×10^6 m^3) per year. As the hydraulic gradients are unlikely to vary appreciably with time under normal conditions, this discharge is not expected to vary greatly from year to year and it is suggested that 4 per cent (see p. 15) is the maximum regional order of variation from the mean. However for the present purposes the discharge is assumed to be constant and the mean annual rainfall contribution is 7.3 per cent.

Transpiration

After deducting the groundwater discharge, the rest of the total infiltration is lost by transpiration, abstraction by pumping, and by downward seepage to deep aquifers.

Pumping would appear, from the hydrographs to be increasing with time. In March to May 1970 the water level has clearly been lowered below the recession line. This is probably more than a local pumping effect near the observation bore, as the peak water level in 1970 falls below the predicted level (Plate 4).

The amount of downward seepage to deep aquifers is unknown, but should be determined by pump tests. There is nevertheless little doubt that a large proportion of water is lost by transpiration.

The transpiration loss is greatest when the water table is highest (18.14 inches at a peak water level of 6.9 feet below ground as compared with 11.52 inches when the peak level is 9.6 feet below ground).

CONCLUSIONS

1. Approximately 93 per cent of the mean annual rainfall of about 31.40 inches (79.76 cm) is currently being lost by evaporation and transpiration and only 7 per cent contributes to groundwater discharge.

2. When the water table is low, water losses by evaporation and transpiration are less than when water levels are high. It is anticipated that pumping will reduce such losses by lowering water levels.

3. Under relatively undisturbed conditions, evaporation and transpiration are increasing the concentration of dissolved salts as much as 12 times, and could similarly concentrate chemical and other non-volatile contaminants entering the aquifer.

4. Over a long period of abstraction, the resultant reduction in the evapo-transpiration loss would improve water quality with time as the proportion of "old" groundwater in storage is reduced.

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THE AQUIFER CHARACTERISTICS AND YIELD OF THE GNANGARA SAND BEDS 1970 PUMP TEST SERIES

by T. T. Bestow

ABSTRACT

Drawdown data derived from test pumping on 13 sites located in the North Gnangara area have been analysed by distance-drawdown methods to derive aquifer characteristics for the Quaternary sand aquifers. The analyses show these to have transmissivities in the range of approximately 6,200 to 36,500 gallons per day per foot (92·5 to 544 m^3/day/m) with a mean of 16,000 gpd/ft (239 m^3/day/m). However the aquifer storage coefficients at all sites have been shown to be dependent on the pumping time. This is due to delayed gravity drainage and it is anticipated that much longer periods of pumping would be required to determine the ultimate values than were available in the test series. The maximum values reached in 48 hours were found to be in the range 0·01 to 0·16.

INTRODUCTION

In the first half of 1970, 13 out of a total of 15 pumping boreholes, in a production field of about 7½ square miles (194 ha) had been test pumped. One was tested for a period of 3 days and the remainder for 2 days. Pumping rates were in the range 5,400 to 25,000 gph (589 to 3,434 m^3/day) with a mean of 12,800 gph (1,397 m^3/day).

The apparently low storage coefficient arrived at by computer-orientated analysis of aquifer characteristics based on leaky-artesian curve-matching techniques, gave cause for concern. A low coefficient would of course indicate that the quantity of water in storage could be less than that needed to sustain long term production, and that large long-term drawdowns would be inevitable.

The current study has therefore been directed to the following objectives:

1. To determine the general hydraulic conditions.
2. To assess the aquifer characteristics.

GEOLOGY

The Gnangara sand beds, which are of Quaternary age, consist of medium to fine-grained, poorly sorted sands with a variable clay content. Within the area of the current tests these sands reach a thickness of up to 170 feet (51·8 m). Locally, clay predominates to form more or less impermeable bands which may persist over appreciable areas. A sandy limestone occurs over parts of the area, particularly near the base of the sequence and immediately above the greensands and silts of the underlying Upper Cretaceous formations. The latter provides a slightly undulating floor which also marks the unconformity below the Quaternary.

HYDROLOGY

Groundwater occurs under essentially unconfined conditions within the sand beds, but may locally be subject to some degree of confinement below clay lenses. The water table is at a depth of between 3 and 15 feet (1 to 5 m) below the natural surface. Recharge takes place directly by infiltration from rainfall and there is also underflow from the north and northwest. The hydraulic gradient is about 13 feet ($2 \cdot 46 \times 10^{-3}$ to one) per mile (Plate 2 of Bestow, 1971). Groundwater discharge takes place by underflow to the southeast and southwest, by spring discharge in the vicinity of bore 140, and also by evaporation from swampy ground and by transpiration from plants. There may also be a downward movement of groundwater into the underlying Upper Cretaceous beds.

TEST CONDITIONS

At each test pumping site observation boreholes were laid out on two lines, approximately at right angles north-south and east-west with the pumping bore at the intersection. Observation bores were generally placed at 50 and 150 feet (15·2 and 45·7 m) on one line and at 75 and 225 feet (22·9 and 68·6 m) from the pumping bore on the other. These bores had 3-inch (7·6 cm) diameter PVC casing inserted, with slots at depths which corresponded with those in which a screen was installed in the pumping borehole. An additional observation borehole was sited approximately 100 feet (30·5 m) from the pumping bore, with casing slots over nearly the full thickness of the aquifer. The screen of the pumping bore was installed in the coarsest sand, the aperture size being determined as a result of sieve analyses of samples recovered from the test interval. A 60 per cent pass figure was taken as being the appropriate aperture size. Bore development was conducted by surging and air lifting.

METHODS OF ANALYSIS

The analyses and interpretation of pump test data must necessarily be based on certain assumptions having regard to the hydraulic conditions. However, natural conditions frequently diverge from the ideal and it is necessary to accept approximations in order to derive meaningful information, however approximate this may be.

Under conditions in which a borehole is pumped at a constant rate, and yet the resultant changes in hydraulic head in the surrounding aquifer have not reached equilibrium, it is theoretically possible by the Theis formula to relate the drawdown or lowering of head, which occurs at a particular distance from a pumping bore, to the aquifer characteristics. This is strictly applicable only if the following conditions pertain:

1. The water-bearing formation is isotropic or has uniform hydraulic properties in both horizontal and vertical directions.
2. The formation has a uniform thickness and is of infinite areal extent.
3. No addition or depletion of the volume of groundwater is made except by pumping.
4. The pumped well penetrates the full thickness of the aquifer.
5. The water removed from storage in the formation is discharged instantaneously as the head is reduced.

Although the Gnangara sand beds are of fairly uniform thickness through the area influenced by a lowering of the hydraulic head during the course of a particular pump test, the formation itself is far from uniform. Both vertical and horizontal variations in permeability undoubtedly occur within the area of influence of a pumping bore.

Although recharge may have occurred in the course of some tests as a result of rainfall, this is likely to have been slight. In no case did the pumping well fully penetrate the aquifer and in consequence the flow lines of water entering the pumping bore from the formation were convergent.

The modified Theis formula states that

$$s = \frac{114 \cdot 6\, Q \quad W(u)}{T}$$

Where s is the drawdown in feet at any point in the vicinity of a constantly discharging borehole, Q is the rate of discharge in gallons per minute.

T = transmissivity in gallons per day per foot.

W(u) is the well function of u.

The Theis formula also states that

$$u = \frac{1 \cdot 56\, r^2 S}{Tt}$$

Where r is the distance in feet from the centre of the pumping bore to the point of drawdown measurement.

S = coefficient of storage.

t = time since pumping started in days.

The parameters T and S may be derived by the well known method of matching a curve of log drawdown (for each observation bore) against log time on an appropriate scale with a master curve of W(u) versus u. Figures for u, W(u), S and t may be derived from a match point and applied to the above formula. However such simple matches are not possible with the data from Gnangara owing to divergence from the type curve. This divergence could be interpreted as a boundary condition consequent upon either recharge at a distance or leakage under confined conditions. Matches are in most cases obtainable with the curves of Hantush and Jacob (1955) which take account of downward leakage through a confining bed under essentially leaky artesian conditions. Pertinent figures for T may be derived by this method but it is questionable whether the vertical permeability or coefficient of storage (S) are valid owing to the difficulty of defining a confining bed and the fact that S is apparently not constant. It can be shown by other methods to vary with time.

One of the assumptions listed above in the derivation of the Theis formula is that the water removed from storage is discharged instantaneously with the decline in head. However, some unconfined aquifers drain relatively slowly within the cone of depression so that complete gravity drainage can take many days depending on the nature of the formation.

The problem of drainage or delayed yield has been analysed by Boulton (1954) who took account of differences of vertical and horizontal permeability. The analysis of pump test data by this method follows similar graphic techniques to Theis in that log plots of s against log time must be matched with type curves on an appropriate scale. However an unambiguous match can only be obtained by the continuance of pump tests for sufficiently long periods of time. In the case of the tests on the Gnangara sand beds this would be dependent on the vertical permeability and is estimated to be between 4 and 110 days. As only short term tests were carried out this method may not be applied.

Lohman (1970) has suggested in unpublished work that in an ideal test situation the coefficient of storage, S, should be calculated on intervals of say 2 days during a long period test and a graph prepared of S against t. This would show that S would approach a maximum value with time and that S and T should be determined for that time.

This period of time would be a constant for all observation wells, hence S and T could be calculated from an equation in which only s and r are variables. In the case of relatively thin unconfined aquifers Jacob's correction to the observed drawdown s and derived value of S should be applied in straight line solutions of the non-steady state flow equation derived by Cooper and Jacob (1946) and also Jacob (1950). Although this method has serious shortcomings in this context, it has been adapted for the derivation of the Gnangara sand bed aquifer characteristics as it is convenient and probably makes best use of the data provided by short term pump tests when S is not constant.

DERIVATION OF AQUIFER CHARACTERISTICS FROM DISTANCE DRAWDOWN

GENERAL APPLICATION

Cooper and Jacob showed that for small values of u, (i.e. $\frac{1 \cdot 56\ r^2\ s}{Tt}$ is less than ·01, the minor terms in the infinite series relating W(u) to u could be neglected so that

$$T = \frac{528\ Q}{\nabla s}$$

Where Q is discharge in gallons per minute and ∇ s is the slope of the distance-drawdown graph (i.e.) change of drawdown in feet over a log cycle plot of distance).

$$\text{and } S = \frac{0 \cdot 36\ Tt}{r_0^2}$$

Where r_0 is the distance at which the projected distance-drawdown line meets the zero drawdown axis (s = o).

However other authorities state that results are acceptable up to values of u of 0·05 (Johnson, 1966).

As the conditions for the Gnangara pump tests generally exceed the limit for u of 0·01 and indeed exceed 0·05 in many instances, it is necessary to be clear as to the effects exercised by the variables contained in this parameter.

$$U = \frac{1 \cdot 56\ r\ S}{Tt}$$

As S appears in the numerator it is obvious that other things being equal, u is larger for unconfined aquifers than it is for confined ones. When the method is applied to unconfined conditions t must be much larger than when testing under confined conditions. As r also appears in the numerator and is squared the use of drawdown measurements in distant bores required that t must be large to compensate. As T appears as a denominator, large values of transmissivity favour the use of the method, whereas small values necessitate larger values of t.

GNANGARA SAND BEDS

The water level measurements for all boreholes subjected to test pumping at t = 45m, 1½h, 3h, 6h, 12h, 24h and 48 hours have been corrected in accordance with Jacob on the presumption that the Gnangara sand beds are underlain by essentially impermeable material.

$$s^1 = s - \frac{s^2}{2b}$$

Where s^1 is corrected drawdown, s is measured drawdown and b is saturated aquifer thickness.

These corrected data have been used to prepare distance-drawdown graphs for each of the sites tested (Plate 5). So far as is practicable, separate lines have been drawn for each of the times listed above. The straight line plots have been drawn through the mean of the drawdown points where these do not actually fall on a straight line. The data provided by boreholes that are not responding to pressure changes have been ignored. In consequence of this, the plots relating to only three sites actually use the data from all five observation boreholes and six plots use the data from only three observation bores.

In most instances the distance-drawdown plots are nearly parallel, which gives consistent values of transmissivity. However at Site 200 marked changes in the slope of the distance-drawdown plots with time probably reflect variations in the pumping rate (Plate 5).

Values of T and S have been calculated from the Cooper and Jacob formulae for each of the times listed, between 45 minutes and 48 hours, and are shown in Table 1.

TABLE 1. AQUIFER CHARACTERISTICS DERIVED FROM DISTANCE/DRAWDOWN

Gnangara Borehole No.	Pumping Rate (gph)	Aquifer Thickness b(feet)	Time		Radius of Depletion Cone r_0 feet	Slope of d.d Plot s	Transmissivity T gallons/day/ft	Storage Coefficient	
			Hours	Days				Derived S	Corrected S^1
100	6,000	135	¾	·03125	154	8·3	6,450	·003	·003
			1½	·06250	171	8·3	6,350	·005	·005
			3	·125	184	8·3	6,350	·008	·007
			6	·25	190	8·2	6,400	·16	·015
			12	·5	190	8·1	6,500	·032	·029
			24	1	195	8·1	6,500	·065	·060
			48	2	195	8·1	6,500	·120	·110
						Mean	6,420		
						Estimated....	6,400		
110	15,300	140	¾	·03125	210	9·5	14,200	·0036	·0033
			1½	·06250	220	9·5	14,200	·0066	·0062
			3	·125	220	9·5	14,200	·0130	·0120
			6	·25	230	9·1	14,800	·0250	·0230
			12	·5	230	9·6	14,100	·0480	·0430
			24	1	230	9·6	14,100	·0970	·0890
			48	2	240	9·6	14,100	·1800	·1600
						Mean	14,240		
						Calculated....	12,000		
120	7,000	127	¾	·03125	340	5·0	12,300	·001	·001
			1½	·06250	366	5·0	12,300	·002	·002
			3	·125	460	4·6	13,400	·003	·003
			6	·25	460	4·6	13,400	·006	·006
			12	·5	460	4·6	13,400	·012	·011
			24	1	460	4·6	13,400	·023	·022
			48	2	460	4·6	13,400	·046	·043
						Mean	13,080		
						Rounded	13,000		

TABLE 1: AQUIFER CHARACTERISTICS DERIVED FROM DISTANCE/DRAWDOWN—*continued*

Gnangara Borehole No.	Pumping Rate (gph)	Aquifer Thickness b(feet)	Time		Radius of Depletion Cone r_0 feet	Slope of d.d Plot s	Transmissivity T gallons/day/ft	Storage Coefficient	
			Hours	Days				Derived S	Corrected Si
130	20,000	129	¾	·03125	330	9·1	19,300	·002	·002
			1½	·06250	330	9·4	18,700	·004	·004
			3	·125	345	9·3	18,900	·007	·006
			6	·25	355	9·3	18,900	·013	·012
			12	·5	370	9·3	18,900	·025	·022
			24	1	380	9·3	18,900	·047	·042
			48	2	390	9·3	18,900	·089	·080
						Mean	18,900		
						Estimated....	18,700		
140	14,000	124	¾	·03125	660	8·3	14,900	·0004	·0004
			1½	·06250	620	9·0	13,700	·0008	·0007
			3	·125	780	8·3	14,900	·0009	·0008
			6	·25	830	8·3	14,900	·0019	·0017
			12	·5	1,300	7·0	17,600	·0019	·0017
			24	1	960	8·0	15,400	·006	·0054
			48	2	1,000	8·1	15,200	·011	·0099
						Mean	15,200		
						Estimated....	15,000		
200	11,900	157	¾	·03125	410	3·25	32,400	·002	·002
			1½	·06250	410	4·20	25,000	·003	·003
			3	·125	440	5·25	19,800	·005	·005
			6	·25	405	6·50	16,100	·009	·008
			12	·5	420	6·60	15,900	·016	·015
			24	1	420	6·70	15,700	·032	·030
			48	2	420	7·10	14,800	·060	·056
						Mean ...	20,000		
210	6,500	159	¾	·03175	320	8·35	6,850	·0008	·0007
			1½	·06250	330	8·60	6,650	·0014	·0013
			3	·125	330	8·90	6,400	·0026	·0024
			6	·25	340	8·80	6,500	·0051	·0047
			12	·5	350	8·75	6,500	·0095	·0081
			24	1	360	8·70	6,550	·0180	·0170
			48	2	370	8·70	6,550	·0340	·0310
						Mean	6,570		
						Estimated....	6,200		
220	10,000	144	¾	·03125	310	6·45	13,600	·0016	·0015
			1½	·06250	460	5·90	14,900	·0016	·0015
			3	·125	580	5·75	15,300	·0020	·0018
			6	·25	630	5·75	15,300	·0035	·0033
			12	·5	660	5·80	15,200	·0063	·0059
			24	1	650	5·75	15,300	·0130	·0120
			48	2	650	5·75	15,300	·0260	·0240
						Mean	15,000		
						Estimated....	15,000		
300	25,000	161	¾	·03125	370	14·30	15,400	·0013	·0011
			1½	·06250	480	13·80	16,000	·0015	·0013
			3	·125	560	13·60	16,200	·0023	·0020
			6	·25	590	13·50	16,300	·0042	·0037
			12	·5	610	13·45	16,300	·0078	·0068
			24	1	610	13·45	16,300	·0156	·0140
			48	2	610	13·45	16,300	·0312	·0250
						Mean	16,100		
						Estimated...	16,100		
320	7,000	164	¾	·03125	390	5·25	11,700	·0009	·0008
			1½	·06250	400	5·20	11,800	·0017	·0016
			3	·125	420	5·15	11,900	·0030	·0029
			6	·25	410	5·30	11,600	·0062	·0059
			12	·5	430	5·25	11,700	·0110	·0100
			24	1	440	5·20	11,800	·0290	·0210
			48	2	450	5·20	11,800	·0440	·0420
						Mean	11,800		
						Estimated....	11,500		
330	5,400	112	¾	·03125	265	1·80	26,200	·0042	·0041
			1½	·06250	340	2·10	26,700	·0044	·0043
			3	·125	400	2·05	23,600	·0065	·0064
			6	·250	640	2·10	22,700	·0097	·0095
			12	·5	500	2·05	23,200	·0170	·0170
			24	1	520	2·00	23,800	·0320	·0310
			48	2	550	2·00	23,800	·0570	·0560
						Mean	23,700		
						Estimated....	23,500		
340	20,800	155	¾	·03125	275	9·95	18,400	·0027	·0025
			1½	·06250	280	10·05	17,400	·0050	·0045
			3	·125	275	11·70	15,700	·0074	·0066
			6	·25	280	11·70	15,700	·0180	·0160
			12	·5	290	11·70	15,700	·0340	·0300
			24	1	300	11·75	15,600	·0620	·0550
			48	2	310	11·80	15,500	·1100	·0980
						Mean	16,300		
						Calculated from Theis curve (at t = 48h)	13,200	·173	·154
25	12,120	126	¾	·03125	540	10·7	10,000	·0004	·0004
			1½	·06250	760	10·5	10,200	·0004	·0004
			3	·125	1,000	10·4	10,300	·0005	·0004
			6	·25	1,400	10·0	10,600	·0005	·0004
			12	·5	1,560	10·2	10,500	·0008	·0007
			24	1	1,700	10·2	10,500	·0014	·0012
			48	2	1,800	10·3	10,400	·0024	·0021
			96	4	1,900	10·4	10,300	·0043	·0037
			192	8	1,900	10·4	10,300	·0086	·0075
						Mean	10,300		

1 gph = 0·1091 m^3/day; 1 ft = 0·3048 m; 1 gallon per day per foot = 0·01491 m^3/day/m.

Fairly typical conditions are displayed at Site No. 140 where bore 140F was pumped at 14,000 gallons per hour (152 m^3/day) and the rate of drawdown increase per log cycle of distance is 8·3 feet (2·53 m) (from Plate 5) at 45 minutes.

Then

$$T = \frac{528 \times Q}{\Delta s} = \frac{528 \times 14{,}000}{8 \cdot 3 \times 60}$$

= 14,900 gallons per day per foot (222 m^3/day/m)

The distance-drawdown line intercepts the zero drawdown axis at 660 feet and as

$$S = \frac{0 \cdot 36\ T\ t}{r_0^2} = \frac{0 \cdot 36 \times 14{,}900 \times 0 \cdot 03125}{660^2} = 0 \cdot 0004$$

As the aquifer tested is relatively thin, it is necessary to apply a correction to this value of storage coefficient so that $S' = \frac{(b - s')}{b} S$

where s′ is the drawdown at the geometric mean distance.

In this instance

$$S' = \frac{(124 - 11 \cdot 5)}{124} 0 \cdot 0004$$

= 0·0004 (to the nearest whole figure)

For this value of S and at r = 226 feet (68·9 m)

$$u = \frac{1 \cdot 56\ r^2\ S}{Tt} = \frac{1 \cdot 56 \times 226^2 \times \cdot 0004}{14{,}900 \times \cdot 03125} = 0 \cdot 068$$

This is in excess of the ideal limit of 0·01 and also the desirable limit of 0·05 (at the outermost observation borehole).

However a check drawdown calculation at r = 226 feet (68·9 m) may be made by applying the Theis equation to using the parameters derived from the distance-drawdown calculation.

$$s = \frac{114 \cdot 6\ Q\ W(u)}{T}$$ so that for

u = 0·068

W(u) = 2·178 and

$$s = \frac{114 \cdot 6 \times 14{,}000 \times 2 \cdot 178}{14{,}900 \times 60}$$

= **3·91 feet (1·189 m)**

This corresponds closely with the corrected measured drawdown of 3·89 (1·186 m) and as the value of u decreases for observations nearer the pumping borehole it follows that the values of S and T derived for this period of pumping are substantially correct.

Values of S and T may be similarly calculated for Site No. 140 from the distance-drawdown data for the pumping periods 1½ to 48 hours. At 48 hours

$$T = \frac{528 \times 14{,}000}{60 \times 8 \cdot 1}$$

= 15,200 gallons per day per foot (227 m^3/day/m) and

$$S = \frac{0 \cdot 36 \times 15{,}200 \times 2}{1{,}000^2} = 0 \cdot 011$$

$$S' = \frac{(124 - 12 \cdot 1) \times 0 \cdot 11}{124} = 0 \cdot 0099$$

The results of calculations (Table 1) for the intermediate pumping times show that the derived values of T remain within comparatively narrow limits. However the values of S almost double with each doubling of the pumping time (t). This relationship is plotted graphically in Plate 6.

The value of u increases with each increase in S and decreases with every increase in t. Nevertheless as S is not directly proportional to t, u tends to decrease with increasing pumping time.

In the case of No. 140 site at t = 2 days and r = 226

$$u = \frac{1 \cdot 56 \times (226)^2 \times 0 \cdot 009}{15{,}200 \times 2} = 0 \cdot 026$$

This value involves a negligible error in the calculation of S and T.

EFFECTS OF HIGH VALUES OF THE PARAMETER u

When a distance-drawdown analysis is made of other pump tests the value of u is generally greater than 0·068 and reaches a maximum at Site 340 when relatively high values of S have been derived. Here u = 0·88 at 45 minutes and 0·246 at 2 days. It is therefore pertinent to compare the straight line solutions with the matching curve technique in order to assess the magnitude of the error involved in the method adopted.

At this site, observation bores B (at r = 78·75 feet (24·00 m)), C (at r = 223·5 feet (68·12 m)) and D (at r = 45·5 feet (13·87 m)) responded to pumping from bore F; and a log-log plot of draw-down (s) against r^2 matches the Theis curve at each of the two sets of three points (for t = 45 minutes and 48 hours) (Plate 5).

The match point for t = 45 minutes corresponds to

W(u) = 10

$\frac{1}{u}$ = 10

r^2 = 6,200 feet (18·90 m)

s = 28 feet (8·53 m)

and as Q = 20,800 gph (2,269 m^3/day)

$$T = \frac{114 \cdot 6\ Q\ W(u)}{s} = \frac{114 \cdot 6 \times 20{,}800 \times 10}{60 \times 28}$$

= 14,200 gpd/ft (212 m^3/day/m)

and

$$S = \frac{T\,t\,u}{1 \cdot 56 \times r^2} = \frac{14{,}200 \times 0 \cdot 03125 \times 0 \cdot 1}{1 \cdot 56 \times 6{,}200} = 0 \cdot 0044$$

then applying Jacobs correction

$$S_1 = \frac{(155 - 13 \cdot 6)}{(155)} \cdot 0044 = 0 \cdot 0040$$

The match point for 48 hours corresponds to

W(u) = 10

$\frac{1}{u}$ = 10

r^2 = 9,800 feet (2,990 m)

s = 30 feet (9·1 m)

Q = 20,800 gph (2,269 m^3/day)

so that

$$T = \frac{114 \cdot 6 \times 20{,}800 \times 10}{60 \times 30}$$

= 13,200 gpd/ft (197 m^3/day/m)

and

$$S = \frac{13{,}200 \times 20 \cdot 1}{1 \cdot 56 \times 9{,}800}$$
$$= 0 \cdot 173$$
$$S' = \frac{(155 \times 16 \cdot 8)}{155} 0 \cdot 173$$
$$= 0 \cdot 154$$

The errors involved in the straight line solution which have been adopted for this bore (and hence probably the maximum errors for the test series) can be summarised:

t	u	Storage Coefficient			Transmissivity (gallons/day/ft.)		
		st. line solution	matching curve	error	st. line solution	matching curve	error
45m	0·88	0·0025	0·0040	—35%	18,400	14,200	+30%
48h	0·246	0·0980	0·1540	—36%	15,500	13,200	+17%

1 gallon/day/ft = 0·01491 m^3/day/m.

Even an error of 36 per cent is probably less than the range of permeabilities and storage coefficients which exist at each site and is within the range of observational errors possible in the pump tests. The straight line distance-drawdown method of analysis therefore provides a reasonable order of recovery to meet the objectives of the study.

AQUIFER CHARACTERISTICS

Transmissivity

As will be seen from Table 1, the transmissivities derived by the distance-drawdown method for each site generally fall within a narrow range for the period of time over which the analyses have been applied, i.e. 45 minutes to 48 hours. The range of transmissivities derived from the tests on Sites 220, 300 and 340 is appreciable and is thought to be due to variations in the pumping rate in the first 1½ hours. The much more extreme range of transmissivities derived for Site 200 is thought to be due to an increasing pump rate during the test. In consequence of this no great reliance can be placed on the mean transmissivity figure of 20,000 gpd/ft (298 m^3/day/m) calculated for this site. It is more probably nearer 14,000 gpd/ft (209 m^3/day/m).

The estimated transmissivities for each of the test sites show a range from 6,200 (92·5) for Site 210 to 36,500 (544) for Site 310 with a mean for all sites of 16,000 gpd/ft (239 m^3/day/m). As the mean saturated thickness is 147 feet (44·8 m) this represents a mean permeability of 109 gpd/ft^2 (5·32 m^3/day/m^2). This is a value typical of a fine sand (Hurr, 1966); however the range of values indicates a typical grading from very fine sand to medium sand.

Storage coefficient

The distance-drawdown analyses clearly demonstrate the time dependence of the value of S derived by the method (Plate 6). In about half of the tests the cone of depression reached near-equilibrium after 6 hours and the remainder in 12–24 hours. The test on Site 200 was exceptional in that equilibrium was apparently not reached until after 48 hours of pumping. This characteristic clearly shows that, subsequent to equilibrium, the pumping rate was largely sustained by gravity drainage within the cone of depression. All tests demonstrate a roughly constant relationship between S and t after equilibrium, so that for every doubling of the pumping time the derived value of S is increased by 80 to 100 per cent. In no case has the pumping continued sufficiently long for gravity drainage to reach completion within the cone of depression, so that even after 48 or 72 hours of pumping the storage coefficient was continuing to rise. During the period subjected to analysis (45 minutes to 48 hours), the values of S increased to between 16 and 52 times the initial value; and the final 48 hour values (corrected for "thin" aquifer conditions but *not* for u), reached between 0·0099 and 0·16. A few of the real values could be up to 40 per cent higher after correction for high values of u.

It is nevertheless clear that the ultimate (long term) value of S would be very much higher than any of those derived from the current series of tests. The nearly straight line relationship between S and t exhibited by the log-log plots on Plate 6 indicates that in order to reach an S value of 0·3 the tests would need to have been prolonged to minimum periods of between 3·8 and 110 days. As these periods of time are approached it is probable that the relationship between S and t will cease to be linear and become asymptotic to S, in which case very much longer periods of pumping could be needed.

The ultimate value of S could be greater than 0·3 but cannot be assessed until after an appropriately long period of pumping. There is no method of analysis available which will provide an accurate figure for S without long period pump tests.

COMPARISON OF RESULTS WITH THE PUMP TEST ON GNANGARA No. 25

A 12–day pump test was carried out during the latter half of 1966 on borehole No. 25E in South Gnangara. The rate of pumping was 205 gallons per minute, and water levels were observed in bores spaced, 9, 244, 245 and 457·9 feet (2·7, 74·4, 74·7, 139·6 m) from the pumping bore. A Theis drawdown analysis (by J. R. Passmore) derived the following aquifer characteristics:

		T gpd/ft	T m^3/day/m	S
Bore 25A	(r = 457·9′)	9,200	137	0·000157
		10,250	153	
Bore 25B	(r = 244′)	43,800	596	0·004840
Bore 25C	(r = 9′)	11,800	176	0·000094
	Mean	13,700	200	0·0017

The same distance-drawdown analysis as that applied to the recent pump tests has now been applied to the No. 25E test. The data are plotted on Plate 5 for the following times: 45 m, 1½ h, 3 h, 6 h, 12 h, 24 h, 48 h, 96 h, and 192 hours (corrected figures). The values of T and S have been derived by the application of the Jacob-Cooper distance-drawdown formulae and are listed in Table 1.

The calculated values of u for the most distant borehole exceed 0·05 for times shorter than 3 hours, but are less for all times and observation bore distances thereafter. The method is therefore fully applicable for the greater part of the test. The distance-drawdown plots indicate that equilibrium was not reached until relatively late in the test (after 24 hours pumping) by which time the cone of depression had extended to 1,700 feet (518 m), a distance in excess of any of the more recent tests.

The transmissivities derived by the method lie in the range 10,000 to 10,600 gpd/ft (149 to 158m^3/day/m) with a mean of 10,300 gpd/ft (154 m^3/day/m) which is close to the values obtained from two out of three observation bores using the Theis matching curve method. This value of transmissivity comes in the lower half of the range exhibited by the current series of tests.

However, the values of storage coefficient rise in the course of the test from 0·0004 to 0·0075 (at 192 hours), but exhibit a rate of increase with time similar to the current tests. It is nevertheless clear that it took longer for gravity drainage to commence at No. 25 Site than at any of the present sites, and also it would take substantially longer for this to reach a maximum value.

The storage coefficient/time graph (Plate 6) indicates that a minimum pumping period of 720 days would be required to reach a storage coefficient of 0·3.

SUMMARY AND CONCLUSIONS

1. The aquifer transmissivities lie in the range 6,200 to 36,500 gallons per day per foot (92·5 to 544 m^3/day/m) with a mean of 16,000 gpd/ft (230 m^3/day/m), which for an average aquifer thickness of 147 feet (44·8 m) represents a permeability of 109 gpd/ft (5·32 m^3/day/m^2). This value corresponds to a "fine sand" grading.

2. Under abstraction conditions the Gnangara sand bed aquifer appears to pass through three hydraulic stages: a comparatively rapid initial development of the cone of depletion which, in the present pumping field takes up to 3 hours, a period of near-equilibrium during which the water pumped is largely obtained by relatively slow gravity drainage, and a final phase in which the cone of depression continues to expand in response to further dewatering. The current tests were confined to the first two stages.

3. During the first stage of testing, the storage coefficients derived by distance-drawdown analysis were in the relatively low range of 0·0004 to 0·004. However, in the course of the second stage of testing, the storage coefficients rose to a value at 48 hours of 14–52 times the initial value, reaching maxima of at least 0·01 to 0·16. Owing to the method of derivation these values are very approximate and real values may be as much as 40 per cent. higher.

4. It is evident that had the pump tests continued for much longer periods, aquifer drainage would have continued and larger storage coefficients would have been derived. By extrapolation, it is estimated that the minimum pumping time required to achieve aquifer drainage, to a storage coefficient of 0·3, would be between 3·8 and 110 days. However, the behaviour of the system under conditions approaching complete gravity drainage is not known, and very much longer periods might be required.

5. A comparison of the results from the current series of tests with those of Gnangara No. 25 Site, suggests that essentially similar hydraulic conditions exist in the southern part of the Gnangara area. It is nevertheless true that No. 25E bore would require a much longer period of pumping for gravity drainage to approach completion (at least 720 days at S = 0·3).

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HYDROGEOLOGICAL RECONNAISSANCE OF PARTS OF NABBERU AND EAST MURCHISON MINING AREAS 1970

by C. C. Sanders and A. S. Harley

ABSTRACT

A survey was made to locate possible shallow aquifers in the Nabberu Mining District, north and east of Wiluna.

The most promising formations yielding large supplies of generally good quality groundwater are alluvial and calcrete valley fills. Other rock types give small supplies of variable quality water.

Several areas are suggested for further hydrological study.

INTRODUCTION

During 1970, the groundwater resources of part of the Nabberu and East Murchison mining areas were investigated. The survey extended over six 1 : 250,000 Geological Sheets, of which Nabberu and Stanley were intensively traversed for existing bores and wells. Some minor traverses, mainly in areas of known watering points, were made on Herbert and Robert Sheets at the western margin of the Officer Basin, and some hydrologic information from Wiluna and Kingston was updated (Sanders, 1969).

Groundwater is mainly in valley fill alluvial and colluvial deposits, although some is obtained from fractured sandstones, shales and dolomites, and weathered greenstones.

The water resources near Wiluna have been documented by others, principally Ellis (1953), Chapman

(1962), and Mabbutt and others (1963), who recognised the aquifer potential of calcrete and alluvial valley fills. At Wiluna, during the peak of gold mining operations, the consumption of potable or slightly brackish groundwater from 34 shallow calcrete wells was up to 1,000,000 gallons ($4 \cdot 5 \times 10^6$ l) per day. Elsewhere in the East Murchison extensive calcrete and alluvial deposits are known to yield large supplies of good quality groundwater (Sanders, 1969).

The present aim was to assess the hydrological potential north and east of Wiluna, in anticipation of water requirements for expanding mining activities.

Plate 7 shows drainage trends, catchment areas, and bore and well salinities; Plate 8 the interpretive solid geology.

REGIONAL GEOLOGY

There is little documented geological information on the area and Plate 8 has been compiled from photo-interpretation, augmented by field observations.

The region falls within the Salinaland and Sandland physiographic divisions of Jutson (1950), characterised by internal drainage terminating in salt lakes. The western four sheets form part of the Precambrian Plateau, with the Archaean Yilgarn block unconformably overlain to the north by Proterozoic sediments. Eastwards, undifferentiated Permian and Mesozoic rocks in the Officer Basin overlie the Precambrian basement and possibly rocks of Lower Palaeozoic age. Capping much of the area is Tertiary and Quaternary alluvial and colluvial material.

ARCHAEAN

The greater portion of the Archaean basement is a series of granites intruding older metasedimentary and metavolcanic rocks. The metasediments are water-laid acid tuff, sandstone, banded chert and banded iron formation, and minor black shale and greywacke. These are interbedded with metavolcanics, which range from acid to basic in composition, and are intruded by sills and minor acid to ultrabasic dykes.

The rocks have a characteristic vertical dip with a northwesterly to northerly strike. The Archaean rocks are deeply weathered, the degree depending on both the chemical and textural composition, and mode of formation.

PROTEROZOIC

These rocks are mainly of sedimentary origin, comprising interbedded quartzite, shale and dolomite, with minor banded iron formation, greywacke, conglomerate and limestone. Some of the carbonate rocks have algal structures and oolitic bands. Some acid volcanics have been reported (Horwitz and Daniels, 1967, p. 51). Lithologically the rocks are comparable with the lower division of the Middle Proterozoic Bangemall Group (Daniels, 1966).

Generally the beds have a shallow dip to the northeast, complicated by at least two fold periods, a primary northwesterly axial direction with a superimposed northeasterly one.

Fine to medium-grained dolerites intrude several areas; two sulphide-rich granophyric intrusions on the southwestern side of the Parker Range dolerite on the Stanley Sheet being probably differentiates unrelated to the exposed dolerite.

LOWER PALAEOZOIC

There is a single outcrop of basalt in the northeastern corner of the Robert Sheet, which is thought to be Ordovician (Lowry, 1970).

UNDIFFERENTIATED PERMIAN AND MESOZOIC

These rocks crop out as mesa and butte features overlying Precambrian and Lower Palaeozoic on the eastern part of the area.

Along the western edge of the zone the outcrops are deeply weathered, partly ferruginised shales, with occasional erratics mainly of granite and quartzite and localised layers of siltstone and sandstone. The beds are probably Permian glacial deposits.

Farther east on Herbert and Robert Sheets, are outcrops of tillite with some erratics, shale, siltstone and sandstone (Lowry, 1970). Only the Permian tillite, and some fossiliferous siltstone beds assigned to the Cretaceous, can be dated.

TERTIARY-QUATERNARY

Sandplain, lake deposits, and desert eolian sands make up more than 50 per cent of the land surface, with alluvial/colluvial and calcrete valley fills occupying about another 5 per cent.

The oldest rocks are on remnants of the ancient plateau preserved mainly north of the Lake Nabberu-Lake Carnegie drainage system. Ferruginous laterite and siliceous duricrust cap most of the surface remnants. After lateritisation during a period of high rainfall, an intensely arid climate produced accumulations of thick eolian sands on the older surface.

The resultant sand plains form a distinctive geomorphological unit between the high bedrock outcrops and the regional drainage lines.

Rock units of the older plateau have extensive marginal colluvium often cemented to form very resistant talus.

Near drainage lines the colluvium becomes finer grained and merges with fluviatile material transported by infrequent floods, the sediments ranging from fine silt and clay to coarse conglomerate. The fluctuating intensities of rainfall and runoff have caused sharp vertical depositional changes in the rock type and therefore the permeability.

The main drainage valleys and most fossil drainage channels have rubbly calcrete overlying fluviatile material, the calcrete in some areas reaching 30 feet (9 m) in thickness and forming the most promising aquifers. Wide calcrete valley tracts often continue for many miles, the most extensive being on Glenayle Station in the northern part of the Stanley Sheet. Patchy calcrete occurs as dissected remnants of what were probably much larger deposits around the salt lakes.

The lower valley tracts and lake basins have fine-textured saline alluvium interbedded with lime, gypsum and salt. Mabbutt and others (1963) report that the amount of fill in some lake basins may exceed 150 feet (46 m) as in Lake Way, south of Wiluna.

ORIGIN OF CALCRETE

Calcrete deposits are common on the Proterozoic rocks of Nabberu and Stanley Sheets, decreasing towards the south and east. Sanders (1969) points out that calcretes in the East Murchison are similarly common in the north, but south of Wiluna become restricted to the main fossil drainages and relict patches bordering the larger salt lakes. The patchy distribution and confinement to drainage lines indicate a genetic and depositional control different from that of the kankar deposits of the Eastern Goldfields, which are the result of soil-forming processes akin to the caliches of Texas and New Mexico.

Calcrete, a calcium and minor magnesium carbonate, probably formed as a primary chemical precipitate from solution in ground and surface waters. Soufoulis (1963) suggested that calcretes were deposited from 'ponded' sections of the drainage after cessation of a past period of high rainfall. However he does not indicate whether this is an annual and cyclic event over a long period, or just long term continued chemical precipitation from supersaturated surface waters. The present authors consider that ponding can explain large areas of calcrete, but that slow replacement by lime of fluviatile silts and gravels was and is aiding in the formation of calcrete. The silica is probably reconstituted as chert. In the Wiluna area localised calcrete within extensive alluvial sediments suggests this latter process.

A major problem is the source and quantity of lime required for the development of extensive calcrete deposits. It has been suggested that the high carbonate concentration resulted from slow water movement over calcium-rich basic and ultrabasic igneous rocks, but most calcrete deposits are in areas away from the Archaean greenstone belts, mainly centred in Proterozoic sediments. It is therefore likely that the dolomites and limestones of the Proterozoic province are also major contributors of lime for calcretes, especially in the area surveyed where few basic rocks are found.

HYDROLOGY

Prior to field inspection, all main drainages and calcrete areas were identified on air-photographs. Nearby bores and wells were sampled, an almost complete census of watering points being made on the northern and eastern sheets.

Groundwater is very common, but is shallowest and freshest in alluvial deposits and the fine gravel and calcrete of the valley fills. These are more extensive on the Stanley Sheet than on Nabberu, Kingston, and Wiluna. Fluviatile deposits are uncommon in the desert basin of Herbert and Robert Sheets, but calcrete occurs as patchy and massive deposits in some depressions, being often obscured by dune sands, but easily identifiable on air-photographs, which also show broad drainage patterns trending toward the calcrete. The drainage lines are difficult to discern on the ground because of movable dunes, the drainages probably becoming active only during rare flash floods. Unfortunately there is no groundwater information available from this area.

Groundwater is at present used for pastoral purposes, domestic and stock requirements being very small compared with potential reserves. The reported yields from bores and wells are not considered reliable, as supplies are usually governed by equipment used, and yields reflect demand rather than potential.

The water table generally is between 10 feet (3 m) and 50 feet (15 m) below natural surface, although it may be as deep as 120 feet (36 m) in zones of fractured or weathered Archaean or Proterozoic rocks. In alluvial and calcrete areas the water table has uniformly low hydraulic gradients and is at shallow depth.

Replenishment occurs entirely from rainfall and mainly during major storms. In the Wiluna-Carnegie area, recharge rates have been calculated by Chapman (1962) for catchments at Lorna Glen Station on Kingston Sheet, and at Wiluna; and also by Sanders for Wiluna, assuming that average groundwater flow equals the long term average recharge. At Lorna Glen, Chapman calculated recharge at 1·3 per cent of the mean annual rainfall on the 50 square miles (129 sq km) of immediate alluvial and calcrete catchment area, while at Wiluna a figure of 3·3 per cent was computed for 100 square miles (259 sq km) of catchment. From the results of recent pumping tests on new bores in fluviatile sediments at Wiluna, Sanders considers between 2·8 per cent and 3·2 per cent of the mean annual rainfall infiltrates to the water table in the 100 square miles (259 sq. km) of alluvium and calcrete catchment. As the catchments at Lorna Glen and Wiluna are similar to others in the region it is reasonable to apply a recharge coefficient of 3 per cent of mean annual rainfall to most trunk valley sediments. On this basis, potential recharge to an aquifer can be estimated. For example, for the calcrete and alluvial aquifer north and east of Glenayle Station homestead, Stanley Sheet (Plate 7, catchment C) with an extent of about 147 square miles (381 sq km) and an assumed average yearly rainfall of 8 inches (20·3 cm), the estimated potential recharge is 1,880 acre feet ($2{\cdot}32 \times 10^6$ cu m) per year.

Similar calculations have been made for other drainage systems, (Plate 7), (Table 1).

TABLE 1. OCCURRENCE, SALINITY, CATCHMENT AREA, POTENTIAL RECHARGE AND YIELD FOR SELECTED ALLUVIAL AND CALCRETED AQUIFERS

1:250,000 Sheet	Station or Locality	Catchment (Plates 7 and 8)	Water Quality ppm TDS	Immediate catchment area, square miles (Plate 8) °	Potential annual recharge, acre feet (assumed mean annual rainfall 8 in., 20·3 cm)‖	Maximum reported yields in gallons per day (gpd)
Nabberu	Cunyu	A	430–6,420	79·0	1,010	1 well, 20,000 gpd*
Stanley	Glenayle	B	3,500	22·8	292	
	Glenayle	C	545–4,400	147·0	1,880	
	Wongawol	D	400–5,000	120·4	1,540	1 well, 35,000 gpd* 1 well, 20,000 gpd* 5 wells, 12,000 gpd*
	Wongawol	E	500–?	62·7	800	1 well, 8,000 gpd*
	Carnegie	F	1,360–7,800	57·0	730	{1 well, 16,000 gpd* {2 wells, 12,000 gpd*
Herbert	'Herbert Wash'	G	....	69·0	880	
Wiluna	Wiluna	H	600–4,000	100·0	1,350†	2 bores, 408,000 gpd
Kingston	Lorna Glen	I	600–2,300	50·0‡	350‡	1 well, 280,000–480,000 gpd
	Windidda	J	....	55·9	720	
	Windidda	K	1,228–?	74·6	950	1 well, 9,000 gpd*
Robert	Robert Desert Basin	L	....	89·3	1,140	

* Indicates pump capacity rather than potential yield of well or bore.
† Computed from pumping tests (Sanders).
‡ Computed from pumping tests, and surface mapping, T. Chapman (1962).
1,350 acre feet per annum is equivalent to a daily extraction of about 1,000,000 gallons.
° Immediate catchment area includes alluvium and calcrete as shown in Plates 7 and 8.
‖ Potential recharge calculated on basis of 8 in. annual rainfall over the region and 3 per cent infiltration to water table.
1 square mile = 2·589998 square kilometres ; 1 acre foot = 1,233·489 cubic metres ; 1 imperial gallon = 4·545961.

Because arid zone drainages are essentially influent, groundwater extraction should not exceed recharge and annual recharge estimates give some idea of possible aquifer yields.

Permian and Mesozoic. Where seen outcropping in the desert areas of Herbert and Robert Sheets, these sediments were generally too fine grained and well indurated to be useful aquifers.

Table 2 gives standard chemical analyses of some bore and well waters.

TABLE 2. STANDARD CHEMICAL ANALYSES OF WATER FROM SOME WELLS AND BORES

Analyses	Cunyu Homestead No. 1 Bore	Glenayle Well	Glenayle Sandy Well	Wongawol Niminga Bore	Wongawol Learys Bore	Carnegie Homestead Bore	Wiluna Town Well 112	Millbillillie Top Kuku-bubba Well	Lorna Glen East Mill Well
Catchment	A	C	C	F	....	....	H	H	I
pH	8·0	8·0	8·1	7·7	8·0	7·9	8·1	7·3	7·7
Total Dissolved Solids, ppm—									
by evaporation	910	1,820	970	1,570	300	1,050	800	2,320	600
by conductivity	980	1,810	1,020	1,600	310	1,060	740	1,880	560
NaCl	445	862	438	806	91	422	239	565	216
Total hardness	364	644	401	631	75	326	380	1,340	260
Total alkalinity	153	281	217	188	95	215	176	233	160
Ca	60	106	75	126	18	63	78	333	66
Mg	52	92	52	77	7	41	45	124	23
Na	148	342	150	260	69	224	106	173	82
K	30	47	28	26	9	20	9	15	16
Fe	<0·05	<0·05	<0·05	<0·05	<0·05	<0·05	<0·1	<0·05	<0·1
HCO_3	186	342	265	229	116	262	214	284	195
CO_3	....	....	....	....	....	....	....	....	....
Cl	270	523	266	459	55	256	145	343	131
SO_4	104	297	96	242	24	187	166	936	38
NO_3	102	147	89	126	47	85	85	57	91
SiO_2	71	76	93	80	34	47	80	45	76
B	0·6	0·8	0·4	0·6	0·5	0·9	....	0·8	....
F	0·8	1·5	1·1	1·2	0·7	1·0	....	1·0	....

Areas worthy of further investigation are:

NABBERU 1 : 250,000 *SHEET*

At *Cunyu Station* 40 miles (64 km) north of Wiluna, potable water is obtained from alluvium and calcrete. One bore for domestic purposes has been tested at 20,000 gallons per day (0·09 x 10^6 l) but no other adequate pump-tests have been made.

The drainage system (A) near Cunyu Homestead trends north into Lake Nabberu, has a catchment area of 79 square miles (205 sq km) and an estimated recharge of 1,010 acre feet (1·25 x 10^6 cu m) per annum. Brookfield *in* Mabbutt and others (1963) considered the catchment area to be 240 square miles (622 sq km) from air-photograph interpretation of the drainage divide; and by applying a recharge coefficient of 1 per cent of the mean annual rainfall for 'depositional land surfaces' and 5 per cent for 'erosional land surfaces', estimated the annual recharge at 4,500 acre feet (5·55 x 10^6 cu m).

The present survey suggests that this latter figure is probably too large.

STANLEY 1 : 250,000 *SHEET*

1. *Glenayle Station* near the northwest corner of Stanley Sheet is at the junction of two fossil calcrete drainage systems (catchments B and C, Plate 7).

There are few bore and well data, especially for catchment B with only one well. Groundwater is used mainly for stock, and wells are developed only to a depth where sufficient supply is obtainable for immediate needs. Well and bore logs are unrecorded and the true depth of calcrete or alluvium is unknown. No adequate pump testing has been done.

For catchment B the groundwater salinity is 3,500 ppm TDS in the existing well, and the estimated annual potential recharge is 292 acre feet (0·36 x 10^6 cu m).

Catchment C is very extensive, having an immediate catchment area of 147 square miles (381 sq km) and an estimated recharge of 1,880 acre feet (2·32 x 10^6 cu m) per year. This figure may be conservative. Proven groundwater salinity ranges from 545 to 4,400 ppm TDS.

2. *Wongawol Station* occupies much of the central Stanley Sheet.

There is a narrow alluvial and patchy calcrete drainage on the southern side of the Parker Ranges, (catchment D) trending southeast along Oolgahroo Creek and finally broadening out into an area of massive calcrete centred about Aqua Spring. Groundwater salinities range from 400 to 5,000 ppm TDS, one well having been tested at 35,000 gallons (0·16 x 10^6 l) per day and five other wells at 12,000 gallons (0·05 x 10^6 l) per day. The total depth of calcrete is not known. The catchment area is about 120 square miles (311 sq km) and estimated recharge is 1,540 acre feet (1·90 x 10^6 cu m) per year.

Two catchments trending east and north-east into Lake Burnside occur on the eastern part of *Wongawol Station* and on *Carnegie Station:*

(i) *Catchment E* is mainly alluvial along tributaries to Genbirr Creek. Potential is considered poor, as the catchment area is about 63 square miles (163 sq km) with a recharge potential of 800 acre feet (0·99 x 10^6 cu m) per annum in poorly permeable formations.

(ii) *Catchment F* along Lalalline Creek comprises areas of massive calcrete and alluvium containing groundwater of 1,360 to 7,800 ppm TDS salinity. One well has been tested at 16,000 gpd (0·07 x 10^6 l) and another two at 12,000 gpd (0·05 x 10^6 l). Although the catchment area, 57 square miles (148 sq km) is smaller than 'E', groundwater extraction would probably be easier because of the high calcrete permeability. Estimated recharge is 730 acre feet (0·90 x 10^6 cu m) per year.

HERBERT 1 : 250,000 *SHEET*

The *Herbert Wash* (G) near the eastern boundary is a broad expanse of massive calcrete. The area is at least 69 square miles (179 sq km) with a conservative recharge potential of 800 acre feet (0·99 x 10^6 cu m) per annum. The Wash is a centre of internal drainage and has a large potential for development, except for its inaccessibility. The groundwater quality is unknown.

WILUNA 1 : 250,000 *SHEET*

This sheet was previously reported by Sanders (1969). However, recent work on the East Wiluna aquifer (H) indicates a safe annual extraction of 1,350 acre feet (1·67 x 10^6 cu m) of groundwater containing less than 2,500 ppm total salts. Yields as high as 408,000 gpd (1·85 x 10^6 1) can be expected from bores.

KINGSTON 1 : 250,000 *SHEET*

1. Chapman (1962) calculated that 350 acre feet (0·45 x 10^6 cu m) of irrigation water per year was available from an area near *Lorna Glen Station*. The catchment area is about 50 square miles (129 sq km) and yields of between 280,000 (1·27 x 10^6 1) and 480,000 gpd (2·18 x 10^6 1) can be expected.

2. On *Windidda Station* two main calcrete and alluvial catchments (J and K) drain north and east into Lake Carnegie. Groundwater information is scant, and reliable groundwater data are available from only one well. Estimated annual recharge for catchment J is 720 acre feet (0·89 x 10^6 cu m) and for catchment K 950 acre feet (1·17 x 10^6 cu m).

ROBERT 1 : 250,000 *SHEET*

No adequate hydrological information is available from the broad desert basin area, although extensive calcrete is apparent on air-photographs. Catchment L has an area of 89 square miles (230 sq km) of calcrete, with a possible yearly recharge of 1,140 acre feet (1·40 x 10^6 cu m).

Empress Spring near catchment L was reported by David Carnegie in 1896 as being in limestone with potable water at a depth of about 50 feet (15 m).

CONCLUSIONS AND RECOMMENDATIONS

Alluvium and calcrete are mainly untested but seem the most promising aquifers in the region.

Further hydrological studies could be made, including drilling, in a number of areas mainly on Nabberu and Stanley Sheets. Broad drainages in the vicinity of Glenayle and Carnegie Stations on Stanley Sheet, and Cunyu Station north of Wiluna, have most potential for groundwater development.

Some broad calcrete areas in the Officer Basin could store large volumes of good quality water. As yet this area is inaccessible.

The Permian and Mesozoic sediments appear to have little potential as good aquifers.

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PETROLEUM EXPLORATION IN WESTERN AUSTRALIA IN 1970

by R. N. Cope

INTRODUCTION

Exploration drilling took place predominantly on the continental shelf of Western Australia during 1970, thus continuing the trend begun in 1968–69. No discoveries of petroleum were made although an 800 bbls (127 m^3) day flow of oil was encountered in the gas appraisal well Dongara No. 19 (see p.32). In September 1970 the Dongara Gas-field was declared to be commercial. The only encouragement encountered was hydrocarbon indications in Flag No. 1, Ripple Shoals No. 1 and Pepper No. 1 (see below).

The amount of exploratory drilling again decreased in 1970 as compared with the previous year, as shown below:—

	1969	1970
New field wildcat wells	14	10
Extension test wells	3	0
Stratigraphic test wells	4	1
Total footage	149,521	103,917
(metres)	(45,572)	(31,672)

One of the wells completed in 1970, Flag No. 1, had already reached 10,871 feet (3,313 m) in 1969, and four new field wildcat wells were still drilling at the end of 1970.

Other exploration activity in 1970 remained at a similar level to that of 1969, as illustrated below:—

Type of Survey	1969 Party months	1970 Party months
Land seismic	20·05	39·1
Marine seismic	12·13	8·6
Aeromagnetic	10,675 line miles	0
Gravity	0	2·0
Geological	6·25	9·8

OIL TENEMENTS

The conversion of tenements held under the Petroleum Act (1936) to conform with the Petroleum Act (1967) has proceeded smoothly and at the end of 1970 the only remaining tenements held under the 1936 Act are Petroleum Leases 1H and 2H relating to oil production at Barrow Island (Plate 9).

As part of the process of transfer of titles, certain onshore areas were relinquished by the holders in the Perth, Carnarvon and Canning Basins. On 11th September, 1970 these areas, together with certain fringe basinal areas not so far released, totalling about 41,000 square miles (106,190 km^2), about 85,000 square miles (220,150 km^2) of the Officer Basin and some 19,000 square miles (49,210 km^2) of the offshore Eucla Basin, were gazetted as available for application under Section 30 of the Petroleum Act, 1967, and Section 20 of the Petroleum (Submerged Lands) Act, 1967 (see Plate 9). The total acreage available for bidding was divided into 30 areas onshore (up to 200 5-minute blocks) and 2 offshore (up to 400 5-minute blocks). For the 18 Officer Basin areas, the closing date set was 1st February, 1971 and for the remaining onshore and the offshore areas, the date was 16th November, 1970. Applications for the latter areas were under consideration at the end of the year.

An important stipulation, additional to those of the Petroleum Acts, attached to the release of the above areas for petroleum prospecting, is that during the first 2-year period the successful applicant will be unable to transfer or dispose of the Exploration Permit and will be held responsible for ensuring that the work commitments of any farm-out agreement which may be entered into are carried out.

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 (Lakes Entrance) Oil Co. N.L., Shell Development (Australia) 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	" " " "
WA-8-P	18	17/6/75	Coastal Petroleum N.L.
WA-9-P	56	17/6/75	" " "
WA-10-P	36	15/6/75	" " "
WA-12-P	5	11/9/75	Associated Australian Oilfields N.L.
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	Australian Aquitaine Petroleum Pty., Arco Ltd.
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 Australia N.L.
WA-20-P	34	10/10/74	West Australian Petroleum Pty. Ltd.
WA-21-P	241	14/11/74	" " " "
WA-22-P	81	3/10/74	" " " "
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., Philips Australian Oil Co., Sunray Australian Oil Co. Inc.
WA-27-P	294	18/5/75	" " " "
WA-28-P	375	24/3/75	Woodside (Lakes Entrance) Oil Co. N.L., Shell Development (Australia) 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 Australia Pty. Ltd., Abrolhos Oil N.L.
WA-40-P	102	12/3/75	" " " "
WA-41-P	33	15/6/75	Coastal Petroleum N.L.
EP 3	200	27/8/75	West Australian Petroleum Pty. Ltd.
EP 5	132	26/7/75	" " " "
EP 6	199	27/8/75	" " " "
EP 7	200	27/8/75	" " " "
EP 8*	200		" " " "
EP 9	200	27/8/75	" " " "
EP 12	182	3/9/75	" " " "
EP 13	200	27/8/75	" " " "
EP 14	200	27/8/75	" " " "
EP 15	200	27/8/75	" " " "
EP 16	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	....	Australian Aquitaine Petroleum Pty. Ltd.
EP 21	90	26/7/75	West Australian Petroleum Pty. Ltd.
EP 23	172	6/8/75	" " " "
EP 24	172	6/8/75	" " " "
EP 25	96	6/8/75	" " " "
EP 26	1	27/8/75	BP Petroleum Development, 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 Exploration Pty. Ltd., and Australian Aquitaine Petroleum Pty. Ltd.
EP 32*	200	....	" " " "
EP 33*	200	....	" " " "
EP 34*	1	....	Woodside (Lakes Entrance) Oil Co. N.L., Shell Development (Australia) Pty. Ltd., B.O.C. of Australia Ltd.
EP 35*	1	....	" " " "
EP 36*	1	....	" " " "
EP 37	149	22/9/75	West Australian Petroleum Pty. Ltd.
EP 38	130	22/9/75	" " " "
EP 39	160	22/9/75	" " " "
EP 40*	81	....	" " " "
EP 41*	188	....	" " " "
EP 42	200	1/9/75	" " " "
EP 43	163	1/9/75	" " " "
EP 44	113	1/9/75	" " " "
EP 45	197	19/11/75	" " " "
EP 46	199	1/9/75	" " " "
EP 47	199	19/11/75	" " " "
EP 48	199	19/11/75	" " " "
EP 50	110	1/9/75	" " " "
EP 51	57	8/9/75	Lennard Oil Pty. Ltd.
EP 52	34	8/9/75	" " "
EP 53	49	15/9/75	West Australian Petroleum Pty. Ltd.
EP 54	123	22/9/75	Alliance Oil Development Aust. N.L.
EP 55	178	22/9/75	West Australian Petroleum Pty. Ltd.

PETROLEUM LEASES

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

* These tenements had been applied for but had not been approved by 31st December, 1970.

DRILLING

The positions of wells drilled for petroleum exploration in Western Australia to the end of 1970 are shown in Plates 10 to 12. The general data relating to each well are given in Table 1.

WELLS DRILLED FOR PETROLEUM EXPLORATION IN WESTERN AUSTRALIA DURING 1970

Basin	Well	* = Subsidised	Concession	Operating Company	Type	Position: Latitude South	Position: Longitude East	Elevation and water depth: G.L.	Elevation and water depth: D.F. K.B.	Elevation and water depth: W.D.	Dates: Commenced	Dates: Reached T.D.	Dates: Completed	Total depth or (depth reached) in feet B.D.F.	Bottomed in	Status
						° ′ ″	° ′ ″									
Perth	Charlotte No. 1	*	WA-14-P	Wapet	NFW	31 48 36	115 26 56	....	99	—132	19/12/70	....	....	5,153	....	Drilling
	Roe No. 1	*	WA-13-P	Wapet	NFW	31 56 28	115 19 07	....	100	—345	23/11/70	13/12/70	18/12/70	7,001	U. Jurassic	P & a
	Warnboro No. 1	*	WA-14-P	Wapet	NFW	32 14 20	115 20 45	....	79	—156	26/11/70	....	....	11,859	....	Drilling
Carnarvon	Flag No. 1	....	WA-23-P	Wapet	NFW	20 27 55	115 38 44	....	+76	—44	2/9/69	13/1/70	3/2/70	12,475	U. Jurassic	P & a
	Pepper No. 1	....	WA-23-P	Wapet	NFW	21 03 29	115 18 05	....	+90	—25	13/3/70	3/5/70	8/5/70	9,000	U. Jurassic	P & a
	Ripple Shoals No. 1	....	WA-23-P	Wapet	NFW	21 07 10	115 24 07	....	+79	—26	6/2/70	4/2/70	9/3/70	7,476	U. Jurassic	P & a
	Tryal Rocks No. 1	....	WA-25-P	Wapet	NFW	20 24 42	115 09 08	....	+93	—152	17/5/70	16/8/60	24/8/70	12,123	U. Jurassic	P & a
	Enderby No. 1	*	WA-1-P	B.O.C.	NFW	20 09 25	116 24 24	....	+30	—177	13/9/70	10/10/70	14/10/70	7,051	? Triassic	P & a
	Legendre No. 2	*	WA-1-P	B.O.C.	NFW	19 37 27	116 46 49	....	+30	—190	16/10/70	16/12/70	23/12/70	11,871	? L. Jurassic	P & a
Canning	Napier No. 4	*	EP 52	Lennard	STR	16 55 00	124 05 35	....	300	....	15/7/70	18/8/70	22/8/70	3,166	Precambrian	P & a
	Napier No. 5	*	EP 52	Lennard	NFW	17 06 30	124 28 06	232	243	....	8/9/70	19/10/70	27/10/70	5,437	Precambrian	P & a
	Lacepede No. 1A	*	WA-31-P	B.O.C.	NFW	17 05 18	121 26 42	....	30	—191	21/6/70	16/8/70	20/8/70	7,500	? Permian	P & a
Browse	Lynher No. 1	*	WA-32-P	B.O.C.	NFW	15 56 24	121 04 59	....	30	—181	25/12/70	....	....	960	....	Drilling
	Leveque No. 1	*	WA-32-P	B.O.C.	NFW	15 45 12	122 00 18	....	+30	—254	22/8/70	1/9/70	6/9/70	2,951	Precambrian	P & a
Bonaparte Gulf	Gull No. 1	....	WA-17-P	Arco	NFW	11 56 29	127 54 37	....	39	—441	5/6/70	....	....	10,765	....	Drilling

P & a = plugged and abandoned.

The general results of the drilling are discussed for each basin in turn below.

PERTH BASIN

The small but promising flow of oil encountered in the Lower Cretaceous in Gage Roads No. 1 early in 1969, was followed up by the commencement of an offshore drilling programme in the Cretaceous embayment extending across the continental shelf near Perth in November, 1970. Roe No. 1 was drilled 3½ miles (5·6 km) west-northwest of Gage Roads No. 1 and near the Cretaceous crest of the same structure, but reached a total depth of 7,001 feet (2,134 m) in the Upper Jurassic, without encountering hydrocarbons. This well was drilled by the "Ocean Digger" semi-submersible rig which then proceeded to spud in Charlotte No. 1, some 23 miles (37 km) northwest of Fremantle. Meanwhile the "Jubilee" jack-up rig was drilling Warnboro No. 1 some 27 miles (43 km) southwest of Fremantle. At the end of the year Warnboro No. 1 had reached 11,859 feet (3,615 m) and Charlotte No. 1,5,153 feet (1,571 m), both without encountering any indications of hydrocarbons.

The only onshore drilling in the Perth Basin during 1970 was the appraisal drilling of Dongara No. 18 and No. 19 (see p. 32).

CARNARVON BASIN

As shown in Table 1, both B.O.C. and Wapet continued with drilling programmes to evaluate their offshore permits in the northern Carnarvon Basin. B.O.C's Enderby No. 1 bottomed in a trachyte flow, probably of Triassic age, at 7,051 feet (2,149 m) without hydrocarbon indications. Their Legendre No. 2, only 5 miles (8 km) northeast of Legendre No. 1 (which produced a flow of 1,014 bbls (161 m^3) /day oil from the Lower Cretaceous), was likewise dry.

Continuing their evaluation of WA-23-P Wapet drilled Flag No. 1, Ripple Shoals No. 1 and Pepper No. 1. Flag No. 1 produced a very small flow of gas and oil (1·1 Mcf (31,149 m^3)/day at 750 psi (53 kg/cm^2) and ½ pint (0·3 l) of oil of 48° API, on a ¼ inch (0·64 cm) choke) from the Lower Cretaceous Muderong Shale. Ripple Shoals encountered a very minor hydrocarbon show in the Neocomian Birdrong Sandstone, while Pepper No. 1 found weak oil and gas shows in the top of the Barrow Group, of lowermost Cretaceous age.

In WA-25-P, however, Wapet's Tryal Rocks No. 1 was completely dry.

CANNING BASIN

Two wells were drilled onshore, one stratigraphic test Napier No. 4 and one wildcat Napier No. 5 both in Lennard's EP 52. Both of these wells penetrated the Upper Palaeozoic sequence known at the surface on the Lennard Shelf, but they failed to locate hydrocarbons.

On the continental shelf, B.O.C. drilled Lacepede No. 1 A in WA-31-P and in the offshore extension of the Fitzroy Trough. This well reached the Permian without encountering any hydrocarbon shows.

BROWSE BASIN

Leveque No. 1, the first well in this basin was terminated at 2,951 feet (899 m) after entering Precambrian basement. It is situated on the shallow Leveque Platform which lies along the southern margin of the basin. Lynher No. 1, 65 miles (105 km) to the west-southwest was drilling ahead at 960 feet (293 m) at year's end.

BONAPARTE GULF BASIN

Arco's Gull No. 1 in WA-17-P encountered a rather monotonous sequence of Mesozoic clastic sediments, but no hydrocarbons. At the end of the year the well was progressing rather slowly owing to increasing lithification, having reached 10,765 feet (3,281 m).

GEOPHYSICAL OPERATIONS

SEISMIC

During 1970, seimic surveys were conducted in the Perth, Carnarvon, Canning, Browse, Bonaparte Gulf and Eucla Basins, Details are as follows.

Basin	Permit No.	Company	Seismic Party Months
Perth	EP 21	Wapet	0·07 land
"	EP 23	"	1·82 "
"	EP 24	"	2·26 "
"	EP 25	"	1·71 "
"	WA-13-P	"	0·43 marine
"	WA-14-P	"	0·27 "
"	WA-20-P	"	0·01 "
"	WA-39-P	BP Dev. Aust. Pty. Ltd.	0·25 "
"	WA-40-P	" " "	0·50 "
Carnarvon	EP 41	Wapet	0·04 "
"	WA-1-P	B.O.C. of Aust. Ltd.	1·31 "
"	WA-7-P	Wapet	0·04 "
"	WA-23-P	"	0·03 "
"	WA-24-P	"	0·04 "
"	WA-25-P	"	0·21 "
"	WA-26-P	Can. Sup. Oil Aust. Pty. Ltd.	0·03 "
"	WA-27-P	" " " "	0·07 "
Canning	EP 3	Wapet	2·72 land
"	EP 5	"	1·87 "
"	EP 6	"	1·03 "
"	EP 7	"	0·07 marine
"	EP 7	"	0·76 land
"	EP 8	"	1·24 "
"	EP 9	"	0·46 "
"	EP 13	"	1·78 "
"	EP 14	"	1·80 "
"	EP 15	"	1·40 "
"	EP 16	"	2·10 "
"	EP 17	"	1·93 "
"	EP 18	"	0·38 "
"	EP 19	"	2·20 "
"	EP 31	Aust. Aquitaine Pet. Pty. Ltd.	2·50 "
"	EP 42	Wapet	3·83 "
"	EP 43	"	1·10 "
"	EP 44	"	0·97 "
"	EP 51	Lennard Oil N. L.	0·50 "
"	EP 52	" "	1·50 "
"	EP 53	Wapet	0·18 "
"	WA-2-P	"	0·63 marine
"	WA-21-P	"	0·18 "
"	WA-22-P	"	0·02 "
"	WA-28-P	B.O.C. of Aust. Ltd.	0·60 "
"	WA-29-P	" "	0·53 "
"	WA-30-P	" "	0·17 "
"	WA-31-P	" "	0·25 "
"	WA-32-P	" "	0·70 "
Browse	WA-33-P	" "	0·32 "
"	WA-35-P	" "	0·48 "
Bonaparte	EP 54	Alliance Oil Dev. N. L.	3·00 land
"	WA-15-P	Arco Ltd.	0·26 marine
"	WA-16-P	"	0·25 "
"	WA-17-P	"	0·22 "
"	WA-18-P	"	0·12 "
"	WA-36-P	"	0·01 "
"	WA-36-P	B.O.C. of Aust. Ltd.	0·12 "
Eucla	WA-8-P	Coastal Pet. N. L.	0·10 marine
"	WA-9-P	" "	0·13 "
"	WA-10-P	" "	0·10 "
"	WA-41-P	" "	0·10 "

Total Party Months : Land 39·11
Marine 8·59

GRAVITY

Gravimetric surveying was undertaken in the Perth and Carnarvon Basins as follows:

Basin	Permit No.	Company	Party Months
Perth	WA-13-P	Wapet	1·00
Carnarvon	EP 45	"	0·27
"	EP 46	"	0·20
"	EP 47	"	0·33
"	EP 48	"	0·20

Total Party Months : 2·00

GEOLOGICAL OPERATIONS

Field geological investigations were carried out by oil exploration companies in the Canning Basin only. The breakdown is as follows:

Basin	Permit	Company	Geological (Geologist months)
Canning	EP 17	Wapet	2·00
"	EP 31	Aust. Aquitaine Pet. Pty. Ltd.	2·00
"	EP 42	Wapet	3·83
"	EP 51	Aust. Aquitaine Pet. Pty. Ltd.	1·00
"	EP 52	Lennard Oil N. L.	1·00

Total : 9·83 geologist months

PETROLEUM DEVELOPMENT AND PRODUCTION IN WESTERN AUSTRALIA IN 1970

by R. N. Cope

BARROW ISLAND (Wapet)

The initial phase of development of the Barrow Island Field ended in July, 1970, with the drilling in this year of 13 Windalia producing wells, 29 Windalia water injection wells and 2 water supply wells.

The positions of all wells drilled on the field to the end of 1970 are shown on Plate 13. The total footage of development drilling on Barrow Island during the year amounted to 120,461 feet (36,717 m), a decrease of 313,144 feet (95,446 m) on the 1969 figure.

Oil production rose from an average of 41,319 barrels (6,569 m^3) per day in December, 1969 to 46,940 barrels (7,463 m^3) per day in December, 1970, giving an increase for the year of 3,295,606 barrels (523,968 m^3). Provision for this increase was made by the installation of a fifth 200,000 barrel (31,798 m^3) storage tank, giving a total storage capacity on the island of 1,000,000 barrels (158,990 m^3).

The increase in production was achieved by drilling 13 additional Windalia producers, by extending gas lift to another 18 Windalia wells and by putting a further 47 Windalia wells on pump. The water flood scheme also contributed by maintaining formation pressure; the maximum field injection rate of about 115,000 BWPD (18,284 m^3WPD) has now been reached.

Artificial lifting capacity has been further increased at an average rate of 14 wells per month. Two 1,000 hp (1,014 PS) compressors are now in operation in order to utilise low pressure Windalia gas for the gas lift system.

It is estimated that production for 1971 from Barrow Island will be in the order of 18·5 million barrels ($2 \cdot 94 \times 10^6$ m^3) of oil and 9 billion cubic feet ($2 \cdot 5 \times 10^8$ m^3) of gas.

Reserves of the Barrow Field are said by Wapet to be 200 million barrels (32×10^6 m^3) of recoverable oil producible by primary and secondary methods.

Details of well status by reservoirs, production figures and wells drilled during the year on Barrow Island, are tabulated below:

TABLE 1. BARROW ISLAND OIL AND GAS PRODUCTION, 1970

Reservoir	Production for year 1970			Cumulative production		
	Oil (bbls)	Water (bbls)	Gas (mcf)	Oil (bbls)	Water (bbls)	Gas (mcf)
Windalia	16,166,734	1,510,348	11,292,677	44,259,599	2,237,930	31,107,674
Muderong	284,952	34,566	215,912	451,683	77,495	372,671
Jurassic 5,500 ft	12,377	49,369	344,334	12,673	49,376	354,316
Jurassic 6,200 ft	24,941	41,275	1,293,421	45,184	64,390	1,764,171
Jurassic 6,600 ft	24,278	82,140	84,114	181,823	201,993	529,428
Jurassic 6,700 ft	179,887	63,121	605,859	839,722	158,639	2,146,312
Total field	16,693,169	1,780,819	13,836,317	45,790,684	2,789,823	36,274,572

Water injected: 30,524,981 bbls. Cumulative water injected: 55,721,397 bbls. N.B.: 1 bbl = 0·15899 m^3 1 cu. ft = 0·028317 m^3

TABLE 2. BARROW ISLAND WELL STATUS BY RESERVOIRS AT 31st DECEMBER, 1970

Reservoir	Flowing	Pumping	Gas lift	Non-producing	Water injection wells	Injection source wells	Total
Windalia	63	96	158	6	153	9	485
Muderong	4	....	4	....	....	....	8
Jurassic 5,500′	1	....	....	....	....	....	1
Jurassic 6,200′	1	....	....	1	....	....	2
Jurassic 6,600′	1	....	....	....	....	....	1
Jurassic 6,700′	2	....	1	2	....	....	5
Total	72	96	163	9	153	9	502

Grand total: 502 wells.

TABLE 3. BARROW ISLAND OIL AND GAS DISPOSAL 1970

	Oil (bbls)	Gas (mcf)
Total production	16,693,169	13,836,317
Field fuel	1,236	405,719
Gas flared	....	13,431,318
Oil shipments	16,674,890	....
Percentage of field utilisation....	0·0074	2·9
Percentage of gas flared	....	97·1
Royalty received	$2,090,883·37	....

N.B.: 1 bbl = 0·15899 m^3
1 cu ft = 0·028317 m^3.

TABLE 4. WELLS DRILLED ON BARROW ISLAND 1/1/70 TO 31/12/70

Well	Elevation: Rotary Table (feet)	Elevation: First Flange (feet)	Total Depth (feet)	Com-menced	Com-pleted	Original Status*
C 57	63	52	3,615	5/2/70	9/2/70	P
D 11	N.A.	N.A.	2,799	23/6/70	28/6/70	P
E 15	110	99	2,552	12/1/70	16/1/70	WI
J 58	137	126	2,535	10/2/70	13/2/70	P
K 33	174	164	2,531	4/1/70	7/1/70	WI
K 73	165	155	2,654	7/1/70	11/1/70	P
L 24	207	197	2,490	16/1/70	19/1/70	WI
L 26	208	197	2,521	19/1/70	22/1/70	WI
L 27	181	171	2,464	26/1/70	29/1/70	P
L 62	183	172	2,377	22/1/70	25/1/70	P
L 82	149	139	2,306	29/1/70	4/2/70	P
P 11	192	182	2,553	21/4/70	23/4/70	WI
P 12	175	165	2,553	7/4/70	10/4/70	P
P 13	184	173	2,545	23/4/70	26/4/70	WI
P 22	184	173	2,553	4/4/70	7/4/70	P
P 24	174	164	2,556	31/3/70	3/4/70	P
Q 28	199	188	2,557	27/2/70	1/3/70	WI
Q 33	136	125	2,467	11/6/70	14/6/70	WI
Q 37	183	173	2,530	14/6/70	16/6/70	WI
Q 42	180	169	2,559	8/6/70	10/6/70	WI
Q 44	149	138	2,493	2/6/70	5/6/70	WI
Q 46	208	197	2,480	5/6/70	7/6/70	WI
Q 46/56	234	223	4,118	16/2/70	27/2/70	WSW7A
Q 48	207	197	2,553	2/3/70	5/3/70	WI
Q 51	140	130	2,522	22/3/70	26/3/70	WI
Q 53	172	162	2,552	17/3/70	22/3/70	WI
Q 55	168	158	2,522	29/5/70	2/6/70	WI
Q 56/57	212	202	4,060	21/7/70	31/7/70	WSW7B
Q 57	218	208	2,587	15/5/70	17/5/70	WI
Q 64	210	199	2,553	14/3/70	17/3/70	WI
Q 65	208	197	2,553	11/4/70	14/4/70	P
Q 66	211	200	2,527	10/5/70	14/5/70	WI
Q 67	195	184	2,493	17/4/70	20/4/70	P
Q 68	174	163	2,497	5/3/70	7/3/70	WI
Q 75	193	183	2,522	25/5/70	29/5/70	WI
Q 77	170	160	2,480	22/5/70	25/5/70	WI
Q 84	161	150	2,460	10/3/70	14/3/70	WI
Q 88	214	203	2,494	8/3/70	10/3/70	WI
R 48	131	120	2,526	17/6/70	20/6/70	WI
R 57	102	92	2,526	22/3/70	26/3/70	WI
S 67 J	127	115	7,601	26/6/70	15/7/70	P
T 83	189	178	2,551	30/4/70	4/5/70	WI
T 86	154	143	2,552	18/5/70	22/5/70	WI
T 88	145	134	2,522	26/4/70	29/4/70	WI
Y 24 J	134	122	7,523	19/5/70	18/6/70	S

Datum adopted for Barrow Island wells is 18·4 feet above mean sea level or 23·44 feet above Indian Spring low water mark.
* P = Windalia Producer.
WI = Windalia water injection well.
WSW = Water source well.
S = Suspended.
Total development drilling during 1970 on Barrow Island was 127,984 feet.
N.B. : 1 foot = 0·3048 m.

DONGARA FIELD

The development drilling programme that was started in 1969 was finished in February 1970 with the drilling of an additional two wells (Table 5, Plate 14).

TABLE 5. DONGARA DEVELOPMENT WELLS

Well Number	18	19
Latitude S	29° 16′ 29″	29° 16′ 14″
Longitude E	115° 01′ 54″	115° 02′ 36″
Elevation G.L.	327′	360′
Elevation R.T.	343′	373′
Date spudded	9/1/70	7/2/70
Date completed	26/1/70	28/2/70
Total depth	6,300′	7,150′
Formation bottomed in	Irwin River Coal Meas.	Holmwood Shale
Perforated interval	5,710–5,740′	5,838–5,858′
Producing Formation	Basal Triassic Sand	Basal Triassic Sand
Product	Gas	Oil
Production rate	10 MMCFD	800 BPD
Choke size	½ inch	½ inch

N.B. : 1 foot = 0·3048 m ; 1 inch = 2·54 cm.
1 cubic foot = 0·0283 m³.
1 bbl = 0·159 m³.

In December 1970 contracts were let for the construction of a 255-mile (410 km) long, 14-inch (36 cm) diameter gas pipeline between Dongara and Pinjarra via Kwinana. Wapet have announced that a through-put of 70 to 80 million cubic feet (20 to 23 x 10^5 m^3) per day would be maintained over a period of 15 years. This would be achieved presumably by drawing on the reserves of the otherwise uncommercial fields of Yardarino, Mondarra and Gingin. Owing to declining production from Dongara, filling the pipeline after 15 years would depend on further gas discoveries. The gas reserves of the Dongara Field alone are said to be in the order of 500 Bcf (14 x 10^9 m^3). Initially in 1972 the principal consumers will be the Alcoa alumina refinery at Pinjarra (60 per cent) and the State Electricity Corporation (20 per cent).

THE PHANEROZOIC STRATIGRAPHY OF WESTERN AUSTRALIA: A CORRELATION CHART IN TWO PARTS

by P. E. Playford and R. N. Cope

INTRODUCTION

The object of the accompanying correlation charts is to present the rock and time-stratigraphy of all the Phanerozoic sedimentary basins of the State in a form which is both comprehensive and readily usable. Separate charts have been used for the Palaeozoic and post-Palaeozoic, firstly to give the clearest possible presentation in a limited space, and secondly to vary the coverage of the sub-basinal columns in a way best suited to the basin stratigraphy. These correlation charts are published here in order to make them available for general use as soon as possible: the charts will also appear in a different form in a volume on the "Geology of Western Australia" currently being prepared for publication.

TIME–STRATIGRAPHY

The vertical time scale is only approximately proportional to absolute age, owing to the uneven distribution of rock-units to be illustrated. Formal time units are taken down to stage level, except in the cases of the Cambrian, Tertiary and Quaternary Periods, where stages have been omitted for reasons of space and of difficulty of correlation. However, where stage names are used the correlation with time-rock units defined outside Australia is usually only approximate. A few exceptions occur, such as the Bajocian of the northern Perth basin.

ROCK-STRATIGRAPHY

Descriptions of most of the rock units figured are available in McWhae and others, 1958, and all will be described in the forthcoming "Geology of Western Australia" already referred to. A number of rock units will be described there for the first time, and those figured on the correlation chart are listed by basins as follows:—Perth Basin: Sue Coal Measures, Yardarino Sandstone, Eneabba Member, Cattamarra Coal Measures Member; Carnarvon Basin: Barrow Formation; Canning Basin: Poulton Formation, Babrongan Beds; Officer Basin: Babbagoola Formation, Browne Formation, Officer Volcanics, Lennis Sandstone. In the Bonaparte Gulf Basin certain rock-unit names have been introduced informally for distinctive intervals of the oil exlporation well Ashmore Reef No. 1 (Craig, 1969). Insufficient data are available regarding the lateral distribution and variation of these potential formations, and informal status is therefore conferred by the use of inverted commas. They are "Ashmore Volcanic Beds", "Woodbine Beds", "Hibernia Beds" and "Cartier Beds".

ADDITIONAL COPIES

Additional copies of these correlation charts may be purchased from the Geological Survey of Western Australia, 5th Floor, Mineral House, 66 Adelaide Terrace, Perth.

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DEFINITION OF TWO QUATERNARY FORMATIONS IN THE PERTH BASIN

by G. H. Low

INTRODUCTION

The purpose of this paper is to define and amend two formations which are to appear on maps published by the Geological Survey. The Yoganup Formation is defined for the first time. The Guildford Formation is an amendment of Guildford Clays. Plate 17 shows the distribution of these two formations.

GUILDFORD FORMATION

The Guildford Formation consists of sands and clays, chiefly of alluvial origin, but it also includes minor marine and estuarine lenses. It underlies the coastal plain between the Coastal Limestone and the piedmont zone at the foot of the Darling Scarp. Exposures of the unit in the Swan River valley from Upper Swan (31° 46′ 30″ S, 116° 01′ 10″ E) downstream to Guildford, together with strata at shallow depths in water bores in the area, were originally called the "Guildford Clays" by Aurousseau and Budge (1921). The sequence was renamed the Guildford Formation in an unpublished thesis by Baker (1954), who pointed out that sand sometimes replaces clay as the dominant lithology. The beds intersected in the West Guildford artesian bore (31° 54′ 30″ S, 115° 57′ 20″ E) down to a depth of 108 feet 3 inches (32·99 m) are proposed here as the type section. The driller recorded the following sequence in the upper part of the bore, from the surface.

Feet	Inches		Feet	Inches	
0	0	—	25	6	Clay, brown
25	6	—	27	0	Sand, brown, coarse
27	0	—	72	0	Clay, brown and blue, interbedded
72	0	—	100	0	Sandstone
100	0	—	108	3	Boulders

(Note 1 foot = 30·48 cm).

The Guildford Formation is best exposed along the valleys of the Swan, Helena, Serpentine and Murray Rivers and is known from numerous water bores over the same area. McArthur and Bettenay (1960) referred to the upper surface of the formation as the Pinjarra Plain and distinguished a sequence of depositional systems for several of the major rivers, mainly on the basis of soils. The formation consists of interbedded lenticular sand and clay, calcareous in places, with occasional thin lenses of basal conglomerate. A thin band of marine shells (including *Anadara* and *Dosinia*) at about 15 feet above present day mean sea level was reported by Fairbridge (1953) from clay pits at Caversham, near Guildford, and at Folly Flats, 30 miles (48·2 km) to the south.

The formation progressively interfingers to the west with shallow neritic to littoral sediments, probably representing the basal part of the Coastal Limestone. It is about 100 feet (30·4 m) thick and ranges from 70 feet (21·3 m) below sea level to 50 feet (15·2 m) above. It unconformably overlies the Paleocene Kings Park Shale or the Cenomanian to Albian Osborne Formation in the metropolitan area east of Perth and is extensively covered by the Pleistocene Bassendean Sand. The formation unconformably overlies Lower Cretaceous South Perth Formation in the Pinjarra area.

The exact age of the Guildford Formation is not known, but it is believed to belong to the Pleistocene, possibly middle to late Pleistocene.

YOGANUP FORMATION

The Yoganup Formation represents a shoreline deposit that includes a basal beach conglomerate and a foredune. Any carbonate originally present has been leached out and the unit is variably lateritised. In some places it carries economic concentrations of heavy minerals, principally ilmenite and zircon.

The deposits form a land surface which McArthur and Bettenay (1960) mapped as the "Ridge Hill Shelf", and Welch (1964) described the deposits under the heading "Lower Escarpment Shoreline". Lowry (1965) mapped them as the "Ridge Hill dune system", and Ward (1967) referred to them as the "Yoganup Shoreline Series".

The formation occurs in a narrow strip up to 1 mile (1·6 km) wide. It is best represented around the foot of the Whicher Scarp southwest from the vicinity of Burekup, but remnants occur north along the Darling Scarp for 120 miles (193·1 km) to the vicinity of Upper Swan. The unit unconformably overlies Lower Cretaceous South Perth Formation or Lower Jurassic Cockleshell Gully Formation and at its eastern boundary abuts against scarps formed along the South Perth Formation or

Precambrian rocks. It is disconformably overlain in places by up to 40 feet (12·1 m) of Pleistocene-Recent alluvium in the form of outwash fans.

The formation is named after the Yoganup Railway Siding and the proposed type section is in Westralian Sands Ltd.'s open cut near Yoganup (33° 38′ 50″ S, 115° 36′ 10″ E). At this locality a thin basal conglomerate with rounded quartz and quartzite clasts is overlain by clayey sand containing two parallel ilmenite-rich bands which are each up to 15 feet (4·5 m) thick (Morgan, 1964). This is overlain by a lenticular bed of grey clay, followed by a yellow sand probably representing a foredune or beach ridge. The section is about 30 feet (9·1 m) thick.

The grey clay unit has not been recognised north of Roelands where the formation abuts against Precambrian rocks. The sand grains in the formation are typically medium to coarse grained, rounded and moderately well sorted.

The base of the formation ranges in elevation from about 120 to 150 feet (36·5 to 45·7 m) above sea level and dips away from the scarps at angles of up to 10 degrees.

No fossils are known from the Yoganup Formation, but because of its stratigraphic position, degree of alteration and dissection and its elevation above sea level, it is believed to be Pleistocene, possibly Middle Pleistocene, in age.

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A GEOLOGICAL INTERPRETATION OF THE BUREAU OF MINERAL RESOURCES GRAVITY MAP OF THE SOUTHWESTERN PART OF WESTERN AUSTRALIA

by J. L. Daniels

ABSTRACT

The Bureau of Mineral Resources (B.M.R.) reconnaissance gravity map of south-west Australia can be subdivided into five main areas. Each of these has its own distinctive gravity pattern.

Some of the gravity features within these zones have been interpreted. Among these, and crossing the Archaean of the Yilgarn Block, are two east-northeast-trending lineaments, which are parallel to an important suite of dykes and thought to represent lines of transcurrent faulting.

Also in the Archaean are several gravity high spots which in some cases correspond to areas in which acid volcanic material is present. It is sugested that these gravity high spots correspond to centres of acid volcanicity, possibly associated with cauldron subsidence.

Between the Archaean of the Yilgarn Block and the Proterozoic of the Albany-Fraser Province, is a wide zone in which elements of the gravity pattern of both regions are present.

INTRODUCTION

In 1969 the Bureau of Mineral Resources undertook a helicopter gravity survey of the southwest of Western Australia. The results were published as a contoured map (1969).

This brief report is an attempt, by a geologist, to subdivide the region and present tentative explanations of some of the features and trends shown on the B.M.R. gravity map.

REGIONAL SUBDIVISION

The map may be subdivided into eight main areas, each of which has a fairly distinctive gravity pattern. The areas are shown in Plate 18, and the general characteristics of each are listed below:

1A. This is a narrow northwest-trending zone with a generally low gravity relief and a regional slope to the northeast.

1B. This broad area has a northwest trend, is of generally low gravity values and is crossed by several widely spaced and poorly defined northwest-trending high and low axes. There are two major breaks, trending east-northeast, in the continuity of the high and low axes, and the centre of the area contains several spot gravity highs.

1C. This zone, in the central north sector of the map area, consists of closely spaced high and low gravity axes with a general northwesterly trend. In several places spot gravity highs occur.

2. Zone 2 is a triangular area forming a large part of the southwest corner of the State. It exhibits high gravity values marginal to the Darling Fault with a gradual diminution to the northeast. Some well-defined northwest-trending high and low axes are present in the southwest and these interrupt the major northerly-trending gravity high ridge which runs parallel to the western margin of the zone. A few vague northeast-trending axes can be seen crossing the zone. Its main gravity characteristics were first described by Everingham (1965).

3. Zones 3A and 3B together form an arc on the south and southeast sides of the above described zones. High and low axes are fairly closely spaced and although somewhat sinuous have a northeasterly trend in the east, becoming more easterly in the southwest. The zone abruptly truncates many of the features of Zones 1 and 2.

The westerly extension of this zone's northerly margin may be drawn in several ways. That shown on Plate 18 excludes the southwest portion of Zone 2 with closely spaced high and low axes. This portion may be related to Zone 3B. However the overall gravity high of the area relates it more to Zone 2. A possible geological explanation is given below.

4. Zone 4 is not well defined, but flanks the southern side of Zone 3B, which it apparently truncates, and would appear to be a zone of moderately high gravity, though the data is meagre.

5. Zone 5 is an oval gravity-low area with an easterly trending long axis. It is developed in Zone 3B in the southwest corner of the State, near Albany.

Some of the main geological inferences derived from this areal subdivision are noted below, and a summary of the known or suggested natures of the boundaries between the areas is given in Table 1.

DISLOCATIONS WITH ZONE 1B

The northwest trend of the gravity highs and lows of this zone is broken in two places in such a way as to suggest the presence, in those places, of major, parallel, crustal fractures. The displacement of the axes suggests that the movement on these fractures is, at least in part, lateral.

Matching of the individual high and low axes across these breaks is open to question, but a minimum lateral displacement of 20 miles (32·1 km) is indicated.

A simple overlay of the map (Plate 18) on the Western Australia geological map (1966 edition) shows that the trend displayed by the suggested dislocations is also that of the so-called east-west dykes.

No lateral movement approaching 20 miles (32·1 km) is known along any of these dykes and hence it is suggested that the main movement along these lines took place before the emplacement of the dykes.

GRAVITY HIGH SPOTS IN THE ARCHAEAN

Several gravity high spots are located in the Archaean of Zones 1B and 1C. They are well developed in the Widgiemooltha (Sofoulis, 1966) and Kurnalpi Sheet (Williams, 1970) areas and correspond with local developments of acid volcanic rocks. The same applies to the gravity high in the northern part of the Jackson Sheet area. The surface geology related to the gravity highs in the Southern Cross and Hyden Sheet areas is not known.

The geological interpretation of this association of low density rocks on the surface with gravity high spots is conjectural. It necessitates the incorporation, in the explanation, of the presence of higher density rocks at depth.

An excellent example of a similar gravity high, on an extensive gravity ridge, in association with acid volcanics is seen in the northeast corner of the Talbot Sheet area in the Warburton Range region. In this example the acid volcanics are confined to a cauldron subsidence area (Daniels, 1969), while the gravity high is thought to be caused by underlying gabbroic rocks, only small amounts of which are exposed at the surface (Daniels, in prep.).

With this example in mind it is suggested that the gravity high spots in the Archaean (Plate 18) are the sites of acid vents and probably also are cauldron subsidence areas. They are worthy of investigation for mineralisation.

ARCHAEAN-PROTEROZOIC CONTACT

The most noticeable feature of the gravity interpretation is the truncation of the structures in the Yilgarn by those developed in the south and southeast. The former reflect the broad regional gravity characteristics of the Archaean while the latter are related to the igneous and metamorphic rocks of the Albany-Fraser Province—a Proterozoic mobile belt. The gravity features associated with this belt presumably developed at the time of formation of the belt and are important in understanding the development of the Proterozoic in Western Australia.

The contact between the two is gradational and there exists between them a wide zone, especially evident in the east and the extreme southwest. This zone shows features of the gravity patterns of both the Archaean and the mobile belt.

The mixed pattern in this contact zone is interpreted to mean that the influence of the mobile belt extends for a considerable distance into the Archaean of the Yilgarn Block.

DISTRIBUTION OF MIDDLE PROTEROZOIC SEDIMENTARY ROCKS

Several elongate outcrops of Proterozoic sedimentary rocks are present within the Albany-Fraser Province (Mount Ragged and Mount Baring), on or near its margin (Stirling Range and Barren Range) or in the mixed zone between the Archaean and the Proterozoic (Woodline Beds). In each case the elongation of the outcrops is parallel to the dominant trend in the gravity pattern. This suggests that the deposits accumulated in long narrow troughs whose development, and perhaps also their preservation, was controlled by movements in narrow zones associated with the later development of the mobile belt.

COLLIE AND WILGA BASINS

The elongation of the Collie and Wilga Basins is parallel to the northwest regional gravity trend in that region. This is the dominant trend in part of a larger area, referred to above, and whose gravity pattern is interpreted as an overlap of the Archaean and Proterozoic patterns. The development of the Collie and Wilga Basins probably took place along lines of weakness related to the mobile belt which forms the Albany-Fraser Province.

ZONE 4

This zone appears to truncate part of Zone 3. It is likely to be an integral part of the Albany-Fraser Province, but because of the possible truncation it may be related to a younger belt of metamorphism and igneous activity of which only the northern margin is present in Western Australia.

ZONE 5

There is little doubt that the large gravity low forming Zone 5 is caused by the Albany Granite.

TABLE 1. KNOWN OR SUGGESTED NATURE OF BOUNDARIES BETWEEN UNITS

Contact of Zones	Known or interpreted nature of geological boundaries
1A–2	" Meckering line ". Zone of seismicity probably representing crustal fracture (Everingham, 1965)
1A–1B	Unknown
1B–1C	Unknown
Western side of 2	Darling Fault
2–3	Possibly metamorphic
3–1A, 1B, 1C	Possibly metamorphic
3A–3B	Fault or major shear (Wilson, 1958)
3–4	Possibly intrusive
3–5	Intrusive

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PORPHYRITIC DOLERITES OF THE EDJUDINA SHEET AREA

by C. F. Gower

ABSTRACT

Porphyritic dolerites with plagioclase phenocrysts up to 5 cm long are described from the Edjudina 1 : 250,000 sheet area. The phenocrysts occur in zones, usually in the upper part of the dolerite, and there is a gradation from non-porphyritic to extremely porphyritic dolerite expressed by an upward increase in the size and abundance of phenocrysts. Feldspar buoyancy is suggested as partly explaining the distribution of the phenocrysts.

INTRODUCTION

During regional mapping of the northern half of the Edjudina 1 : 250,000 sheet area many occurrences of porphyritic dolerite were recorded. The phenocrysts in the dolerites are plagioclase feldspar and, due to their large size and great abundance, give the rock an extremely distinctive appearance. The phenocrysts are in zones which show little change laterally, but considerable vertical variation.

FIELD OCCURRENCE

Although only porphyritic dolerites occurring within the Ejudina sheet area are considered here they are not unique to this region and have been recorded from other parts of the Eastern Goldfields. For example, by Jutson (1914) from Ora Banda, by I. R. Williams (pers. comm.) from northwest of Bulong, and in the Norseman area by Halberg (1970). Various names have been applied to the rock-type and have been discussed by D. A. C. Williams (1967). The names include gabbro porphyrite, diabase porphyrite, porphyritic andesite, porphyritic microgabbro in addition to the term porphyritic dolerite which is used here. "Cat Rock" is the local name for these dolerites, originally applied by the goldminers because of its spotted appearance.

The best development of porphyritic dolerite on the Edjudina sheet area is between Pyke Hill and Eucalyptus, and there are also minor occurrences in the vicinity of Mount Percy, Yerilla, Kookynie and Glenorn (Plate 19).

The porphyritic dolerites trend parallel to the strike of the country rock and in general appear to be concordant and intrusive, though it is possible that some of the finer grained varieties may be extrusive. Fine-grained porphyritic basic rocks, almost certainly lavas, are also present and may be related genetically to the dolerites. The decision whether the porphyritic dolerite is intrusive or not must often be made on grain size and other textural grounds, since poor outcrop obscures diagnostic criteria, including detailed field relationships. The thickness of the porphyritic dolerites ranges from less than 10 feet (3 m) to over 400 feet (122 m), though the larger thicknesses are generally the result of multiple intrusion. Where outcrop is good, the porphyritic dolerites can be traced laterally over distances of up to 10,000 feet (3,000 m).

Homogeneous non-porphritic dolerites and gabbros, some of which are layered, are frequently associated with the porphyritic dolerites. These both intrude the porphyritic dolerites and are intruded by them. It is obvious that the igneous history is complex and that the porphyritic dolerite intrusive events are inseparable from those involving the non-porphyritic dolerites and gabbros. The country rock is almost always basalt, often containing intercalated sediments which, in places, have been used as avenues along which the dolerites and gabbros have intruded.

FELDSPAR PHENOCRYSTS

The plagioclase phenocrysts are white or creamy, subhedral to euhedral and may be up to 5 cm long. Often they weather out as small bosses on the surface of the rock, but the reverse may also be true, giving the rock a pitted appearance. They have been extensively saussuritized, and it is impossible to determine the original composition of the phenocrysts. Comparison, if valid, with similar but less altered rocks from other parts of the Eastern Goldfields indicates that the phenocrysts were probably in the andesine-labradorite range. They are often zoned, and inclusions are common.

The phenocrysts show considerable distributional variation within the dolerites. In some parts of an intrusion they may be completely absent but at other parts of that same body they can be so numerous that the groundmass is relegated to interstitial status. Where they are absent there is sometimes evidence of mineral layering and small-scale differentiation.

One feature noted was a change from non-porphyritic dolerite to extremely porphyritic dolerite, expressed by a gradual increase in the size and abundance of feldspar phenocrysts accompanied by an increase in groundmass grain size. The feldspars are rarely more than 0·5 cm when they first appear, but within a distance of about 10 feet (3 m) they may be as large as 5 cm. Often where the phenocrysts are very numerous they cluster to form glomerocrysts up to 10 cm in diameter. It seems that the change from non-porphyritic to porphyritic dolerite takes place in an upward sense with most of the phenocrysts collected at or near the top of the dolerite. However it was not possible to prove that this is always the case. No evidence of a gradation in a downward sense was observed, but bands of phenocrysts near the (interpreted) base of some of the intrusives were seen. Exposure is not good enough to decide whether or not these bands represent separate intrusions. The base of some of the intrusions is difficult to ascertain. Differentiated gabbros and dolerites near the porphyritic intrusives sometimes indicated facing; pillow lavas and graded bedding in intercalated sediments also occasionally proved useful.

DESCRIPTION OF SELECTED SECTIONS

Locality 1

This is a small island about 7,000 feet (2,100 m) east-southeast of Pyke Hill, located near the edge of Lake Carey (see Plate 19). The island is elongate north-south, parallel to the strike, and is roughly 500 feet (150 m) long and 150 feet (45 m) wide. The rocks dip eastwards at about 80°. A suite of specimens was collected across the width of the island at the southern end where exposure is good. On the west side of the island is a medium to coarse-grained basic rock composed originally of plagioclase and pyroxene with minor quartz and accessory opaque minerals. The plagioclase has been saussuritized and the pyroxenes largely uralitized. The grain size ranges up to about 0·5 cm. The texture is variable with good mineral layering and some small-scale differentiation developed, indicating that the succession is east-facing. A few feet farther east the rock shows an increase in feldspar content in the groundmass and also has a few plagioclase phenocrysts. These are generally euhedral and less than 1 cm long. Continuing east the rock shows an increase in the number and size of phenocrysts, though there is little change in the groundmass. Near the top the phenocrysts are very large (4 cm) and the matrix subordinate. At the top, on the eastern side of the outcrop, the rock is glomeroporphyritic with feldspar in clusters which have diameters up to 10 cm. The groundmass is now coarse grained (0·6 cm.) and confined to interstices between the phenocrysts. Neither the top nor the base of the body is exposed and although it is often the case that the margins of exposure also represent the boundaries of geological units there is no evidence that this is so here, thus how representative the exposed section is of the whole body cannot be ascertained.

Locality 2

This is a roughly circular outcrop located about 8,000 feet (2,400 m) northeast of Eucalyptus Bore (see Plate 19). It is made up of a varied sequence of both porphyritic and non-porphyritic basalts, dolerite and gabbro with thin acid bands and a thin ultramafic. The strike of the rocks is east-northeast; they dip very steeply south-southeast and are in places vertical. Much of the northern half of the outcrop consists of a thick south-facing differentiated gabbro. South of this is a variable gabbro which is succeeded by two thin acid bands, probably tuffaceous in origin, separated by a thin ultramafic. Porphyritic dolerite is present south of the thin acid bands and makes up most of the southern half of the outcrop. The dolerite is porphyritic at its base in contact with the acid layer, with phenocrysts ranging up to 2 cm long set in a medium to coarse-grained groundmass. There is a rather abrupt change to medium-grained dolerite (non-porphyritic) southwards though no obvious break in continuity could be seen. The medium-grained dolerite grades into porphyritic dolerite in which the phenocrysts are up to 3 cm long, set in a coarse-grained groundmass. The change from non-porphyritic to porphyritic dolerite takes place over a distance of about 3 feet (91 cm) and is expressed by an increase in the quantity of phenocrysts without any marked change in their size. South of this is a broad band of porphyritic dolerite containing large euhedral, but sparsely scattered, phenocrysts and this is followed by a narrow zone, about 2 feet (61 cm) wide, of extremely porphyritic dolerite. The rock-type at the south side of the outcrop is porphyritic basalt. The total thickness of the section is 1,300 feet (400 m) of which porphyritic dolerite comprises 400 feet (122 m).

DISCUSSION

The most important features of the dolerites to be discussed are: (i) lateral uniformity, (ii) vertical variation, (iii) a gradation from non-porphyritic to porphyritic dolerite, (iv) the confinement of phenocrysts into zones within the dolerites, and (v) the accumulation of phenocrysts in quantities far in excess of that to be expected during normal intrusion and crystallisation.

The obvious mechanism is gravitational separation with the phenocrysts migrating into zones. The gradation from non-porphyritic to porphyritic dolerite can be explained as due to migration uncompleted at the time of crystallisation. That there is a change from non-porphyritic to porphyritic dolerite in an upward sense and that the phenocrysts are most common in the upper levels suggests that the feldspars were rising. This concept is not new and has been appealed to by Grout (1928), von Eckermann (1938), Morse (1968) with supporting laboratory evidence by Tilley and others (1965). Grout also points out that the large phenocrysts would tend to rise more quickly than the small ones of the same density. This explains the gradation in size in the transition zone.

Buoyancy does not explain all the features observed. It does not explain why phenocrysts sometimes occur near the base of a dolerite, or why there is sometimes a non-porphyritic section near the top. Some of these anomalous features may be explained as the result of multiple injection and the boundaries to individual intrusions have not been recognised either because they are not developed or because they are obscured by poor outcrop.

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GEOLOGY AND MINERAL RESOURCES OF THE WODGINA DISTRICT

by J. G. Blockley

ABSTRACT

The Wodgina district, located about 80 miles (129 km) south of Port Hedland in the Pilbara Goldfield, includes a typical Archaean "greenstone" belt preserved in a synclinal keel in granitic rocks. The "greenstones" comprise metamorphosed basalt, tuff, ferruginous chert, clastic sediments, felsite and untramafic rock. These rocks were intruded by an older gneissic granite and a younger porphyritic granite. Pegmatite veins, generated from the porphyritic granite, have been past sources of tin, tantalum and beryllium minerals. They also contain significant, but so far un-mined deposits of lithium. A small amount of copper ore was produced from mineralised shears and from a disseminated deposit near a felsite sill. The district has untested deposits of iron ore, and layered ultramafic rocks of the type elsewhere associated with nickel mineralisation.

INTRODUCTION

Since tin was discovered at Wodgina in about 1902, the Wodgina district has been an important source of pegmatite minerals, yielding cassiterite, tantalo-columbite and beryl as well as a little copper. It also has significant deposits of lithium minerals, some iron ore and potential for nickel.

Although there have been many published descriptions of the economically and scientifically interesting pegmatites, there is no geological map of the whole field showing the locations of the various deposits or mining centres. This, together with the lack of lease surveys, has resulted in several of the centres being either not marked, or placed incorrectly, on plans.

The present report is an attempt to correct this gap in the records by presenting a 1 : 100,000 scale geological map of the district, showing as many of the mines as could be located, together with a brief description of its geology and mineral resources (Plate 20). This mapping was done in 1969 during a survey of the tin deposits of the Pilbara Goldfield.

LOCATION, ACCESS AND FACILITIES

The Wodgina district, as the term is commonly used, includes the mining centres of Wodgina, Stannum, Mill's Find, Numbana and Mount Francisco. It covers a tract of country extending from lat. 21° 20′ S, long. 118° 40′ E to Lat. 21° 28′ S, long. 118° 33′ E, and includes two prominent ranges of 'greenstone' hills which rise to heights of about 600 feet (180 m) above the surrounding granitic plains. The area forms part of the Marble Bar 1 : 250,000 Sheet area (Noldart and Wyatt, 1962).

Wodgina, the main centre in the district, is 75 miles (121 km), by graded road, south of Port Hedland. The other centres in the district are connected to Wodgina by tracks. The greater part of the district is in the Yandeyarra Aboriginal Reserve, and non-aborigines require a permit from the Department of Native Affairs for entry.

When mapped by the writer in 1969, the only mining activity in the district was a little prospecting. During past mining operations, water was obtained from wells sunk close to the workings or treatment plants. Supplies were always considered inadequate, and any future operators will probably have to seek water in the alluvium and jointed granite along the Turner River.

PREVIOUS WORK

The first, and most complete account of the geology of the Wodgina district is that by Maitland (1906). His report includes geological maps of the Wodgina and Stannum centres and descriptions of the mines working at that time. Montgomery (1907), Woodward (1910), Blatchford (1913), and Cleland (1913) all described tin and tantalite deposits in the district. Finucane and Telford; (1939), Miles, and others (1945), and Ellis (1950) gave accounts of the tantalite workings in the district; the first of these also included a geological map of the Wodgina centre. Simpson (1912, 1919, 1928) recorded the occurrence of uranium and thorium minerals in the pegmatites, and the compilation of the State's mineral occurrences by the same author (Simpson, 1948, 1951, 1952) summarised information on the tin, tantalum, lithium and beryllium deposits of the district. Low (1963) published some details of a copper deposit at Mount Francisco.

GENERAL GEOLOGY

The rock assemblage of the Wodgina and Mount Francisco ranges is typical of an Archaean 'greenstone belt', and includes metamorphosed basalt ferruginous chert, clastic metasedimentary rocks, and acid and ultramafic intrusives. These rocks are preserved as roof pendants along a synclinal keel in a large area of granitic rocks, consisting of an older gneissic granite and younger porphyritic granite. Near its contact with the metamorphic rocks, the porphyritic granite grades into a marginal phase which is even-grained or pegmatitic in texture. Prominent pegmatite veins, in most places closely associated with the marginal granite, cut the metamorphic rocks and were the source of the tin, tantalite and beryl mined from the district.

The main structural feature in the Wodgina district is a syncline trending north-northeast which passes through the middle of the Wodgina range and extends with interruptions by granite intrusion to Mount Francisco. Upon this syncline are superimposed many complex drag folds, particularly in the chert bands, and northwesterly-trending cross folds. The interpretation of the overall structure is further complicated by the lenticular shape of many of the rock units, and by a number of cross faults. A major north-northeasterly fault can be traced, by means of quartz reefs and its displacement of rock units, from south of Mount Francisco to the central part of the Wodgina range. Farther north, its course is marked by topographic lineaments such as straight creek beds, but displacement and quartz filling are no longer seen.

The disposition of the thicker basalts and clastic sedimentary rocks along the axis of the syncline suggests that the present structure follows a former depositional trough (perhaps controlled by the major fault) in which the lavas and sediments accumulated.

Younger rock units in the district are duricrust, pisolite and ferruginous sandstone of probable Tertiary age, and recent residual soil, outwash and alluvium.

ARCHAEAN METAMORPHIC ROCKS

The following brief descriptions of the metamorphic rocks are based on field observations and the examinations of a few thin sections.

Ferruginous chert

Recrystallised ferruginous chert, with interbedded slate and rare iron formation is the most abundant of the metamorphic rocks. It forms the higher ridges in the district and its outcrop has controlled the topography, which reflects the geological structure. In thin section, it consists of finely crystalline quartz, grunerite and iron oxides with accessory apatite. In some exposures, the chert grades upwards into a cream coloured rock composed of fine-grained quartz and zoisite, but in general, attempts to subdivide the ferruginous chert stratigraphically were unsuccessful.

Metabasalt

Metabasalt is well exposed at Wodgina, Stannum and in a broad valley north of the Comet mine. The unit as mapped also includes some metamorphosed tuff, agglomerate and dolerite. Although these basic rocks are now recrystallised to quartz-epidote-plagioclase amphibolites, primary structures such as amygdales, pillows and agglomeratic bands are well preserved, and attest to their volcanic origin. All of the metabasalt units are lenticular, and are thickest in the keel of the main syncline.

Amphibole schist

The most poorly exposed of the metamorphic rocks is the amphibole schist. It is commonly, though not always, found associated with the metabasalt, and in places, grades laterally into this rock. The schist is made up of well foliated actinolitic amphibole, plagioclase and quartz. No direct evidence of the original identity of this rock was seen, but its basic composition and close association with the metabasalt suggests that it is a metamorphosed basic tuff.

Ultramafic rock

Ultramafic rock is well exposed in the hills north of the Wodgina centre, along the west side of the Wodgina range, and at Mount Francisco. It also forms a number of small remnants in the granite, particularly between Round Hummock and Mount Francisco. In most outcrops, this rock is conformable with the other metamorphics, but in some places, transgression and rafting were noted, and a few cross-cutting dykes were also seen.

Ultramafic rock is particularly well exposed in the Wodgina district, forming ridges 200 to 300 feet high (60 to 90 m), with very little soil cover. Many exposures have a coarse layering, clear on air-photographs, but less so on the ground. This layering is parallel to the attidude of the surrounding metamorphic rocks, and is folded. It seems to be primary, and not due to metamorphism.

In the area north of the mines at Wodgina, the ultramafic rock shows not only the coarse layering, but also a fine banding, of the order of one or two centimetres thickness. In this area, many outcrops of the rock have a spotted texture due to clots of more iron-rich material about one centimetre in diameter. The origin of these structures is not known at present, but their close analogy with features described from the Tumbiana Pisolite (Trendall, 1965) and elsewhere, suggests that in this locality the ultramafic rock may be tuffaceous.

The ultramafic rock consists of fine-grained tremolite, chlorite, talc and magnetite. In some specimens, the outlines of primary olivine grains can be discerned, but in all thin sections examined, the original rock-forming minerals were completely recrystallised.

Metasediments

Metamorphosed clastic sedimentary rocks crop out on the eastern side of the Wodgina range, near the Stannum centre. The most conspicuous rock type amongst these is a deformed conglomerate with pebbles of chert and quartz stretched out at right angles to the fold axes, parallel to the "a" lineation direction. Other rock types present are chlorite and biotite schist (with pebble bands) and quartzite.

Felsite

Lenticular sills of felsite are exposed at Stannum, in the valley north of the Comet mine, and near Wodgina. The rock is very fine grained, with local spheroidal textures, is cream to white, and is cleaved. The sills were intruded close to, or along the contact of chert and metabasalt or amphibole schist. In most places they are conformable, though a discordant contact was noted near the Stannum tin mine.

The felsite consists of small phenocrysts of altered plagioclase and irregular patches of amphibole and chlorite set in a fine-grained matrix of granulated quartz and feldspar. Fresh microcline is developed in pressure shadows alongside the phenocrysts.

GRANITIC ROCKS

Gneissic granite

Gneissic granite, composed of quartz, microcline, plagioclase, green biotite (partly replaced by chlorite) and actinolite, crops out on the western and southern sides of the Wodgina range, and underlies much of the sand-plain between Wodgina and the Yule River. It ranges from well banded gneiss to foliated granite. Remnants of greenstone, aligned parallel to the foliation, are common. In many places the gneiss contains concordant bands of porphyritic granite with phenocrysts set parallel to the gneissic trend, and is cut by dykes of massive, even-grained granite. Concordant pegmatites are common in the more gneissic parts.

Porphyritic granite

The porphyritic granite intrudes the gneissic granite, with much interfingering at the contact. It occupies most of the southern part of the Wodgina district, and extends considerably beyond it (Blockley, 1970). Although aligned phenocrysts and broad compositional banding were noted in a few places, the rock is generally massive, forming tors and rounded domes in contrast to the more subdued outcrops of the gneiss. It is made up of phenocrysts of microcline set in a matrix of quartz, oligoclase, microcline and brown or green biotite.

The marginal phase of the porphyritic granite varies from even, medium-grained granite to pegmatite. It contains muscovite rather than biotite, and in some outcrops carries pink spessartite garnet. In many places it is foliated parallel to the attitude of the adjacent metamorphic rocks. Its composition is generally more acid than the porphyritic granite, but varies considerably due to assimilation of the intruded metamorphic rocks.

Pegmatites

The rare-metal pegmatites form clearly intrusive veins within the metamorphic rocks, or rarely, as at Numbana, in the granite. Most veins have a north-northeasterly strike, parallel to that of the host rocks, but many dip only gently, and cut the bedding direction of their host rocks. The greater number of pegmatites have irregular shapes and were probably intruded into tension gashes. However, some, like the Tantalite lode at Wodgina, follow well-defined faults.

The pegmatites consist mainly of inter-grown quartz and albite, but lenses or veins of blue quartz, pure albite, or quartz-albite-muscovite are common. Microcline, green muscovite, blue-green tourmaline, lepidolite and spessartite are other common constituents of the pegmatites. Some pegmatite veins have a more or less zonal arrangement of the mineral assemblages, but in others this is not so. Simple pegmatites also occur, and consist usually of either quartz-albite or blue quartz. Some of the tin-bearing pegmatites at Wodgina have a late-stage phase of blue tourmaline and muscovite, which may occur along the edge of the veins, or as detached veins on parallel shears. Wall-rock alteration about pegmatites cutting basic and ultramafic rocks has produced a selvage of biotite.

MINERAL DEPOSITS

Tin deposits

About 470 tons (478 tonnes) of tin concentrate were mined from the Wodgina district. It was won from pegmatites, and from eluvium in small gullies in their immediate vicinity. Because of the wide scattering of the tin-bearing pegmatites, and the unfavourable topography, no concentrations of alluvial cassiterite suitable for large-scale placer mining were formed.

The Mount Cassiterite tin mine at Wodgina had the largest production in the district. The cassiterite was won from a pegmatite lode striking about 080°, dipping southerly, worked in patches from three adits over a total length of 450 feet (135 m) to a depth of 250 feet (75 m) below its highest point. The width of the lode ranged from 12 inches (30 cm) to 14 feet (4·3 m), and averaged 5 feet (1·5 m) on the No. 3 level. Cassiterite occurred in the pegmatite, in marginal veins of blue tourmaline, and in the biotite selvage to the main vein. Pieces of up to 80 pounds (35 kgm) in weight were recorded. The ore milled averaged about 3 pounds of tin concentrate to the ton (1·4 kgm per tonne).

Smaller tin mines were located on a number of pegmatites cropping out on the ridge east of the Mount Casserite mine, and all the gullies in that area were hand-worked for alluvial tinstone.

At West Wodgina, Stannum, Mill's Find and Mount Francisco, cassiterite was mined from quartz-albite pegmatites in which it is found in small, but very rich patches. In many of these veins, the tinstone is associated with lepidolite. One pegmatite worked at West Wodgina yielded 9 hundred-weights of tin concentrate from 20 tons (460 kgm from 20·3 tonnes) of ore. Three samples of the faces worked at the Bright Star mine at Mount Francisco assayed 1·71, 0·47 and 0·77 per cent tin respectively, and a sample from the dump at Mill's Find assayed 0·50 per cent tin.

Tantalum deposits

The production of tantalite and tantalo-columbite from the Wodgina district is recorded as 178 tons (181 tonnes), of which 110 tons (112 tonnes) came from the Tantalite lode on M.C. 107 at Wodgina. The main tantalum mineral produced was mangano-tantalite, but mangano-columbite, tanteuxenite and microlite have also been recorded.

The Tantalite lode is a pegmatite vein striking north, dipping 40° east, and extending for about 2,200 feet (670 m) along strike. It has a true width of from 10 to 30 feet (3·0 to 9·1 m). It consists of a granitic textured core, with marginal and cross-cutting veins of almost pure albite. The tantalite is invariably found in the albite-rich parts. Mining was restricted to depths of 30 feet (9·1 m) or less. The ore treated on the lease averaged about 3 pounds of concentrate to the ton (1·4 kgm per tonne), but this included some eluvial ground and only the richer parts of the lode.

At Wodgina, tantalite was also mined from pegmatite veins north west of the main lode, and from the Terra Nova mine south of Mount Tinstone.

Tantalite and tantalo-columbite has also been mined from near Stannum, Mount Francisco and Numbana. Most of the production was from eluvium, though some may have been won by knapping and hand-cleaning the better grade pegmatite lodes.

Beryllium

Beryl was first identified at Wodgina by E. S. Simpson in 1927, and first mined in 1943, since when 1,177 tons (1,198 tonnes) containing about 136 tons (138 tonnes) of BeO have been produced. Much of the beryl is of the variety rosterite, having a high content of caesium. The ore is white or grey, lacks distinctive cleavage and crystal form and is readily mistaken for quartz.

The greatest production of beryl came from the north end of the Tantalite lode at Wodgina where it occurred in bunches and masses associated with albite. One mass was reported to have been 38 feet (11·6 m) long, 24 feet (7·3 m) high and 18 feet (5·5 m) wide, lying more or less horizontally. Beryl was also mined from two pegmatites on the east side of the range below Mount Tinstone, and from near M.C. 310, northwesterly from the Tantalite lode.

At Mount Francisco several benches and open cuts have been put in on gently dipping pegmatites cropping out in an area northwest of the trigonometrical station B10. Beryl and tantalite were seen in the workings, and it is assumed that these mines produced most of the beryl recorded from the Mount Francisco centre, although descriptions of the positions of the unsurveyed tenements listed in Table 3 place some of them at other locations.

Beryl was also mined from a quartz-cored pegmatite at Numbana where is it associated with columbite and books of muscovite.

Lithium

Lithium minerals such as lepidolite, spodumene and lithiophyllite occur in many of the pegmatites in the Wodgina district, although as yet no production has been recorded.

Lepidolite is known from the main Tantalite lode, from the Tinstone lease, and from a vein about 1 mile (1·6 km) north of Wodgina along the Port Hedland Road. It is present in the tin pegmatites at West Wodgina, Stannum, and the Eve Eva mine at Mount Francisco. A chip sample of the pegmatite at Stannum assayed 1·62 per cent Li_2O.

Lithiophyllite occurs in the Tantalite and the Rock Hole lodes at Wodgina, and in the Mount Francisco centre. Samples have assayed from 4·5 to 7·9 per cent Li_2O. Spodumene is known from the Mount Cassiterite and Stannum tin mines.

Copper

About 8 tons (8·1 tonnes) of copper ore were mined from Stannum and Mount Francisco. The latter deposit was not located, but Low (1963) considers it to have been in a quartz vein in granite.

At Stannum, disseminated malachite was worked in two places, on, or immediately below a felsite sill. Although low in grade, the "stratiform" disposition of the lode should be an encouragement to further prospecting. About 1½ miles (2·4 km) west of Stannum, a copper bearing shear in amphibolite schist has been recently opened up. The lode is about 150 feet (45 m) long, up to 6 feet (1·8 m) wide and contains malachite and chalcanthite.

Iron ore

The pisolite and canga deposits, although not sampled, are probably of comparable grade to similar material in the Hamersley Range area. The largest pisolite mesa is estimated to contain about 1 million tons (1,000,000 tonnes) of limonite. Total resources of the area would be in the order of 5 to 10 million tons (5 to 10 million tonnes) of pisolite and canga.

Other minerals

Simpson (1928) records 74 minerals from the Wodgina district, including such potentially economic minerals as bismuth, gold, molybdenite, galena, chalcocite, sphalerite and mineralogical curiosities such as the radioactive minerals thorogummite, pilbarite, hydrothorite, maitlandite and nicolayite.

The large area of ultramafic rocks gives the district potential for the discovery of nickel and associated metals.

TABLE 1. TIN PRODUCTION FROM THE WODGINA DISTRICT

Centre	Tenement No.	Name of Lease or Operator	Period	Concentrate Produced				Value $ Aust.	Remarks
				Lode Tons	Stream Tons	Total Tons	Metal Content Tons		
Wodgina....	MC 84	Mount Cassiterite	1904–08	133·52	13·85	147·37	N.A.	28,368.00	Part same ground
	ML 84, 93, 148	Mount Cassiterite Leases....	1908–18	195·50	1·60	197·10	N.A.	33,826.00	
	ML 93	Mount Cassiterite North	1906–07	9·67		9·67	N.A.	1,942.00	
	ML 89	Tinstone	1906–09	14.70		14·70	N.A.	2,780.00	Part same ground
	ML 255	Mount Tinstone	1913–14	2·45		2·45	N.A.	560.00	
	MC 109	McLeod, D. W.			3·94	3·94	2·12	5,757.13	
	ML 86, 87, 95	H.M.—Anchorite Leases	1917		5·00	5·00	N.A.	1,000.00	Part same ground
	ML 195	Cassiterite No. 1	1912	0·35		0·35	N.A.	98·00	
	ML 85	Commonwealth	1906	2·95		2·95	N.A.	696.00	
	ML 88	Chamberlain	1906	0·35		0·35	N.A.	120.00	
	Sundry Claims		1903–51	5·78	50·94	56·72	N.A.	11,633.84	
West Wodgina	ML 203	Wodgina Queen	1912–13	1·60		1·60	N.A.	380.00	
	ML 213	Referenda	1912	1·05		1·05	N.A.	294.00	
	DC 732	McLeod, D. W.	1968		3·93	3·93	2·42	5,955.31	
Stannum	ML 77	Stannum	1902–06		6·10	6·10	N.A.	922.00	Same ground
	ML 198	Stannum	1912	0·90		0·90	N.A.	252.00	
	ML 192	Comet	1912	0·30		0·30	N.A.	72.00	
Mills Find	ML 178	Siffleete's Reward	1910–13	3·50		3·50	N.A.	712.00	
	Sundry Claims		1906		0·85	0·85	N.A.	138.00	
Mount Francisco	MC 390	McPherson, N. E. and Fetwadjieffa	1957		0·13	0·13	N.A.	144.80	
	MC 910	Crow, Yegarla	1967			5·67	3·03	7,874.00	Mainly stream tin
	DC 15 WP	McLeod, D. W.	1967			1·54	0·97	2,654.13	
	PAs. 312, 313 WP	Nomads Pty. Ltd.....	1965			2·48	1·73	6,004.50	
	PA 2751	McLeod, D. W.	1965			0·25	0·18	604.80	
	Crown Land	Sundry Persons	1963–64			1·57	0·83	1,828.20	
						470·47			

TABLE 2. TANTALO-COLUMBITE PRODUCTION FROM THE WODGINA DISTRICT

Group	Tenement No.	Name of Lease or Operator	Period	Tantalite			Tantalite/Columbite (Mixed Oxides)			Tantalo-columbite Total		Remarks
				Tons	Ta_2O_5 Units	Value $ Aust.	Tons	Ta NbO_5 Units	Value $ Aust.	Tons	Value $ Aust.	
Wodgina	MLs 86, 87, 95	HM & Anchorite	1905–29	104·49	N.A.	38,822.00				104·49	38,822.00	Part same ground
	ML 293	May Be	1925	2·00	N.A.	480.00				2·00	480.00	
	MC 107, etc.	Northwest Tantalum NL	1956	·60	30·15	2,550.50				·60	2,550.50	
	MC 107, 355	L. J. Wilson	1957–67	3·18	191·98	20,777.82				3·18	20,777.82	
	ML 89	Tinstone	1934	·50	N.A.	260.00				·50	260.00	
	ML 352	Terra Nova	1932	·45	N.A.	282.00				·45	282.00	
	PA 2438	J. H. Walkerden	1955				·15	10·53	796.00	·15	795.30	
Stannum	PC 732	D. W. McLeod....	1968	2·79	86·62	15,098.61				2·79	15,098.61	
Mills Find(?)....	PAs 2454, 2456, 2458	McPherson & Party	1956				0·37	23·57	1,862.00	·37	1,862.00	
Mount Francisco	MC 350	J. Ball	1956	·04	·84	53.40				·04	53.40	
	MC 390	McPherson & Fetwadjieffa	1957				·05	3·12	18.05	·05	18.05	
Numbana	PA 2413	L. C. Stein & Party	1953				1·26	95·98	7,161.30	1·26	7,161.30	
	MCs 294, 306	Rare Metals Ltd.	1954				1·70	128·22	10,840.00	1·70	5,420.00	
	MCs 373, 378 379, 380	and Graydon & Party	1956				·56	35·93	2,836.00	·56	2,836.00	
Miscellaneous Tenements	MC 340	Sherlock & Parker	1956	·07	1·44	93.80				·07	93.80	10 miles SE Mt. Francisco
	DC 126, 127	Northern Minerals	1956				3·01	187·76	14,060.00	3·01	14,060.00	Pastoral Ck 8 miles E Wodgina
	MC 364, 365 MC 260	Syndicate Blanithensca	1955				2·18	132·71	9,174.00	2·18	9,175.30	14 miles SE Mt. Francisco
Crown Land & Sundry Person			1905–64	54·77	N.A.	23,693.08				54·77	23,693.08	
										178·17		

TABLE 3. BERYL PRODUCTION FROM THE WODGINA DISTRICT

Mining Centre	Tenement No.	Operator	Period	Production			Remarks
				Beryl Tons	BeO Units	Value $ Aust.	
Wodgina	MC 107 etc.	Tantalite Ltd. (Defence Project 83)	1943–52	754·26	8,607·68	51,496.00	Same ground
	MC 107	L. J. Wilson	1958	0·91	7·36	227.40	Same ground
	MCs 305, 314, 355	Northwest Tantalum Ltd.	1955	0·64	7·41	209.00	
	PA 2438	J. Walkerden & Party	1954–55	4·15	45·27	1,367.20	Near MC 310
	PA 2575	M. Seigne	1957–59	4·08	46·61	1,451.20	¾ mile S ML 88
	PA 2096	A. E. Rogers	1944	3·32	43·79	256.60	Location unknown
	PA 2104	G. Lamont	1944	46·68	563·66	3,569.80	Location unknown
	PA 2116	G. Hooley	1944	4·29	56·59	331.70	Location unknown
	PA 2337	J. Gilbert	1950	0·99	12·61	185.70	Location unknown
Stannum	MC 352	W. Marshall	1956	4·27	48·28	1,361.50	
Mount Francisco	MC 365	Hooley, Rogers & Radley	1947–48	27·54	347·80	2,511.22	Partly same ground
	MC 350	J. A. Johnston	1954–56	46·69	545·70	15,855.70	Partly same ground
	MC 512	W. Hall	1959	13·90	156·89	5,059.80	Partly same ground
	PA 2411	Thompson, Coffin & Ball	1953	10·36	118·70	3,338.70	Partly same ground
	PA 2534	F. O'Donnell	1956–57	2·71	32·24	995.90	Partly same ground
	PA 2559	R. H. Otway	1957–58	8·83	105·35	3,255.40	Partly same ground
	MC 234	R. H. Otway	1951–53	6·71	81·17	2,276.12	Partly same ground
	MC 286	W. Coffin	1953–54	18·22	194·82	5,844.60	Partly same ground
	MC 614 (PA 2591)	D. J. Butterfield	1959–62	9·62	109·41	3,368.40	Partly same ground
	MC 311	A. Hall	1954	2·09	25·48	718.40	Partly same ground
	MC 393 (PA 2467)	W. Ball	1955	2·16	26·00	733.30	
	PA 2442	C. Newlands	1955	0·57	6·92	195.00	
	ML 370	J. M. Henderson	1958–62	30·56	353·70	11,179.20	
Numbana	PA 2413 (MC 306)	Stein & McAlpine	1952	2·91	36·72	1,035.60	
	MC 294, 306	A. E. Hall & F. D. Pinchin....	1953–54	4·78	55·11	1,560.90	
Miscellaneous	MCs 340, 343	Sherlock & Parker	1954–62	19·53	236·81	7,032.40	15 miles SSE Wodgina
	PA 2410	Bell Bros. & D. C. Watkins....	1953	·75	9·66	277.80	19 miles N Wodgina
Wodgina-Mount Francisco area	Crown land	Sundry Persons	1945–61	146·23	1,701·36	39,979.34	
				1,177·75	13,583·10		

TABLE 4. COPPER PRODUCTION FROM THE WODGINA DISTRICT

Centre	Tenement No.	Operator	Period	Production		Value $
				Tons ore	Units Cu	
Mount Francisco	P.A. 2529	P. Coffin	1957	4·17	17·67	16.40
Stannum	P.A. 2687		1963	3·65	22·81	47.90

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THE ARCHAEAN STRATIGRAPHY OF THE TALLERING RANGE AND NUNIERRA HILL AREA

by J. L. Baxter

ABSTRACT

In the Tallering Range and Nunierra Hill area a folded and faulted succession of Archaean sediments is divided into two formations, the Eerada Formation and the overlying Tallering Formation. The succession is intruded by adamellite, granodiorite and gabbro. Lithologic, chemical and palaeogeographic evidence suggests that the succession was deposited in a basin sinking more rapidly to the south. Banded iron formation occurs in both formations, and is of different types, each type being related to its associated sedimentation.

INTRODUCTION

The Tallering Range area is 30 miles north of Mullewa and is reached from the Mullewa-Gascoyne Junction road. The ranges contain banded iron formation in which there are lenticular deposits of hematite.

The area was mapped by the writer during 1969 as part of the Yalgoo 1 : 250,000 sheet mapping programme.

HISTORICAL

H. Y. L. Brown (1871) first noted the occurrence of the hematite deposits, when he carried out the reconnaissance of the area with a view to locating gold-bearing rocks. Maitland (1924) collected specimens from the banded iron formation and the hematite deposits and briefly described the geology. Johnson (1950) carried out a reconnaissance of the area during mapping of the Murchison region. Connolly (1960) described drilling carried out by the State Government to assess the potential of the hematite deposits. In 1961 Western Mining Corporation took up a Temporary Reserve for iron over Tallering Range and began detailed exploration of the deposits.

GENERAL GEOLOGY

The Archaean stratigraphic succession has been subdivided into two formations, the Tallering Formation and the Eerada Formation. These formations have been intruded by gabbro and adamellites. The Archaean rocks are overlain by Cainozoic superficial deposits. (Plate 21).

STRATIGRAPHY

EERADA FORMATION

The Eerada Formation has a thickness of approximately 2,000 feet (600 m) where exposed in the area, but the base of the formation is not seen. It consists essentially of fine-grained quartz-actinolite rocks which also contain varying amounts of feldspar, sphene, tourmaline, epidote and sericite. There is a thin banded iron formation unit at the top of the formation. The type area is 3 miles south of Eerada trigonometrical station, after which the formation is named. Three rock types have been separately mapped within the formation: banded iron formation, acid volcanic rocks, and actinolite-quartz schist.

Banded iron formation is developed in lenses at the top of the formation. It consists of bands of quartz and amphibole with discontinuous bands of hematite and magnetite. It occurs with actinolite-quartz-feldspar rock similar to that described below from the lower part of the formation.

Acid volcanic rocks with quartz-sphene rocks and quartz-muscovite schists are developed throughout the formation, usually in thin bands. In the Eerada area there is sufficient thickness for separate mapping in the central part of the formation.

The actinolite-quartz schist consists of fine-grained actinolite and quartz with varying amounts of chlorite, epidote, sericite, tourmaline, sphene, feldspar and minor apatite. Four analyses of this rock appear in Table 1. This rock type is best developed in the lower part of the formation, in which there is a cyclicity, with the cycles varying from 10 feet (3 m) to 50 feet (16 m) in thickness. Each cycle is marked by a decrease in the amount of actinolite from bottom to top.

TABLE 1. CHEMICAL ANALYSES FROM EERADA FORMATION

Locality 4 miles (6·4 km) bearing 335° from Tallering Trignometrical Station

Sample	24274	24275	24276	24277
SiO_2	58·32	56·29	50·12	56·74
Al_2O_3	15·83	15·25	16·84	14·37
Fe_2O_3	0·87	0·07	0·57	1·83
FeO	5·60	5·67	7·63	6·23
MgO	5·91	8·26	11·16	7·43
CaO	7·86	6·97	8·50	7·48
Na_2O	3·17	1·93	0·65	2·51
K_2O	0·23	0·96	0·51	0·32
H_2O^+	1·09	2·77	2·30	1·57
H_2O^-	0·09	0·15	0·09	0·05
CO_2	0·01	0·10	0·04	0·01
TiO_2	0·62	0·48	0·41	0·59
P_2O_5	0·16	0·12	0·10	0·12
MnO	0·13	0·13	0·15	0·13
Total	99·89	99·15	99·07	99·38
C.I.P.W. Norm q	11·90	10·94	3·94	11·99
c	0·00	0·00	0·09	0·00
Or	1·35	5·67	3·01	1·89
Ab	26·82	16·32	5·49	21·23
An	28·28	30·11	41·26	27·00
Di	7·81	2·46	....	7·49
(Wo	4·00	1·27	....	3·86
En	2·38	0·80	....	2·42
Fs)	1·42	0·38	....	1·20
Ay	19·69	29·18	40·93	24·06
(En	12·33	19·76	27·79	16·07
Fs)	7·36	9·41	13·14	7·99
Mt	1·26	0·10	0·82	2·65
Il	1·17	0·91	0·77	1·12
Ap	0·37	0·28	0·23	0·28
Cc	0·02	0·22	0·09	0·02

Analyst R. S. Y. Pepper.

TALLERING FORMATION

The Tallering Formation is approximately 5,000 feet (1,500 m) thick, but lithological units within it vary in thickness over the area. It consists essentially of fine-grained quartz-muscovite schist with minor quartzite, conglomerate and banded iron formation. The type area is Tallering Range. The subdivision of the formation is shown in Table 2.

TABLE 2. TALLERING FORMATION SUBDIVISION

Rock Types	Lithological Map Unit	Description
Quartz-muscovite schist	Atj	iron-stained sericite-quartz schist
Cherty banded iron formation		irregularly banded cherty magnetite iron formation
Quartzite		fine-grained quartzite with minor sericite
Quartz-muscovite schist	Ats	predominantly quartz and muscovite with chlorite and feldspar in some bands—there is minor chlorite
Chlorite schist	Atb	Chlorite-feldspar-quartz rock
Hematite banded iron formation	Ati	fine-grained hematite-quartz banded iron formation with regular banding and lenses of hematite
Acid volcanics		fine-grained quartz-chlorite rocks with phenocrysts of feldspar
Conglomerate		conglomerate of fine-grained quartzite pebbles in a sandy matrix
Magnetite banded iron formation		fine-medium-grained magnetite-quartz banded iron formation with accessory amphibole and local concentrations of pyrite
Quartzite		fine-grained quartzite with minor sericite
Quartz-muscovite schist	Ats	predominantly quartz and muscovite with chlorite and feldspar in some bands—the unit has numerous quartz veins through it from which traces of gold have been found
Conglomerate	Atc	pebble to cobble size conglomerate with sandy matrix, clasts fine-grained quartzite and granitoid rocks
Chlorite schist	Atb	pale green slightly pleochroic chlorite, feldspar and quartz rock with minor actinolite

INTRUSIVE ROCKS

INTRUSIVE COMPLEX OF DOLERITES

Intruding the Tallering Formation there is a complex of dolerites with numerous basic and sedimentary xenoliths. This has been mapped as one unit as the outcrops are small and the rocks mixed.

GABBRO

Medium-grained gabbros intrude the succession. These are mainly conformable, although they show disconformable relationships due to thickening. They appear to be simple intrusions.

MEDIUM TO COARSE-GRAINED ADAMELLITE TO GRANODIORITE

Medium to coarse, even-grained adamellitic to granodioritic rocks are exposed on the northwest and southeast of the layered succession. The rocks appear to be related to the syncline, as there is a foliation in the adamellite concordant with that of the adjacent sedimentary succession.

PORPHYRITIC ADAMELLITE

A porphyritic adamellite has intruded the entire succession. The bodies of adamellite are elongated parallel to a major direction of faulting in the area. There was stress along this direction while this rock was emplaced, as there is shear and flow directional evidence of the stress in the intrusion.

DEPOSITIONAL ENVIRONMENT

The following features of the rocks are significant for environmental interpretation:—

1. Boulders in Tallering Formation conglomerate on the north limb of the syncline have diameters of up to 15 inches (38 cm), whereas those on the south limb have a maximum diameter of about 8 inches (20 cm), and there is thinning of the conglomerate bands to the south.

2. The thicknesses of the quartz-muscovite schist units of the Tallering Formation increase to the south.

3. The grain size of all sediments decreases to the south.

4. The banded iron formation exposed on the north limb of the syncline contains lenses of quartzite, and is coarser grained than that on the south limb, and there is better development of the hematite and magnetite bands on the south limb.

From these features it is suggested that there was land to the northwest at the time of deposition of the Tallering Formation and that the basin of deposition was subsiding to the south.

STRUCTURE

The observed geological structure of the area is consistent with a compressional force applied to the layered succession from a direction of 150 degrees. This is reflected by faults parallel to the directions of maximum shear and folds at right angles to the direction of force. Cross-folding, probably related to the intrusion of the porphyritic adamellite has taken place about an axis trending 130 degrees. This intrusion appears to have distorted the axes of pre-existing folds and the direction of faults along its margins suggesting that the intrusion was from the southwest (Plate 22).

FOLDING

The main northeast-plunging syncline is a similar fold (Hills, 1963) which has been slightly distorted by the thickening of the Tallering Formation to the south.

The warp produced by the younger granitic intrusion may be a parallel fold (Hills, 1963) for, although at Tallering Range there is a pronounced plunge down the axis of this fold, 3 miles north of Tallering Range there is little evidence of its presence.

The faulting appears to be in part strike-slip and in part, hinge faulting. This is inferred from the different displacement of individual beds within the succession. Most faults are arcuate. The inferred faults have been interpreted from lineaments on air photographs and differences in strikes of rocks on either side of the faults. The major north-south fault along the eastern edge of the younger intrusion predates the intrusion, and has probably controlled its shape.

GEOLOGICAL HISTORY

A suggested interpretation of the geological evidence in this area is given below. Interpretation is uncertain, as there are two envoronments present and the relationship of these to the overall development of the Yilgarn Block is not known.

Stage 1

The first event recorded in the area is the deposition of a possible dolomitic mud which was presumably laid down in deep water, the clays being contributed from a land mass of low relief. Intermittent acid volcanicity on the land contributed to the deposition of the acid volcanic rocks exposed in the north of the map area. This period closed with the formation of thin lenses of what is now a banded amphibole-quartz rock within the otherwise argillaceous succession. This banded rock has concentrations of magnetite and hematite in it and is interpreted as a type of banded iron formation, presumably laid down during a period of quiescence which may have been caused by the isolation of the basin from the source of argillaceous material.

Stage 2

Following the period of quiescence, a short period of basic volcanicity deposited the rocks on the south side of the syncline in the Tallering Formation. This was accompanied by a steepening of the depositional slope with a concomitent increase in the rate of deposition, with fine-grained sandstone and intermittent conglomerate being laid down. The source of this material appears to have been northwest of the basin. Three major banded iron formation horizons were formed in the Tallering Formation, presumably during a period in which there was little contribution of terrigenous material to the depository.

Banded iron formation associated with quartzite, conglomerate and acid volcanics (probably tuffaceous) was deposited between two fine-grained sandstone units, and represents a change in the normal conditions of deposition. This may have been effected by fluctuations in the rate of subsidence.

Stage 3

During Stage 2 the basin must have been sinking steadily to the southeast as there is a marked increase in the development of the sandstone in this area. It is suggested that at this stage the compressive stress developed along a northwest-southeast line and folding of the basin began. At this stage the intrusion of the older even-grained granodiorite also began to affect the area, and may have been the cause of the stress that formed the syncline and subsequent faulting.

Stage 4

In the closing stages of folding there was a series of gabbros intruded into the succession.

Stage 5

The final episode recorded in the Archaean in the area was the intrusion of the porphyritic adamellite which appears to have been controlled in direction by a major north-south fault. The adamellite disturbed the adjacent country rocks, rotating them toward the north along both margins.

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"SPINIFEX TEXTURE" IN A SLAG, AS EVIDENCE FOR ITS ORIGIN IN ROCKS

by J. D. Lewis

ABSTRACT

Textures found in an iron/silicate slag bear a remarkable resemblance to "spinifex texture" as found in the Archaean mafic and ultramafic rocks of Western Australia, and provide evidence on the origin of the texture. Fayalite in the slag has crystallized as complex dendritic crystals or, more commonly, as thin plates elongated along the a and c axes. The arrangement of the olivine plates gives rise to a variety of textures which are described and compared with the natural texture. By analogy with the slag textures it is shown that spinifex texture is an original igneous texture formed by rapid chilling of the magma. Preservation of the delicate structure indicates a lack of convection currents and mechanical disturbance during crystallization, and recent work on ceramics suggests that crystallization may have been from an initially formed glass. Spinifex texture can be found in both intrusive and extrusive bodies and cannot, by itself, be used as a criterion for determining the mode of emplacement.

INTRODUCTION

The term "spinifex texture" is in common use in Western Australia to describe a distinctive assemblage of minerals in which tremolite, chlorite or serpentine form long bladed crystals or aggregates set in a granular matrix of chlorite or tremolite, or both. The rocks in which this texture is commonly present are the altered ultramafic rocks of the Archaean greenstone belts which are often colloquially named "spinifex rock".

The name "spinifex" is derived from spinifex grass (*Triodia* sp.), common in the arid areas of Australia; the long dry blades grow in clumps up to several feet high and the matted older growth bears a marked resemblance to the patterns found on rock surfaces. The term was first used by miners in the Eastern Goldfields of Western Australia (Blockley, 1956) but since the recent interest in ultramafic rocks in the search for nickel the name has become widely used among geologists.

Interpretation of the origin of spinifex texture has varied from primary igneous to metamorphic, depending on the significance attached to small amounts of remnant olivine or pyroxene. An igneous origin for spinifex texture presumes that olivine has been replaced without destroying the original texture, whereas the metamorphic interpretation relies on the replacement of olivine or pyroxene along particular zones leaving lath-like remnants of the original mineral. The most commonly accepted view is that spinifex texture is formed in rapidly cooled zones of the ultramafic magma, and represents a primary igneous texture. The origin of spinifex texture assumes importance when the mode of emplacement of the ultramafic bodies and their possible association with sulphide ore deposits is considered.

The purposes of this paper are to describe in detail the variety of textures found in a slag, and to compare them with the textures found in nature, in the belief that this, along with other work on glass and ceramics, will give clues as to the origin of spinifex texture.

THE EULAMINNA COPPER MINE

The slag samples examined were collected at the old Eulaminna Copper mine in the Mount Margaret Goldfield, 27 miles (43·5 km) east of Leonora. The mine was active between 1899 and 1908, producing a total of about 4,200 long tons of copper. Mainly ores from the oxidised zones were smelted but some sulphides were also treated. The sulphide ores were roasted in a reverberatory furnace to produce a copper matte and an iron silicate slag. From the old workings it appears that the slag was then transferred to large crucibles, transported a short distance, and then poured out on the ground. The temperature of the slag at this point is problematic but the temperature at the discharge of the furnace would have been about 1,100°C so that solidification and crystallization probably took place at about 800°–1,000°C. At the time of pouring the slag was sufficiently liquid to spread out in a thin film so that cooling would be very rapid.

Two specimens of the slag have been studied in detail, one is in the form of a very thin "flow" about 2–3 cm thick and the second from a "flow" at least 15 cm thick. The slag consists of olivine and glass, the olivine being a pale yellow, slightly pleochroic fayalite, and the glass, of unknown composition, is dark brown and highly charged with iron oxides. Spinifex texture is present throughout the thickness of each of the thin flows but is developed only marginally in the thick flow, the central part being made up of larger discrete skeletal olivine crystals.

SPINIFEX TEXTURES IN THE SLAG

Crystals grown in the slag take several forms. Most commonly, fayalite crystallised in thin plates showing approximately equal development along the a and c axes and negligible development along the b axis. More rarely growth took place preferentially along the c axis, resulting in acicular crystals. The crystal plates are either fans or in random orientation. Alternatively crystal growth was dendritic, the original plate giving rise to second and third order growths in optical continuity. In all cases growth was skeletal, but for the dendritic forms, where cooling had been sufficiently slow, there has been later growth along the b axis, with consolidation of the crystal.

The textures found in the slag will be described under two headings, those formed by the arrangement of single olivine plates and those formed by the dendritic growth of a single olivine crystal. The textures seen in thin section, however, depend not only on the mutual arrangement of the olivine plates but also on the direction in which the rock is sectioned, and similar patterns may arise from both dendritic growth and the arrangement of single plates.

Single crystal plate textures

The most typical of spinifex textures both in the natural rock and the slag is that the olivine plates are arranged like the pages of a book and radiate from a point. In thin section this produces a fan which usually extends through an angle of only 10°–15°. The plates have a length/breadth ratio of up to 150 : 1 and are skeletal crystals usually showing a line of glass inclusions along the centre. Although crystal growth has proceeded from a single nucleus the plates are not in strict optical continuity and the formation of branches, or dendritic growth, is not pronounced. Several types of fan are shown in Figure 3. In type a (lettered types in the succeeding text refer to the lettered sketches of Figure 3) the thin olivine plates of uniform thickness radiate from a point so that progressively more glass is found in the fan, but in type b further plates have been added so that the fan has grown to keep the proportion of glass roughly constant throughout. The third type of fan is of wedge shaped olivine plates and is found in the thicker flows where cooling has been slower. The terminations of the crystal plates are rarely seen, except in type c, but where noted they are usually pyramidal.

Random sectioning of a fan of olivine plates produces a variety of patterns including fans which do not proceed back to a point of origin and, if the section is parallel to the 001 plane, a lamellar pattern which can also be found in sections of dendritic crystals.

The fans of olivine plates invariably have their point of origin within the glassy margin of the flow of slag which means that although the a and

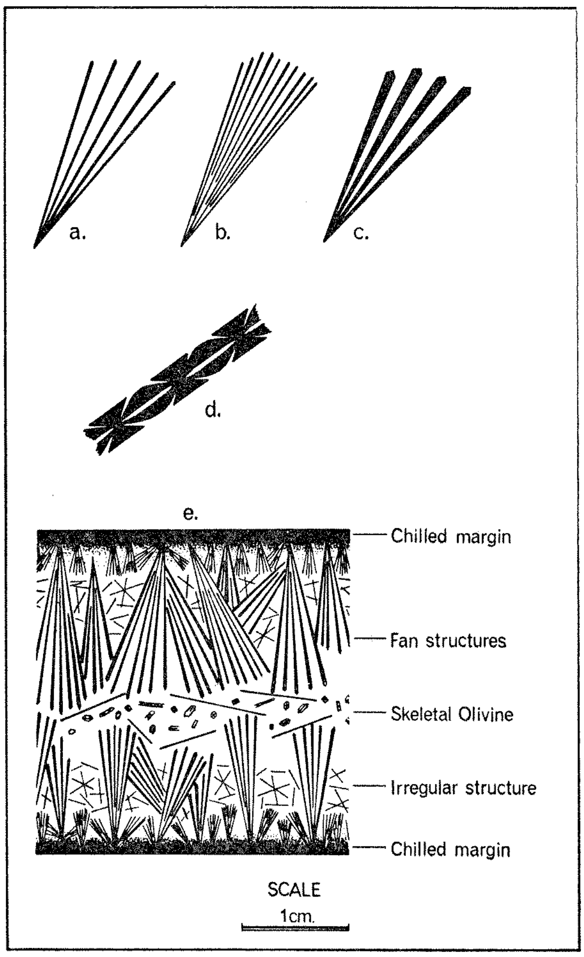

FIG. 3 a,b,c: Typical fan structures found in the slag. d: skeletal structure of olivine plates within a fan. e: zonation of structures within a 'flow' of iron/silicate slag.

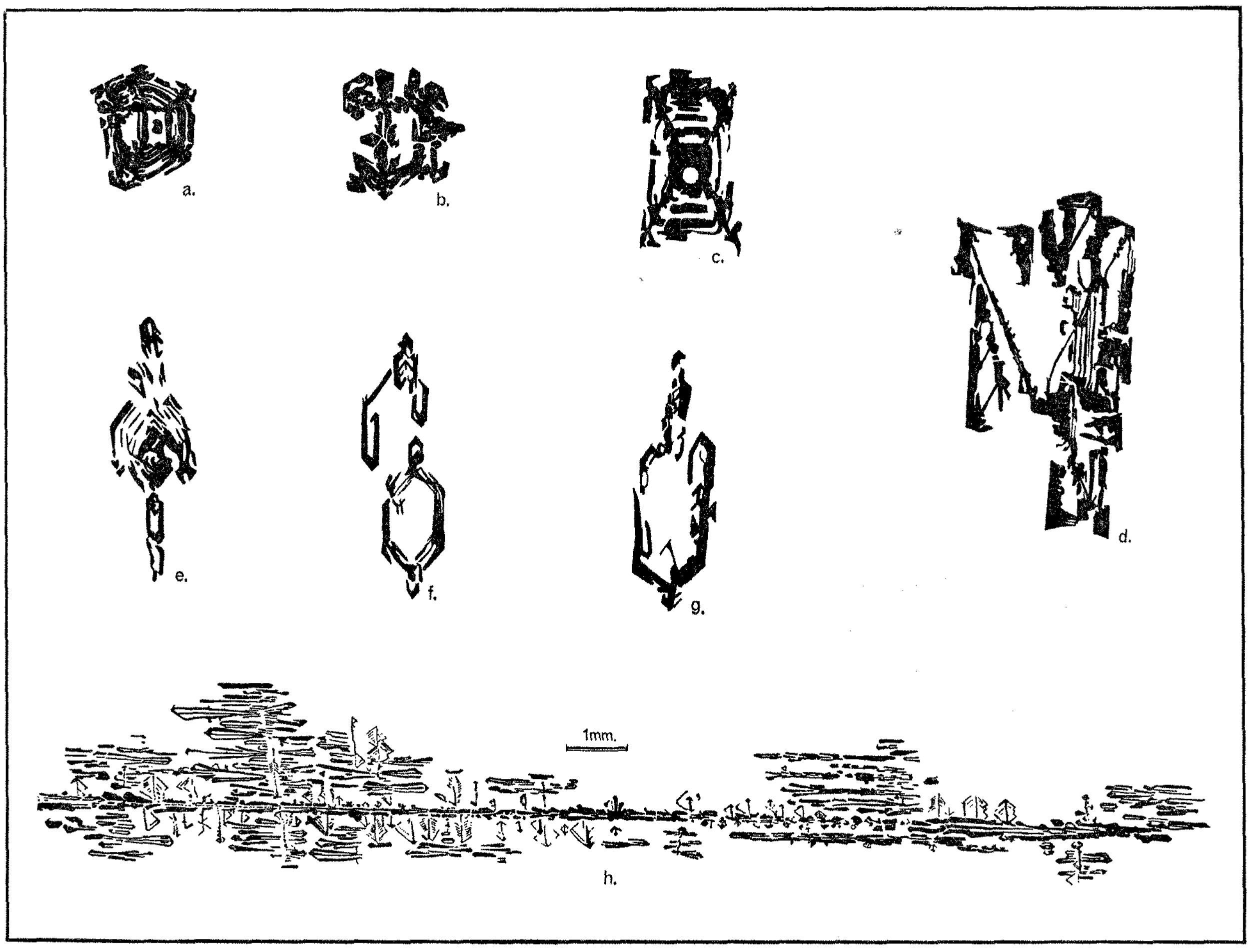

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FIG. 4
a–d Skeletal fayalite in iron/silicate slag (x20).
e–g Skeletal olivine from an ultramafic body $2\frac{1}{2}$ miles (4 km) north of Eucalyptus, Mount Margaret Gold Field (x20).
h Part of a single dendritic fayalite crystal from the slag (All drawn from photographs).

b axes of fans may be in random orientiation the c axes are parallel to within 10°–15°. If several such fans are sectioned perpendicular to their c axes the result is a pattern with an apparent three dimensional effect in which the individual lamellae appear to step down towards a central depression. This is illustrated in Plate 23b, the overall effect being similar to a hopper crystal of halite.

Fan textures and their derivatives are developed in the marginal zones of the slag, but the thin plates of olivine nearer the centre of the flow are often in random orientation, giving a distinct but irregular pattern. This irregular texture may not, however, be completely random, as it contains stellate groupings where two or three plates intersect at a point. This arrangement does not appear to be fortuitous, as two of the plates appear to have a constant angle of about 50° between them, the third plate being placed in the obtuse angle. The relationship may be due to twinning.

Textures due to dendritic growth

Dendritic crystals in the slags are developed on a coarser scale than the single crystal plates described above and are associated only with the thicker "flows" which presumably cooled more slowly. Fan textures are less prominent, confined to marginal zones and are of type c with wedge-shaped skeletal crystals. The complexity of individual crystals is shown by Figure 4b where small scale secondary growths have produced major third order growths parallel to the original crystal. As with the previously described types the basic unit is a crystal plate developed along the a and c axes. Second order growths, parallel to the 001 plane are developed on a very fine scale at intervals along the original growth, and these give rise to further third order skeletal growths which are also plate like and parallel to the original crystal. The result, when fully developed, is a texture which is macroscopically similar to the fan textures already described, but with the fans replaced by bunches of parallel plates of olivine in strict optical continuity with each other.

On a finer scale there are also many instances where a herringbone texture has developed as part of the dendritic growth. In Figure 4h these are seen at intervals along the main crystal plate and are caused by the development of the dome faces of the olivine rather than the pinacoid faces that give the predominant texture. The mode of formation of herringbone textures is best seen on the larger skeletal crystals (Fig. 4d). In the 001 plane skeletal growth is initially concentrated along the direction of the prism faces giving a cruciform shape to the crystal, but when growth in this direction ceases the pinacoid faces develop. Growth takes place from several points along the arms of the original cross and leads to a herringbone texture. This style of growth takes place in all planes so that the final crystal appears to be successive shells of olivine separated by glass.

ZONATION OF TEXTURES WITHIN THE SLAG

In the "flows" of slag greater than 10 cm thick, where cooling has been slower, spinifex texture has developed only in a narrow marginal zone, but in the thin "flows" the texture is developed throughout. Most of the textural varieties described can be found within a single flow with a distinct zoning as shown diagrammatically in Figure 3e. The most typical arrangement is that both top and bottom margins are black glass from which has arisen a narrow zone of very fine fan texture of type b. The fans are perpendicular to the cooling surfaces and have their point of origin within the glassy margin. This zone is succeeded by a narrow zone of irregular and stellate groupings. Centrally there is a wide zone of fan structure of type a, the fans having their point of origin within the outer zones and growing inward towards the centre. The fans developing from the upper surface are usually better developed than those from the lower so that the zones are slightly asymmetric. In particular flows, perhaps depending on the thickness and rate of cooling the central part is often crowded with skeletal olivine crystals that show equal development along all axes.

COMPARISON WITH NATURAL OCCURRENCES

The study of naturally occurring spinifex texture is complicated by the fact that most specimens have been completely pseudomorphed by tremolite, chlorite or serpentine. Additional difficulties arise from the fact that natural magmas have a more complex composition than the slags and therefore there has been multiphase skeletal and dendritic growth. Nevertheless a broad correlation is easily demonstrated between the natural and artificial textures. Plates 23 and 24 show examples of various textures found in natural rocks, slag and a remelted basalt, while Figure 4 illustrates the shapes of skeletal olivine found in slag and an ultramafic body at Yundamindra, north of Kalgoorlie.

The ultramafic body at Mount Hogan, northeast of Kambalda had an original mineralogy consisting of large plates of olivine with smaller interstitial plates of clinopyroxene and dendritic growths of chromite. In the present rock the olivine has been replaced by serpentine and the pyroxene by tremolite. The hopper texture developed by the main fans of olivine plates (Plate 24a) compares well with similar textures in the slag (Plate 23b) while on a smaller scale there is a marked resemblance between the natural texture of the ultramafic rock and the textures developed in a melted and chilled basalt (Plate 24b and 23d). The pyroxene of the Mount Hogan mass often shows well developed fans and irregular textures, similar to that in a high magnesian basalt from the Seabrook Hills, about 20 miles east of Mount Hogan (Plate 24), and these can be compared with the irregular textures developed in an ultramafic body at Yundamindra, southeast of Leonora, and textures in the slag (Plate 24c and 23a).

Dendritic growth of olivine in the natural rocks has not been observed except for a few poorly developed examples in the Yundamindra mass but dendritic growth of chromite is illustrated from Mount Hogan (Plate 24b) and dendritic magnetite is prominent in the remelted basalt (Plate 23d).

A further point of comparison between the natural and artificial spinifex textures is the mode of growth of the olivine plates. In most examples of natural spinifex texture the process of replacement of the original mineral by serpentine or tremolite has destroyed the delicate internal structure and resulted in a pseudomorph in which the structure reflects that of the new mineral. In the specimen of ultramafic rock from Yundamindra, however, instead of a felted mass of tremolite blades the original olivine has been replaced by small flakes of tremolite which outline the original structure of the olivine. A close examination of Plate 24c shows that each individual olivine plate is a complex skeletal growth which contains numerous small inclusions of glass arranged either as a central core or as a diagonal pattern depending on how exactly the crystal plate was sectioned. Although not easily seen on the photograph (Plate 24c) many of the olivine plates within the Yundamindra mass show the same pattern and indicate that their mode of growth was similar to that in the slag.

The scale of development of spinifex texture is usually much greater in the natural rock than in the slag. Specimens of ultramafic rock showing plates of olivine up to 30 cm long by 15 cm across are not uncommon whereas in a flow of slag greater than about 5 cm thick the olivine plates cease to grow and are replaced by equidimensional skeletal olivine crystals. Despite this difference in scale, however, the textures produced are broadly similar.

DISCUSSION

Dendritic and skeletal growth of crystals is common in metals and forms an important topic of study for metallurgists. Theories of the formation of such crystals are many and have been reviewed by Buckley (1951) and Saratovkin (1959). Geologically the problem has received little attention since the work of Fouque and Michel-Levy in the nineteenth century which has been reviewed more recently by Drever and Johnston (1957). Spinifex texture in Archaean ultramafic rocks from Canada has been reported and discussed by Naldrett and Mason (1968) and Naldrett and Gasparini (in press) and an allied texture, harrisitic texture, described by Brown (1957) and Wadsworth (1961) from the tertiary volcanic rocks of Rhum, Scotland. Recently work on the production of opal glass and ceramics has led to renewed interest in nucleation and crystal growth in glassy media (Rodgers, 1970) which has a direct bearing on geological phenomena.

The causes of dendritic and skeletal growth are not fully understood but some substances, for example metals in the early stages of crystallization, seem to favour the dendritic habit while others will only adopt this habit if impurities are present. Other factors which favour dendritic growth are rapid cooling and the lack of mechanical stirring or convection currents, both of which would tend to equalise concentration and lead to the uniform development of the crystals (Buckley, 1951, p. 486). Saratovkin (1959, p. 47) sums up the growth of dendritic and skeletal crystals thus: "The forms occur in rapid growth when the space around the crystals contain foreign particles not removed by convection or diffusion".

In the slags described above, the thinness of the individual flow led to rapid cooling and the lack of convection currents. The preservation of delicate fans of olivine plates perpendicular to the cooling surface suggests that by the time crystallization

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PLATE 23 (opposite)

Microphotographs of slag and remelted basalt

A 15133. Nearly complete section through a thin "flow" of slag showing well developed fan texture developed from upper margin and poorly developed fan and irregular texture at lower margin(PPLx5).
B 15133A. Section of fan structures at right angles to the plane of A showing hopper texture. Note the skeletal structure of individual crystal plates (PPL x 30).
C 15133B. Detail of margins of slag "flow" showing two generations of fan structures (PPL x 30).
D Section of remelted and chilled olivine tholeiite basalt from Carnarvon Ranges, S. Queensland. Plates of olivine outline a spinifex texture along with dendritic magnetite and feathery masses of feldspar (PPL x 75) (Photo: D. R. Hudson C.S.I.R.O.).

subject to mechanical disturbance. While the ultramafic bodies in which natural spinifex textures are found are not thin bodies, the presence of the texture would suggest that convection currents and mechan-
started the slag had ceased to flow and thus was not
ical disturbance were not present in those parts of the mass where the texture is found. Whether the spinifex texture developed directly from the crystallization of the molten material or represents the products of devitrification of an initially formed glass it is not now possible to determine. Drever and Johnston (1957, p. 310) use the fact that skeletal olivines were found mainly at or near the chilled margin of the rocks that they studied to suggest that their formation depended in part on undercooling and increased viscosity and quote their own and other experiments to show that typical skeletal olivine can be generated by annealing an artificially melted basalt. Plate 23d shows an example of the shapes taken by olivine and magnetite in a basalt which has been melted and chilled.

The work of Rodgers (1970) on crystal growth in glasses provides further evidence for the origin of spinifex texture. In his experiments small quantities of ferric and chromium oxide were added to a glass and specimens heated to allow nucleation and crystallization (devitrification) to take place. A glass of composition CaO 26 per cent, MgO 6 per cent, Al_2O_3 15 per cent, SiO_2 53 per cent with 0·6 per cent added Cr_2O_3 was found to devitrify in two stages, first the dendritic crystallization of diopside followed by the crystallization of feathery masses of anorthite between the diopside crystals. This appears to be analogous to the presence of large plates of olivine with smaller interstitial growths of clinopyroxene and chromite found in the less siliceous ultramafic rocks of the Eastern Goldfields. Nucleation in the glasses studied by Rodgers took place both at the surface and internally, the early formed diopside growing from nuclei within the glass while the later formed anorthite grew from surface nuclei (Rodgers, 1970, fig. 5). In the slags studied the reverse applies, initial nucleation being from the cooling surface with internal nucleation following. The source of nuclei for the olivine in natural spinifex texture cannot be determined but clinopyroxene appears to have nucleated on the surface of the existing olivine plates while chromite grew on independent internal nuclei.

Although the textures in the slag and glasses were undoubtedly formed during rapid cooling a related dendritic growth of olivine is found in the layered ultrabasic rocks of Rhum (Brown, 1956; Wadsworth, 1961), where parallel growths of olivine plates sometimes exceed 1 foot (30 cm) in length. The olivines grow upward from the preceding layer of cumulate material and are believed to be formed during periods of non-deposition of plagioclase (Brown, 1956, p. 18). Alternatively, the same result would follow if the rate of crystallization of olivine increased for any reason. But whatever may be the cause of this type of olivine growth, the rocks are relatively deep seated and cooled slowly.

Spinifex texture, as developed in the Archaean ultramafic rocks of Western Australia and Canada (Naldrett and Mason, 1968; Naldrett and Gasparini, in press) appears to have more affinity with the quickly cooled iron-silicate slag described in this article and the devitrified glasses described by Rodgers than with harrisitic structure developed in the ultrabasic rocks of Rhum, but the conditions required for its formation in nature remain obscure. The texture is probably due to the quenching of the magma and its sudden supersaturation, the cause of the rapid cooling being the particular environment into which the body is emplaced. Naldrett and Mason report the texture from intrusive bodies but Naldrett and Gasparini suggest that its presence may indicate an extrusive ultramafic lava. From the natural and artificial examples cited in this article it is evident that spinifex texture could form in both intrusive and extrusive rocks, so that the present state of our knowledge is perhaps best summed up by Drever and Johnston (1957, p. 310) who write that: "The only hypothesis that can be established which is consistent with all the evidence is that the growth of olivine is rapid, that the morphology of individual crystals is extremely sensitive to, and dependent on, the physical and chemical environment of their point of growth and that olivine of almost any shape or size can crystallise from a magma"!

PLATE 24 (opposite)

Microphotographs of natural spinifex textures

A Ultramafic intrusive body, Mount Hogan, E. Coolgardie Gold Field. Plates of olivine, now pseudomorphed by serpentine, outline a characteristic hopper texture. Interstitial material is tremolite after clinopyroxene, and chromite (PPL x 5).

B Detail of Mount Hogan Ultramafic body. Between the large plates of olivine are smaller pyroxene plates and dendritic chromite grains (PPL x 15).

C 26792. Irregular spinifex texture in a small ultramafic body 8 miles south-east of Yundamindra Homestead, Mount Margaret Gold Field. Note that the skeletal nature of the original olivine plates is still preserved (cf. Plate 23B) (PPL x 15).

D High magnesian basalt, Mount Seabrook, E. Cologardie Gold Field. Spinifex texture outlined by tremolite pseudomorphs after clinopyroxene (PPL x 15).

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THE GEOLOGY OF SOME CARBONATE INTRUSIONS IN THE MOUNT FRASER AREA, PEAK HILL GOLDFIELD, WESTERN AUSTRALIA

by J. D. Lewis

ABSTRACT

Six small carbonate-rich intrusive bodies in the Mount Fraser area contain a variety of agglomerates, carbonated shales and intrusions of quartz-pyrite rock and carbonated quartz dolerite. In each body the emplacement of small plugs of quartz-pyrite rock or quartz dolerite has been followed by the formation by fluidisation of vent agglomerates, consisting of fragments of locally available sedimentary and igneous rock with a matrix of ankerite. One body consists largely of carbonated and remobilised sediments.

The absence of fenitization and alkali-rich igneous rocks indicates that these bodies are not carbonatites, while the presence of chloritoid demands a low-temperature origin. The origin of the carbonate is unknown but is possibly related to a greenstone belt in the underlying Archaean Shield. Except for No. 5, all the bodies are emplaced in the axial zone of the Mount Fraser Anticline and although they bear certain resemblances to both volcanic vents and diapiric intrusions their mode of emplacement is best described as pseudo-volcanic.

INTRODUCTION

Five small carbonate-rich intrusive masses were discovered by Dr. W. N. MacLeod during the regional mapping of the eastern part of the Robinson Range 1 : 250,000 sheet. In a preliminary report (MacLeod, 1970) these were distinguished from the carbonated basic and ultrabasic rocks found elsewhere in the Archaean Shield of Western Australia, and were thought to be carbonatites. Due to the possible economic importance of carbonatites, and the distinct lack of such bodies in Australia, a programme of detailed mapping and geochemical sampling was undertaken during 5 weeks in April and May 1970. Only the geological investigations will be reported in this article, the geochemistry being the subject of a separate report (Lewis and Williams, 1971).

REGIONAL GEOLOGY

The Mount Fraser area lies at the northern edge of the Archaean Yilgarn Block (Plate 25). To the south of the Murchison River, granites, gneisses and greenstones of the Shield are exposed, but to the north the rocks are principally the strongly folded Robinson Range Beds, which consist of shales, siltstones and banded iron formation with minor greywackes (MacLeod, 1969). The age of the sedimentary series is probably Archaean but may possibly be Lower Proterozoic and equivalent to the Mount Bruce Supergroup found in the south of the Pilbara. MacLeod (1969, p. 6) bases their assignment to the Archaean on their similarity to other Archaean clastic sequences and the presence of gold mineraliza tion. Metamorphism of the sediments is slight, the finer grained shales now having a slaty cleavage parallel to the bedding.

The general structural trend of the Robinson Range Beds is west-southwest to east-northeast but this trend is disturbed by several cross folds trending north-northeast to south-southwest. In the vicinity of the carbonate intrusions there is a north-plunging asymmetric anticline, complementary to the Mount Fraser Syncline (Sofoulis, 1970), both being outlined by the superior resistance of banded iron formation beds. The anticline trends north-northeast and the western limb through Mount Padbury dips at 45°–70° westward; the eastern limb through Mount Fraser either dips vertically or is slightly overturned to the east.

Later geological history is now represented only by the products of erosion and lateritisation. Fossil drainage channels have formed the repository for manganese deposits which more recent erosion has left as mesaform remnants and spur cappings at 50–100 feet (17–33 m) above the present valley floor (de la Hunty, 1963).

THE CARBONATE INTRUSIONS

Five of the carbonate intrusions to be described lie in a straight line along the axial zone of the Mount Fraser Anticline, the sixth being about 2 miles (3·2 km) to the east and emplaced in the vertical eastern limb of the fold. Throughout the axial zone of the anticline there are small intrusions of quartz-pyrite rock of a similar type to that associated with the carbonate rock, but these were not mapped in detail and will not be described. Except No. 4, all the intrusions are of a similar size and measure no more than 1,000 feet (305 m) across; individual units within each complex are small, and in the northernmost complex agglomerate bands only a few feet wide by a few yards long can be distinguished. The true size of No. 4 is difficult to gauge, as its eastern margin is covered by alluvium and rock scree; its length is about 1 mile (1·6 km) and it might well extend beneath the thick alluvial cover to include No. 6 on the other side of the valley.

The carbonate bodies are intruded into Robinson Range Beds which, in the central zone of the Mount Fraser Anticline, are predominantly shales and siltstones, with only minor banded iron formation and greywackes. The easternmost body, No. 5, is intruded into a more iron rich part of the sequence.

The nature of the carbonate rocks has led, in most cases, to very deep weathering with the result that their preservation appears to depend on the surrounding country rocks. All the intrusions are exposed on hillsides, where they are easily seen due to the contrast between the light-coloured quartz-pyrite scree and the rust-red shale scree.

For convenience the numbering system of MacLeod (1970) has been retained, and the intrusions will be described in detail from north to south.

No. 1 (Plate 26)

This is the northernmost intrusive body that contains carbonate rocks and the best exposed. The intrusion occupies the crest and southern half of an isolated hill which rises about 150 feet (50 m) above the level of the plain and measures about 1,500 feet (455 m) from east to west by about 600 feet (182 m) north to south. The northern slopes of the hill are formed of shales, siltstones, greywackes and banded iron formation that dip steeply northward. Contact relationships between the carbonate and country rock cannot be seen in detail but appear to be sharp and complex as tongues of carbonate agglomerate intrude the shales. To the south of the hill the limits of the carbonate cannot be established because of scree cover.

The principal components of the mass are several small intrusions of quartz-pyrite rock and innumerable lenses of carbonate-rich agglomerate. Minor components include small dykes of almost pure carbonate and viens of white milky quartz carrying a little specular hematite. Quartz-pyrite rock appears to be the earliest intrusion, individual bodies ranging from about 200 feet (60 m) across to small plugs and dyke-like bodies only a few feet across. Most are oval and elongated east-west, parallel to the main axis of the complex. The quartz-pyrite rock is well jointed, fine grained and pale grey when fresh, it weathers to a pale brown colour. Flow banding, when present, is nearly vertical, parallel to the margin of the intrusion and is often outlined by trains of small pyrite cubes. Marginally the rock is often brecciated by the later emplacement of the carbonate agglomerates. This is well displayed on the small plug at 327710, where the quartz-pyrite intrusion contains dark veins of limonitised pyrite, small flakes of green biotite, and ankerite. The intrusive nature of the quartz-pyrite rock is demonstrated by the occurrence at 340670 where the shales surrounding a small mass of quartz-pyrite rock have been disrupted.

The bulk of the complex is made up of agglomerates consisting of fragments of country rock and quartz-pyrite rock in a carbonate matrix. Three distinctive types of agglomerate can be mapped. The commonest type contains small fragments of shale up to 1 inch (2·5 cm) across set in a sparse carbonate matrix; the shale fragments are themselves highly carbonated and the whole weathers to a characteristic grey-green rubble. Less commonly the agglomerate contains fragments of quartz-pyrite rock which may form up to half the agglomerate. This type of agglomerate is usually adjacent to quartz-pyrite intrusions and its distribution probably depends on the local availability of such fragments. Near the southern margin of the body there are several agglomerate lenses that contain angular fragments of an altered igneous rock, and probably represent the last phase of agglomerate formation.

The last phase of carbonate intrusion was the emplacement of several small dykes of almost pure carbonate. The best example, consisting mainly of ankerite with a little quartz and muscovite, occurs near the summit of the hill at 295695, it is about 2 feet (61 cm) thick and exposed over a length of about 100 feet (30 m). Smaller examples are found in several other localities. Irregular sheets and veins of white milky quartz up to 2 feet (61 cm) thick and sometimes carrying a little specular hematite make up the final phase of activity within the complex.

The quartz-pyrite rock agglomerate is sufficiently distinctive in the field to allow the general structure of the body to be determined. The agglomerate occurs in lenticular masses with the fragments in a planar alignment parallel to the margin and usually near vertical. The lenses are dyke like and range up to a length of about 200 feet (60 m) with a width of up to 20 feet (6 m); throughout the body the lenses have a roughly east-west trend. In the main mass of agglomerate the rock type is more uniform but small included lenses of shale and subtle differences within the agglomerate indicate that the mass was emplaced in the form of closely spaced lenses which have coalesced. Again the lenses are dyke like and trend roughly east-west so that the overall structure of the mass is that of a group of closely spaced lenticular bodies that have coalesced. Some of the shale remnants caught between the agglomerate lenses are quite large, and MacLeod (1970, p. 28) mentions one that is about 300 feet (90 m) square. Detailed mapping shows that this block is not entirely surrounded by agglomerate so that with the general structure of the body there is no basis for postulating a ring dyke of agglomerate.

The fragments contained in the agglomerates are of rocks of local origin, either shale or quartz-pyrite rock. This combined with the distribution of the agglomerate with quartz-pyrite fragments suggests that the agglomerates have not been transported for large distances.

No. 2 (Plate 27)

The two small hills which make up this body are a little to the north of the Mount Fraser manganese mine. The northerly hill rises sharply about 150 feet (15 m) above the plain, while the southerly hill is much lower and rounded. The whole body occupies an area of only 900 feet (250 m) by 400 feet (120 m).

The northern outcrop consists of a roughly circular plug of quartz-pyrite rock carrying varying amounts of small cubes of pyrites up to 5 mm across, it is intruded into vertical or steeply dipping shales and includes a lens of shale within it.

The southern hill consists of two carbonated igneous intrusions and a small quartz-pyrite intrusion with a mass of carbonated and brecciated shale between them. The largest intrusion has a roughly triangular shape and a sharp margin against the carbonated shale, it is a fine-grained pale grey rock carrying small rhombs of carbonate. The eastern third of this hill is composed of a fine-grained altered igneous rock which contains much carbonate. Lenses of carbonated shale within the mass, and its indented contact with the country rock, give the impression that this intrusion was formed by the coalescing of several north-south trending lenticular bodies. Two small intrusions of quartz-pyrite rock are also present in the southern part of the complex, and adjacent to one is a small area of carbonate agglomerate containing fragments of both shale and quartz-pyrite rock.

The bulk of the rock exposed between the intrusive masses is a strongly carbonated shale. The rock appears to be a highly weathered shale but closer inspection reveals many small rhombs of carbonate and the development of green chromian muscovite. The extent of the carbonated shales cannot be determined, as much of the surrounding area is scree covered.

Narrow dykes of quartz-pyrite rock occur in the surrounding area; all trend north-south and appear to be connected with the activity of this centre.

No. 3 (Plate 27)

Centre 3 lies about a mile (1·6 km) south of the Mount Fraser manganese mine and half a mile (0·8 km) west of the main north-south track. A prominent ridge formed by two quartz-pyrite intrusions stands out on the flank of a hill of shale and banded iron formation while the carbonate rocks lie poorly exposed in the dip between the intrusions and the main hillside or slightly better exposed as a separate body a little to the northwest of the quartz-pyrite rock.

The body is intruded into steeply dipping shales, siltstones and banded iron formation. Both carbonate and quartz-pyrite rock are concordant with the bedding of the host rock but in a few places the actual margin can be seen and their intrusive nature demonstrated.

The main intrusions of quartz-pyrite rock form a prominent ridge about 80 feet (24 m) high on the south side of the body. At its western end the rock is strongly banded, the banding being outlined by pyrite cubes and the weathering out of ankerite. At this point the intrusive relationship of the quartz-pyrite rock to the enclosing shales can be seen. The margin of the quartz-pyrite rock dips northward at 45°, which is the dip of the banding within the mass, and the enclosing shales have been slightly carbonated and hornfelsed.

Apart from the intrusions of quartz-pyrite the main rock type is a uniform, fairly fine-grained and highly carbonated agglomerate. The agglomerate is deeply weathered, and much of the outcrop is covered by a grey-green rubble. Originally the fragments within the agglomerate were shale but carbonation and weathering have destroyed all but the megascopic structure. Small outcrops of carbonate agglomerate are present to the north of the quartz-pyrite intrusions, but the main mass is to the north-west. Numerous lenses of shale occur within the agglomerate, and to the west of the complex several small lenses of agglomerate have been mapped within the shale.

Other rock types within the complex are several fairly thick sheets of milky quartz and two narrow dykelets of pure calcite at 480660. A single basalt dyke intruded into the shales near the western margin of the body probably predates the carbonate.

Because of the deep weathering and uniform rock types the detailed structure of this body cannot be determined, but the presence of lenses of shale within the agglomerate suggest that the agglomerate was intruded as lenses similar to those in complex No. 1. The northeastern margin of the body is, however, quite well exposed and can be accurately followed over the spur of the hill. Where best exposed the margin of the agglomerate dips steeply westward at 70° and intrudes shales with a similar dip. A 20-foot (6 m) wide marginal zone surrounding the agglomerate is less resistant to weathering than either the shale or the agglomerate so that the margin of the carbonate body stands out against this narrow aureole of slightly altered shale. The uniform nature of this contact suggests that if lenticular intrusions were involved in the formation of this body they were rather larger than those in complex No. 1.

No. 4 (Plate 28)

This body is probably the largest in the district but is also the poorest exposed. The western margin, protected by the more resistant shales and banded iron formations, is well exposed at several points over a distance of nearly a mile (1·6 km) but a few hundred feet downslope, scree cover becomes complete. The exposed mass is, then, a narrow band of disconnected outcrops scattered along a hillside. From the detailed mapping the suggestion of MacLeod (1970, p. 28) that this complex might extend across the valley floor and even include complex No. 6 as part of its eastern margin, cannot, because of the cover of scree and alluvium, be proved.

The western margin of the body is marked by several small intrusions of altered igneous rock which carries plentiful cubes of pyrite. The largest intrusion is only about 300 feet (90 m) long and all form prominent crags. The altered igneous rock is fine grained and pale grey when fresh but it is usually highly veined by carbonate minerals and some exposures show small iron-stained rhomboidal pits due to the weathering out of ankerite. Large pyrite cubes up to 2·5 cm across are especially prominent in a white quartz vein which invades the rock at 190740. The intrusion at the southern end of the complex is different from all other exposures in containing large pyritohedra rather than cubes of pyrite.

Most of the carbonate rock is very poorly exposed and consists of patches of grey-green calcareous rubble from which little indication of rock type or structure can be deduced. At the southern end of the body, however, are some relatively good exposures which indicate that most of the carbonate rock observed elsewhere probably consists of an agglomerate of altered and carbonated shale fragments set in a carbonate matrix. Outcrops in the vicinity of 180420 show good examples of intrusive agglomerates and structures similar to those of a small volcanic neck. The carbonate rocks of this area consist principally of a fine-grained and highly weathered agglomerate, but intruded into this are lenses of much coarser and less weathered agglomerate in which the shale fragments are more angular, and commonly make up the major portion of the rock. These lenses are arranged in an arcuate fashion around a plug of altered igneous rock and dip steeply towards it. This is the only structure in the whole region that shows a concentric structure. Within the igneous intrusion there are also several lenticular brecciated zones from a few inches to a few feet wide where carbonate-rich fluids have invaded the rock. Angular fragments of acid igneous rock make up the bulk of these zones, carbonate forming only a minor matrix.

Throughout the length of the contact between the carbonate body and the enclosing shales and banded iron formation there appears to be little or no contact metamorphism but at 190510 the shales have been converted to a talc-carbonate schist. In parts the rock appears to be almost pure talc but usually it is a talc-rich shale with rhombs of carbonate. This small area of talcose rock grades into normal shale, and appears to be the product of localised metasomatism.

No. 6 (Plate 29)

MacLeod (1970, p. 28) reported an area of talc-carbonate rock on the eastern side of the valley containing No. 4 and suggested that these might have been derived from an ultrabasic body. The rocks in question crop out on a low spur, and mapping shows that they grade eastward into normal shale and banded iron formation. Westward from this spur there are several small outcrops of highly carbonated igneous rock, and it is probable that the altered shales are part of a marginal zone of a carbonate body that is largely hidden by scree. The talcose rocks are quite variable, and generally grade from almost completely altered rocks in the west to only slightly altered shales in the eastern part of the area. The altered igneous rocks present are strongly veined with carbonate, and many outcrops are agglomeratic, with carbonate minerals making up over half the rock.

The total area covered by this body is at least 2,000 feet by 1,000 feet (600 m and 300 m) but most of this area is covered by scree and alluvium, so that nothing can be determined of the structure of the mass.

No. 5 (Plate 30)

The small plug of quartz-pyrite rock at the northern end of this body rises a hundred feet or so above the level of the gravel plain and stands out strikingly against the hillside of banded iron formation and shale. The associated carbonate rocks form a low rounded hill about 600 feet (180 m) in diameter to the south of the quartz-pyrite plug.

This body is in several ways somewhat different from others in the area, the most obvious being that it is intruded into the steeply dipping eastern limb of the Mount Fraser Anticline, rather than the axial zone. The rock types present are also slightly different, in that the plug of quartz-pyrite rock and dykes of similar rock carry abundant chloritoid and the carbonate rocks have the overall appearance of a highly folded sedimentary sequence. Carbonate-rich agglomerates are present but only in small amounts. Exposure over much of the complex is very good but nowhere are the margins of the body visible, the carbonate being surrounded by a scree of shale fragments and hematite blocks from the surrounding hills. Secondary carbonate deposits, or kankar, also obscure some areas.

The quartz-pyrite plug at the northern end of the body is approximately circular and about 150 feet (46 m) in diameter. The margins of the plug are obscured by scree, but vertical flow banding within the mass indicates an intrusive body. The fresh rock is fine grained and pale grey with a few small cubes of pyrite and a little green chromian muscovite and chloritoid visible. Parts of the mass have been extensively veined by carbonate material with the development of rhombs of ankerite, and in others masses of pale green chromian muscovite have been developed. Dykes of similar material occur within the main carbonate mass, and to the east of the main plug there are three small dykes which once carried cubes of pyrite up to 1 cm across, now completely altered by secondary silicification.

Within the carbonate mass there are a few small areas of carbonate-rich agglomerate carrying angular quartz-pyrite rock set in a matrix of ankeritic carbonate. The remainder of the mass appears to have been a sedimentary sequence that has been highly folded and carbonated. In many areas what at first appear to be quartz-rich fragments in an agglomerate are in fact previously continuous bands of quartzite that have been extended to give lenticular boudins. The whole rock appears to be a thinly laminated series of quartz-rich and carbonate-rich bands. Almost everywhere the laminations are vertical and if followed along strike several folds can be easily traced. In the nose of certain folds, as at 300560 there is an accumulation of quartz-chloritoid rock and at 300580, where the folds have broken, a dyke-like intrusion of the same rock type. The laminations are only coincidentally parallel to the margins of the intrusion and at the eastern margin strike perpendicularly to it.

Field evidence suggests that this body consists largely of a remobilised mass of finely laminated sediments. The original sediments could have been alternating bands of sandstone and shales but of a type not seen at the surface elsewhere in the district.

Other localities

Throughout the axial zone of the Mount Fraser Anticline there are numerous small intrusions of quartz-pyrite rock easily distinguished from other quartz intrusions by the presence of pyrite. None of these intrusions is associated with any carbonate rock, but some show alteration of adjacent shales similar to parts of No. 6.

PETROGRAPHY

Although each of the carbonate bodies is slightly different they are composed of few rock types, so that it is convenient to describe them as a single petrographic province. The rock types commonly met with are quartz-pyrite intrusions and highly carbonated igneous intrusions, agglomerates, carbonated and altered shales, and small dykes and veinlets of almost pure carbonate.

Quartz-pyrite intrusions

In hand specimen this rock is usually pale grey and fine grained, and carried numerous cubes of pyrite. In thin section a fine-grained equigranular mosaic of quartz is seen to comprise 90 per cent or more of the rock, the remainder being small cubes of pyrite and a little chromian muscovite or biotite. Some specimens contain a small amount of carbonate, usually a clear dolomite or ankerite. The pyrite has altered to limonitic material. The carbonate is a secondary mineral introduced during the emplacement of the agglomerates. In several slides, notably 15124 and 15057 which are from brecciated portions of quartz-pyrite intrusions, the ankerite is present in veins in the rock.

Rocks of this type occur in bodies No. 1, 2, and 3, but only one small area has been found in No. 4. A somewhat different rock type is present in No. 5, where in addition to quartz and pyrite there is abundant chlorite and chloritoid, a little chromian muscovite and many small grains of rutile. The intrusive mass to the north of No. 5, dykes within the complex and quartz-rich lenses at the nose of folds all contain chloritoid with the characteristic "bow-tie" structure. The bulk of the rock is a fine-grained mosaic of quartz but often small flakes of muscovite have developed along the margins of the grains. Chromian muscovite is especially prominent in a specimen taken from a pod within the main outcrop (15044). A pale green chlorite with anomalous Berlin blue interference colours forms a significant proportion of many slides and this is usually associated with many small prisms of rutile.

Carbonated igneous intrusions

These rocks are present in bodies No. 2, 4, and 6, and in hand specimen appear to be highly altered dolerite with cubes of pyrite. Unlike the quartz-pyrite rock most specimens have been strongly carbonated and now contain 40 per cent or more of ankerite, often as discrete rhombs. Carbonation and recrystallization of the original minerals makes identification of the original igneous rock type almost impossible.

In thin section the rock contains about 50 per cent of ankerite which has usually exsolved hydrated iron oxides. Albite (An_{3-10}) is the next commonest mineral, and in several specimens forms medium-grained laths which give the rock the appearance of an altered dolerite (e.g. 15087, 15090). This texture is possibly an original texture, and every variation can be found, as the rock has been recrystallized, to the feathery intergrowths of quartz and untwinned plagioclase present in 15077 and 15078. Specimen 15090 shows good examples of interstitial micropegmatite, and many specimens contain small grains of rutile, which, in 15081 and 15132, are arranged as rods which appear to be relict textures after ilmenite. The only mafic minerals present are a little brown or green biotite and chlorite which gives an anomalous brown interference colour.

Ankerite, pyrite and chromian muscovite, present to a greater or lesser degree in all specimens, appear to have been introduced into the original rock after its emplacement. In most specimens the minerals are distributed throughout the rock, but in some they form discrete veins. Specimen 15078 from No. 4 contains a vein of coarsely crystalline ankerite, albite and chlorite, and in specimen 15098 both ankerite and pyrite are confined to veins.

The igneous intrusives have been extensively altered since their emplacement but sufficient remnant textures remain to suggest that they were originally doleritic in character. Carbonate metasomatism and extensive recrystallization have produced the variety now found. There has also been the introduction of soda, silica, sulphur and chromium. Specimen 15098 from No. 2 has been so silicified that it appears as a quartz-pyrite rock with lenses of albite having a doleritic texture, while in specimen

15128 from No. 6 the rock is now about 60 per cent ankerite with large masses of chromian muscovite and even a little tourmaline.

Agglomerates

The agglomerates are usually so highly weathered that thin sections are of little use. Megascopic features have often been preserved and in the field several types can be distinguished. In thin section however, it is seen that many of the fragments, especially of the shales, have been so highly altered and carbonated that it is difficult to distinguish fragment from matrix.

With the exception of the northernmost body, No. 1, the agglomerates contain only fragments of locally available rock, either sedimentary or igneous. Agglomerates with shale fragments are the commonest but the shale has been so altered that it is almost unrecognisable and now consists usually of a fine-grained assemblage of quartz, sericite, chlorite and ankerite. Fragments of quartz-pyrite rock often occur in agglomerates near intrusions of the rock, and have usually been little altered except for the growth of rhombs of ankerite. In No. 4 fragments of carbonated igneous rock are common but often, due to the carbonation of the original rock, the fragments appear to grade into the matrix. Even in specimen 15132, from a small breccia vein in an igneous mass at the southern end of No. 4, matrix is indistinguishable from fragments, although in hand specimen angular fragments are easily outlined. Only in specimen 15058 can carbonated igneous rock fragments, of a type not known elsewhere in the complex, be easily distinguished from a matrix of pure ankerite and later quartz veins.

The matrix of the agglomerate probably consists of comminuted rock fragments as well as the introduced carbonate. Many small grains of quartz and chlorite lie within the matrix, probably derived from the breakup of the smaller fragments. In specimen 15058 where the fragments have been little affected by carbonation the matrix is of pure ankerite. Specimen 15123 from complex 3 contains abundant large flakes of biotite, probably derived from an igneous rock not found exposed.

Carbonated shales

Several of the complexes contain outcrops of rock which appear to be highly altered shales. These vary from the complete conversion of the shale to a pure talc-carbonate rock at 190510 in No. 4 to exposures in No. 2 which retain all the characteristics of shale but contain porphyroblasts of ankerite. In addition nearly the whole of No. 5 appears to be a finely laminated sedimentary sequence that has been carbonated.

The carbonated shales of No. 6 (spec. 15125) now consist of a fine-grained aggregate of talc containing many flakes of brown biotite and clots of chlorite. Carbonate minerals originally present have been pseudomorphed by chalcedony with their original rhombic outline preserved by limonite. Similar shales from No. 1 (spec. 15068, 69) have been converted almost entirely to ankerite, only their megascopic features indicating their origin. From No. 2, specimen 15089 is an altered siltstone which has been recrystallized to a fine-grained aggregate of quartz feldspar and sericite and in which discrete porphyroblasts of ankerite have grown. The carbonation in this specimen was probably accompanied by shearing as the porphyroblasts show an augen structure.

No. 5 consists entirely of a carbonated sedimentary sequence. The quartz-rich bands have the same mineralogy as the quartz-pyrite intrusion at the north end of the complex and consist of a fine-grained quartz mosaic with much chlorite and some chloritoid and small rutile grains. Shale-rich bands have been altered to a fine-grained chlorite-quartz rock which carries a high proportion of ankerite in the form of veins and discrete rhombs. Carbonate veining of at least two generations can be seen. In specimen 15050 the host rock is now a fine-grained chlorite-quartz aggregate, and there are many parallel veins of iron-stained ankerite traversing the rock. This pattern has been disrupted by the emplacement of a fine network of veins of clear carbonate which has fragmented the earlier carbonate veining.

Carbonate-rich dykes and veins

Small veins of pure carbonate are present in many of the intrusive bodies, but two examples are noteworthy. In No. 1 there are several well-defined dykes of a fine-grained rock consisting of ankerite with a little interstitial quartz and muscovite. The texture of the ankerite is equigranular but the muscovite sometimes outlines flow banding.

About 500 feet (150 m) to the southwest of No. 3 two veins of almost optical quality calcite were located. The veins contain a little quartz and chlorite as secondary veinlets but otherwise consist of large crystals of calcite up to an inch (2·5 cm) across. The relationship of these veins to the main carbonate complex is unknown.

ORIGIN OF CARBONATE

In recent years much work has been done in efforts to establish definite criteria for the differentiation of carbonate minerals derived metasomatically and magmatically. The geological characteristics of carbonatites have been listed by Verwoerd (1967) and Pecora (1956). Gold (1963) provides a comparison of the trace element content of magmatic and sedimentary carbonates. Geologically, carbonatites belong to alkaline petrographic provinces, and the usual associated igneous rocks are silica-deficient and include nepheline syenites, ijolites and more basic rocks. In addition most carbonatites are surrounded by an aureole of alkali metasomatism (fenitization) and contain a distinctive suite of accessory minerals including apatite, magnetite, soda-rich amphiboles and pyroxenes, and often radioactive and rare-earth minerals such as pyrochlore.

The Mount Fraser carbonate rocks conform to none of the above criteria. The associated intrusives are quartz-pyrite rock and a possible quartz dolerite, alteration of the surrounding rocks is limited to the introduction of carbonate and the conversion of the shales to talc-rich rock, and no trace of apatite or alkali-rich minerals have been found. On the contrary the general lack of alteration of the country rock and the abundance of such low-temperature minerals as chlorite, muscovite and chloritoid suggest that no elevated temperature was reached during the emplacement of the Mount Fraser carbonate bodies. Siliceous rocks are sometimes found associated with carbonatites as at Songwe Scarp (Brown, 1964) where a siliceous intrusive breccia has been emplaced after the carbonatite and where late-stage quartz veining is also common. The Songwe Scarp carbonatite is also similar to the Mount Fraser intrusions in being predominantly ankeritic, containing pyrite rather than magnetite and lacking many of the alkali minerals usually associated with carbonatites. The presence of a wide zone of feldspathised schists, the radioactivity of certain sections of the intrusions and the concentration of characteristic trace elements, however, all point to a carbonatitic origin for the Songwe Scarp intrusion while the lack of such features in the Mount Fraser rocks indicates otherwise.

The geochemistry of the Mount Fraser carbonates is dealt with in a separate report (Lewis and Williams, 1971), where it is shown that trace elements do not indicate a magmatic origin for the carbonate minerals.

The alternative to a magmatic origin for the carbonate is a metasomatic origin in which the carbonate is derived from some pre-existing sedimentary sequence, remobilised and emplaced into its present position. The difficulty of this explanation is to find a suitable source rock from which to remobilise the carbonate materials. The only description of the local stratigraphy is by MacLeod (1969) for the neighbouring Peak Hill area and nowhere are carbonates mentioned in a thick sequence of shales, sandstones, greywackes and banded iron formation. Low temperature emplacement of the carbonate is, however, required by the presence in No. 5 of chloritoid, which is usually a low-grade regional metamorphic mineral, but has also been found in association with hydrothermal quartz-carbonate veins (Milne, 1949) and with hydrothermal quartz veins (Heitannen, 1951; Michot, 1954). Similarly rutile, the high-temperature polymorph of TiO_2, found in several of the carbonated dolerites and throughout the rocks of No. 5, is also associated with chloritoid (Heitannen, 1951; Michot, 1954; Simpson, 1931). Although MacLeod (1970) wished to distinguish the Mount Fraser carbonate bodies from the carbonated basic and ultramafic rocks of the Eastern Goldfields they do in fact have certain mineralogical resemblances to the rocks described by Simpson (1931) from Lake View near Kalgoorlie. In the Kalgoorlie region the carbonate metasomatism appears to be unrelated to the presence of ultramafic rock, and is clearly later than the serpentinization of these masses (Williams, in press). There appears to be a connection between carbonation and the presence of sedimentary and acid volcanic rocks but the source of the CO_2 remains unknown. It is possible that the carbonate found in the Mount Fraser area is related to a greenstone belt in the Archaean shield which underlies the area at no great depth.

Ultramafic rocks cannot be ruled out as a source of the carbonate, however, as lime metasomatism is often associated with the serpentinization of diopsidic pyroxene and the formation of rodingite dykes, as at Eulaminna in the Mount Margaret Goldfield (Miles, 1950). The carbonate rocks of the Mount Fraser area have been enriched in both Ni and Cr compared with both sedimentary limestones and carbonatites (Lewis and Williams, 1971) so that a connection between the carbonates and an unexposed ultramafic body cannot be entirely discounted. A magnetometer traverse over several of the complexes, however, does not suggest the presence of an ultramafic mass at shallow depth (Lewis and Williams, 1971).

One last possibility is that the carbonate is derived from dispersed carbonate from within the Robinson Range Beds. Although MacLeod (1969) found no carbonate horizons within the sedimentary sequence it is possible that dolomite is present as a dispersed phase throughout the sequence and has been concentrated in the core of the Mount Fraser Anticline by tectonic forces. No carbonates were found in the few thin sections of sedimentary rocks studied, but the Mount Bruce Supergroup in the Pilbara, to which the Robinson Range Beds are possibly related, does contain dolomites and dolomitic shales (Daniels, 1966). Such an origin would explain the carbonate minerals but would not account for the high nickel and chromium values found.

MODE OF EMPLACEMENT

The alignment of five of the six carbonate intrusions along the axis of the Mount Fraser Anticline points to some form of tectonic control over the emplacement of the complexes. The relationship of the folding in the Robinson Range Beds to basement structures in the area is not known, but the emplacement of a line of dolerite and quartz-pyrite intrusions which originated from the basement along the axis of an anticline in the overlying sediments seems unlikely to be fortuitous. Although the origin of the carbonate material is not known, its rise to its present position appears to be controlled, and may have been initiated by the rise of the dolerite magma. In each complex the earliest rock type has been either a plug of dolerite or quartz-pyrite rock.

The carbonate material probably rose in the form of a tenuous aqueous fluid, rich in carbonates, which was able to insinuate itself into the sedimentary shales and siltstones to give the carbonated shales of No. 2 which contain porphyroblasts of ankerite. Further reaction of the carbonate fluids with the silica of the shales has produced the talc-chlorite-carbonate rocks of No. 6. In addition the carbonate-rich fluids were able to metasomatise the dolerite and to a lesser extent the quartz-pyrite rock to produce the complex assemblage of minerals now found.

The gradual conversion of shales ultimately to talc-rich rocks was only able to operate while the pressure remained high and CO_2 remained in solution. The release of pressure, probably occasioned by fracturing of the overlying rock allowed the rapid release of CO_2 and the formation of the agglomerates found in all the complexes. Only in No. 4 does one of the intrusive bodies appear to have been the direct cause of pressure release. At the southern end of the complex, agglomerate is arranged in an arcuate fashion around a dolerite plug which itself contains brecciated zones. In the best exposed body, No. 1, pressure release appears to have been governed by weaknesses along the bedding planes of the shale, so that the agglomerate forms lenses parallel to the bedding. Formation of agglomerate in No. 1 extended over a considerable period of time as evidenced by the detailed structure of the agglomerate mass. Small lenses of shale remain, apparently undisturbed, within the agglomerate and show that the agglomerate consists of many small lenses that have coalesced. Each lens represents a separate vent with only one or two active at any given time. The fact that agglomerates containing fragments of quartz-pyrite rock are only found close to intrusions of that rock also shows that the activity was not explosive but rather a steady release of gas at high pressure. This lack of transport of the fragments indicates that each vent formed a small fluidised bed, a process now recognised to be important in the emplacement of fragmental volcanic rocks (Reynolds, 1954).

No. 5 has been emplaced by a different mechanism from the other bodies as throughout most of its area little or no trace can be found of the shales and banded iron formation which must have been present. The rocks now found appear to be a thinly laminated quartzite/shale assemblage in which the shale members have been highly carbonated. It is probable that this took place at depth and that the whole mass was then intruded in the solid state into its present position with the carbonate minerals acting as a lubricant. The formation of vents and their associated agglomerates are only a minor feature of this complex.

DISCUSSION

The Mount Fraser carbonate intrusions do not apparently correspond exactly with any described category of intrusion. The bodies contain elements similar to volcanic phenomena but also contain other features which suggest a relatively low temperature origin for the carbonate rocks. Again, the fact that the carbonate probably originated locally and that No. 5 is formed of a sedimentary sequence remobilised and emplaced in the solid, indicates an affinity with diapiric structures. Most diapiric structures involve evaporite beds, usually gypsum or halite, which under particular conditions of overburden have been remobilised and intruded into the overlying sedimentary sequence. Such salt dome structures may be initiated in several ways but usually there is no association with any igneous intrusion. In Western Australia diapirs are known from the Woolnough and Madley Hills area of the Gibson Desert (Wilson, 1967). In the Madley Hills, six small diapirs have been found along the crest of an anticline. The diapirs are considerably larger than the Mount Fraser intrusions, measuring up to 2 miles across and consist of a central core of brecciated blocks of Upper Proterozoic dolomite with a matrix of gypsum that intrudes the Permian and Jurassic sediments. In the Mount Fraser area the agglomerate is formed of locally available material and there has been little transport of material from lower strata except in No. 5.

In South Australia many diapiric structures have been recognised in the Flinders Ranges. Coats (1964) has shown that the Blinman Dome consists largely of brecciated carbonaceous and argillaceous members of the underlying Willouran Series that have been remobilised and intruded into the overlying Sturtian rocks. The diapirs are located in the cores of anticlines and are thought to have been initiated by tectonic forces. Although evaporites do not form a great part of the Willouran sequence casts of halite cubes are common in rocks of the Blinman Dome (Webb, 1961) and the presence of evaporites no doubt assisted the intrusion of the diapir. Dolerite plugs are common in the Blinman Dome but Coats (1964 p. 18) has shown that these post-date the formation of the diapir. By contrast the igneous intrusions associated with the Mount Fraser carbonates pre-date the formation of the agglomerate and appear to have initiated the rise of carbonate-rich fluids into the sedimentary strata.

Diapirs characteristically show deformation of the enclosing sediments. In both the Western Australian and South Australian examples cited the rim rocks have been upturned and in parts overturned. In the Mount Fraser complexes, however, the enclosing sediments appear to be almost undisturbed to within a few feet of the carbonate agglomerate. In No. 1 many small shale lenses within the agglomerate appear to be undisturbed, showing that the mass could not have been intruded in the solid. No. 5 however, probably was intruded as a solid mass, but the enclosing sediments are everywhere hidden under scree, so that no marginal effects can be seen.

Individual carbonate complexes in the Mount Fraser area have the characteristics of both diapiric and volcanic origin, yet they do not fit easily into either category. In summary it appears that, in response to deep seated structures, a series of quartz-dolerite and quartz-pyrite plugs were intruded into the core of the Mount Fraser Anticline and that these rocks on their passage upward collected and concentrated pre-existing carbonate-rich fluids. On nearing the surface these fluids were able to break through the sedimentary cover so releasing the gases which broke up the country rock to form the agglomerates now seen. The carbonate-rich fluids were also able to metasomatise the dolerite and the enclosing sediments.

The mode of origin and emplacement is perhaps best termed "pseudo-volcanic".

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THE PROTEROZOIC OF THE GERALDTON–NORTHAMPTON AREA

by R. Peers

ABSTRACT

The Proterozoic of the Geraldton 1 : 250,000 sheet area is confined to the southern half of the Northampton Block, and may be divided into three broad units: granulite, granite and migmatite. The granulites were formed by regional metamorphism to granulite facies of a pile of geosynclinal sediments, mainly greywackes but with some intruded gabbro sills. A later porphyritic granite was intruded into the granulites and a zone of migmatite developed along the contact. This migmatite is a product of granite intrusion and not anatexis of a pre-existing rock *in situ*. A garnet and cordierite-bearing border facies to the granite is the result of direct contamination by the invaded granulite. A narrow border of cordierite-bearing granulites adjacent to the migmatite and granite may be a reflection of original sediment composition, or a variation of metamorphic grade, but in view of its close association with the intruded granite is most likely to be the result of local metasomatic activity.

INTRODUCTION

The Proterozoic of the Geraldton-Houtman Abrolhos 1 : 250,000 sheet area (SH/50–1 and part of SH/49–4) occupies about one third of the mainland area and is confined to the southern half of the structural unit known as the Northampton Block (see Plate 31).

The Northampton Block may be divided into three broad units (Horwitz, in prep.), the granulite, the granite, and the migmatite. The granulites are of sedimentary origin with intruded gabbros and were metamorphosed to granulite facies grade by regional metamorphism. During the Middle Proterozoic they were intruded by granite with the production of migmatite along the granite-granulite contact in addition to contact effects within both the granite and the granulite.

The purpose of this investigation was to describe the petrographic variations within the three Proterozoic units and to examine their mutual relationships. Accordingly, 128 specimens were collected from the area during a 6-day field excursion made by the author in August, 1970, and these form the basis of this report. Dr. R. C. Horwitz mapped the Proterozoic of the Geraldton-Houtman Abrolhos 1:250,000 sheet area in 1968 and 1969. The geological sketch map which accompanies this report is a simplified version of the map subsequently prepared (Horwitz, in prep.).

PREVIOUS WORK

The earliest geological descriptions of the Geraldton area were by A. C. Gregory (1849), J. W. Gregory (1849), F. von Sommer (1849), and F. T. Gregory (1861), (Horwitz, in press). In 1903 A. G. Maitland carried out a systematic mapping project of the Northampton Mineral Field. He recognised various rock types among the "crystalline rocks" of the Northampton Block, including granites, garnetiferous gneisses, mica schists, quartz schist and pegmatite, noting that "it has been found quite impossible to draw any line separating these rocks . . . " (Maitland, 1903, p. 9). In a more recent publication Prider (1958) gave an account of the garnet granulites of the Galena area, which although outside the northern boundary of the sheet area is still within the Northampton Block. Finally, in 1962, Jones and Noldart published a description of the regional geology of the Northampton Mineral Field covering the four 1 inch to 1 mile (1 : 63,360) Military Edition sheets of Ajana, Hutt, Northampton and Nanson.

PETROGRAPHY OF THE GRANULITE

The granulite unit (Pm) is composed largely of garnet granulites, which represent metasediments of an original greywacke composition. About half of the specimens examined from this unit are cordierite-bearing and with one or two exceptions were collected from the eastern margin of the granulite unit, adjacent to the migmatite and granite. The granulites outside the eastern margin of the granulite unit are in general free from cordierite.

GARNET GRANULITES

The garnet granulites have a gneissic banding which is mainly a reflection of grain size variation but is in part due to a variation in the concentration of biotite and garnet. Small-scale pegmatitic layers and schlieren are common and emphasize the banding.

In hand specimen these granulites are well banded with a saccharoidal fabric. They are studded with red garnets which usually reflect the grain size of the layer in which they occur and which weather to an orange colour.

The main rock-forming minerals in order of abundance are quartz, microcline, plagioclase, garnet and biotite. Accessory minerals include zircon, apatite, pyrite, graphite, and an opaque mineral altering to sphene and leucoxene. Sometimes the texture is equigranular, but more commonly a weak foliation is indicated in the general elongation of quartz and feldspar grains and in the preferred orientation of the biotite flakes.

Quartz is abundant, forming anhedral grains with lines of two-phase inclusions and distinct strain extinction. Microcline is the predominant feldspar and occurs as anhedral grains which are fresh and well twinned. All of the microcline is microperthitic with included spindles and blebs of plagioclase. Plagioclase typically forms anhedral grains which are not well twinned and are usually sericitized. When sufficiently unaltered to be identified, the plagioclase was measured as a sodic andesine. Ragged fragments of microcline are included in a coarse antiperthite texture, and where microcline and plagioclase grains are adjacent, myrmekite is typically developed. These granulites are rich in garnet, which occurs as subhedral and anhedral grains of variable size and which is unaltered except for the development of minor muscovite along fracture planes. Most of the garnets poikiloblastically include rounded grains of quartz which in some instances are so abundant as to reduce the garnet to a skeletal grain. Biotite forms elongate flakes which parallel (and help define) the foliation. They are strongly pleochroic with X = pale yellow, Y = orange, and Z = dark reddish-brown, and include small zircon grains which are often surrounded by distinct pleochroic haloes. Accessory minerals include well rounded (relict sedimentary) zircons, rare apatite, minor fresh pyrite, graphite, and a black opaque mineral (ilmenite?) altering to leucoxene and sphene

CORDIERITE-BEARING GARNET GRANULITES

The cordierite-bearing granulites are typically coarser grained than the garnet granulites but are not as well banded although they have a distinct foliation. They do include schlieren of pegmatitic material but not in distinct bands. In general the cordierite-bearing granulites are greasy in appearance and lack the saccharoidal fabric typical of granulites. In those specimens which include abundant sillimanite it is visible in the hand specimen as bundles of white needles and rods.

Mineralogically the main distinction of the specimens in this group is that they include cordierite, although sillimanite is commonly, and spinel rarely associated.

The main rock-forming minerals are microcline, plagioclase, quartz, cordierite, garnet and biotite. Other minerals include sillimanite, spinel, pyrite, leucoxenized opaque grains and graphite.

Microcline is the predominant feldspar and occurs as fresh, anhedral grains which are well twinned and have a well developed microperthitic texture. Rounded grains of quartz are commonly included, and where plagioclase is adjacent there is commonly a development of myrmekite. Plagioclase occurs in varying amounts but is alway subordinate to the microcline. In some specimens it is present only within a narrow band of myrmekite fringing microcline grains. More generally plagioclase forms anhedral grains of mildly sericitized sodic andesine. Quartz occurs as anhedral grains with lines of two-phase inclusions and marked strain extinction.

Cordierite in these granulites is distinguished by its fresh appearance. It occurs as anhedral grains which show well developed lamellar and sector twinning and is only marginally altered to pale yellow pinite. Some of the commonly included zircons are rimmed by pleochroic haloes. The two cordierite-bearing granulites collected from the western side of the granulite unit include only a trace of cordierite, most of which is pseudomorphed by pinite.

Garnet is ubiquitous within the granulites, but concentration varies from band to band. The grains are fresh, euhedral and subhedral, and are colourless in thin section. Most of the garnets poikiloblastically include quartz grains. Biotite is abundant as elongate flakes arranged parallel to the foliation. It is strongly pleochroic with X = pale yellow, Y = orange, and Z = dark reddish-brown, and includes zircon grains rimmed by pleochroic haloes. Sillimanite occurs in all specimens of cordierite-bearing granulite examined but is well developed only in a few specimens. Without exception these are granulites adjacent to a granulite-granite contact. Where poorly developed, sillimanite occurs as bundles of very fine needles, but where well developed it forms euhedral rods arranged in bundles parallel to the foliation. In one specimen the sillimanite developed as a rim about spinel grains which are enclosed within large grains of cordierite. Spinel was noted in only four of the specimens examined and is always closely associated with sillimanite. It varies in colour from olive green to emerald green and is probably hercynite. Accessory minerals include graphite, well rounded (relict detrital) zircons, minor pyrite and black opaque grains (ilmenite?) altering to leucoxene and sphene.

PEGMATITE BANDS IN GRANULITE

A few of the pegmatite bands within the granulite were sampled. They are composed mainly of perthitic microcline with subordinate sericitized plagioclase, quartz and a trace of muscovite. Some of the pegmatites include large red garnets.

QUARTZITE BANDS IN GRANULITE

To the north of the sheet near Rocky Hill there are some feldspathic quartzites which are considered to be metasediments of a more siliceous nature than the granulites within which they are intercalated. They crop out as fine-grained, light-coloured, saccharoidal rocks, spotted white where the feldspar has been kaolinized.

The predominant mineral is quartz which forms large anhedral grains with sutured boundaries. They are crammed with two-phase inclusions and fine needles of sagenite. Microcline forms anhedral grains and is thoroughly kaolinized. The only other minerals are well rounded detrital zircons and minor muscovite.

BASIC GRANULITES

Small gabbroic sills were intruded into the upper part of the sedimentary sequence which now forms the granulite unit, and are now represented by basic granulites. The intrusion near Nabawa has an observed intrusive discordant contact (Horwitz, in press). The following is a description of a pyroxene granulite collected from that intrusion.

The megascopic appearance is of a medium-grained, greasy, brown rock in which feldspar, pyroxene and biotite are readily recognisable.

The principal minerals are plagioclase, orthopyroxene, clinopyroxene, biotite and amphibole. Plagioclase (An_{65}) forms clear, unaltered, anhedral grains which are well twinned on albite, Carlsbad and pericline laws, and enclose rare grains of quartz and calcite. Orthopyroxene (hypersthene?) forms roughly lath-shaped grains up to 3 mm long which are colourless, non-pleochroic, and show incipient alteration to red biotite. Clinopyroxene occurs in less abundance than the orthopyroxene, forming smaller, anhedral, colourless grains. Biotite forms flakes up to 2·5 mm in diameter but also occurs as an alteration product. It is strongly pleochroic with X = pale yellow, Y = orange, and Z = reddish-brown and includes rare zircons surrounded by pleochroic haloes. Ragged blades of amphibole, associated with the pyroxenes, are weakly coloured but distinctly pleochroic with X = very pale yellow, Y = Z = pale yellow.

Other minerals present include a few large, clear, grains of quartz, minor muscovite, euhedral apatite crystals, opaque grains and rutile. The opaque grains are fresh pyrite, and magnetite (?) altering to hematite. Rutile forms anhedral, golden-brown rod-shaped crystals. The texture is granoblastic.

PETROGRAPHY OF THE GRANITE

The granite unit (Pg) is composed of a porphyritic granite and a border facies granite which is contaminated and is characterised by the development of garnet and/or cordierite.

PORPHYRITIC GRANITE

The uncontaminated granite is medium to coarse grained with a well developed foliation due to the alignment of tabulate, pink microcline phenocrysts. This foliation is most striking in outcrop but is less apparent in hand specimen.

The microcline phenocrysts are of variable grain size dependent upon the general grain size of the matrix, but they can be as large as 2 cm x 3 cm x 0·5 cm. They are well twinned on both albite and pericline laws giving the typical "cross-hatched" appearance of microcline, but commonly exhibit simple Carlsbad twinning as well. The margins of the phenocrysts are not sharply delineated and are sometimes rimmed by an irregular zone of myrmekite. The phenocrysts are perthitic but may also include anhedral grains of quartz, plagioclase and biotite. Alteration is minimal and restricted to minor kaolinization.

In the matrix the main components are quartz, microcline, plagioclase and biotite, with minor muscovite and accessory minerals. Quartz forms anhedral grains which have in some instances recrystallized to a mosaic. Two-phase inclusions are abundant and most grains have strain extinction. The microcline of the matrix is similar to the phenocryst microcline, but lacks the Carlsbad twinning. Plagioclase (oligoclase), the subordinate feldspar, occurs as anhedral grains which are poorly twinned and lightly sericitized. Commonly large grains of microcline are included in a crude antiperthite structure. The biotite of the granite is pleochroic, usually with X = pale yellow, Y = orange, and Z = reddish-brown but rarely the biotite is more green than brown. It forms flakes which include zircon grains rimmed by pleochroic haloes, and is rarely altered to chlorite. A trace of muscovite was noted. Accessory minerals include an opaque black mineral (ilmenite?) which is sometimes altered to leucoxene, and sphene, zircon, and apatite.

Texturally the granites are porphyritic with a medium-grained matrix. In some instances there is a very fine-grained, granulated area between the large grains of quartz and feldspar, which may be due to minor local shearing.

One specimen of pegmatite was collected from the granite. It is composed of pink microcline with some quartz, and a fine-grained, intergranular mosaic of quartz, microcline and plagioclase.

CONTAMINATED GRANITES

The contaminated granites do not belong to a clearly delineated zone but appear to represent a marginal facies of the porphyritic granite. Compositionally the contaminated granites fall into two broad categories; those containing garnets and those containing cordierite (which with only one exception also include garnet).

Typically the garnet granites are medium-grained, porphyritic granites which include euhedral and subhedral garnets and are rich in biotite. Both the abundance of garnet and the grain size of the garnet vary. According to Horwitz (in press), the garnets in the contact granites are much larger than the granulite garnets. In one specimen of contaminated granite, garnets with a diameter of 1·5 cm were measured. Apart from the presence of garnet, these granites are indistinguishable from the porphyritic granites.

The cordierite-bearing granites are fine to medium-grained and are only rarely porphyritic. In most respects they are similar to the garnet-bearing granites particularly when only minor cordierite is present. The proportion of cordierite in these rocks is extremely variable. Where it has occurred in small amounts it is pseudomorphed by pinite, but where it forms a major component of the rock, alteration is not so extensive. Sillimanite is an ubiquitous accessory mineral associated with cordierite and biotite, and varies in abundance roughly in accord with the cordierite. It is typically altered to sericite, but is more resistant to alteration than the co-existing cordierite. Several specimens include grains of green spinel (hercynite?).

Three specimens of granophyre were collected from the marginal facies of the granite and are considered to be closely related to it. They are composed of finely intergrown quartz, kaolinized microcline and plagioclase, with minor pinitized cordierite, muscovite and green biotite. The occurrence of numerous small grains of green spinel and some sillimanite is characteristic of these rocks. Accessory minerals include leucoxenized opaque grains, and zircons.

PETROGRAPHY OF THE MIGMATITE

Included under this heading are the true migmatite and the marginal granite with rafted granulite. The migmatite is a mixture of the older granulite to the west of the Northampton Block (the paleosome metamorphic phase) and the younger intrusive porphyritic granite to the east of the Northampton Block (the neosome igneous phase). The contaminated border facies zone of the granite has already been described. However, I have chosen to describe the granite in which granulite blocks are rafted together with the migmatite to overcome the problem of distinguishing between the two. The contacts between the various facies of the Proterozoic units and indeed between the units themselves are gradational and highly subjective.

An additional problem when describing the migmatite is that the two phases, igneous and metamorphic, are not always easily distinguished. However an attempt has been made from the combined evidence of field observations and hand specimen appearance to separate this suite of specimens into those of granitic and those of granulitic origin. A possible mineralogical distinction is to be found in the composition of the plagioclase. When it could be identified (and this was not very often, because of extensive alteration) the plagioclase was always more sodic in the granite than in the granulite.

GRANULITE FROM MIGMATITE

In hand specimen the granulites occurring within the migmatite are indistinguishable from the granulites of the unit Pm.

The main minerals are quartz, microcline, garnet, biotite and plagioclase. Four of the 25 specimens examined include cordierite which is commonly associated with sillimanite and spinel.

Quartz is the most common mineral in these rocks. It forms anhedral grains with sutured grain boundaries and distinct strain extinction, and includes numerous two-phase inclusions and relict detrital zircons. Where the granulite has suffered minor local shearing the quartz forms a lens-shaped mosaic aligned parallel to the foliation.

Microcline microperthite is the predominant feldspar, forming anhedral, well twinned grains separated from adjacent plagioclase grains by a band of myrmekite. Alteration is limited to minor kaolinization and sericitization. Garnet is ubiquitous within the granulite but varies both in abundance and grain size. It forms anhedral and subhedral crystals which typically enclose round quartz grains in a poikiloblastic texture. Sheared garnets are lens shaped with biotite "pressure-tails". Biotite is generally abundant as flakes which are pleochroic with X = pale yellow, Y = orange, and Z = dark reddish-brown. Distinct pleochroic haloes surround included zircons. In the sheared granulites biotite emphasizes the foliation. It is rarely altered, and then to pale green chlorite. Plagioclase is invariably subordinate to microcline. It forms anhedral grains which are not always well twinned and are commonly sericitized and kaolinized. Where it could be identified it is a sodic andesine. Sometimes coarse grains of microcline are included in an antiperthitic texture. The granulites which are rich in cordierite have only a small amount of plagioclase.

Cordierite constitutes between 10 per cent and 20 per cent of the rock by volume in the cordierite bearing granulites. It is well twinned and forms anhedral and subhedral grains which are commonly altered to pinite along the margins. In one of the specimens pinite has pseudomorphed the cordierite completely. Sillimanite is commonly associated with the cordierite in needles and rods, and sometimes rims a green spinel (hercynite?).

Accessory minerals include graphite, zircons, apatite, and an opaque mineral (ilmenite?) altering to leucoxene and sphene.

GRANITE FROM MIGMATITE

In hand specimen the granite from the migmatite is similar to the granite from the unit Pg except that about half of the suite is non-porphyritic.

The predominant minerals are microcline, quartz, plagioclase and biotite. Minerals which are not always present include garnet, cordierite, sillimanite, spinel, chlorite and muscovite. Accessory minerals include zircons, apatite, epidote and an opaque mineral.

In the porphyritic granites the phenocrysts are composed of well twinned, fresh microcline often showing simple Carlsbad twinning. The microcline is microperthitic and includes round grains of quartz. Where the granite has been sheared the phenocrysts are disrupted and often marginally recrystallized. Myrmekite is common along grain boundaries.

In both the porphyritic and non-porphyritic granites microcline is the predominant feldspar. It is usually less altered than the co-existing plagioclase and forms well twinned, microperthitic, anhedral grains. Quartz forms anhedral grains which have distinct strain extinction and include numerous two-phase inclusions, zircons and very fine, acicular rutile(?). Quartz also occurs within myrmekite and poikilitically included within cordierite. Plagioclase is the subordinate feldspar and was identified (where this was possible) as oligioclase. Usually it is well twinned but sericitization commonly obliterates the twinning. Inclusions of microcline form a coarse antiperthitic texture. Biotite is the characterising mafic mineral in these granites and is usually abundant. It forms flakes, parallel to the foliation in the sheared specimens, and is pleochroic with X = pale yellow, Y = orange, and Z = dark reddish-brown. Included zircons have distinct pleochroic haloes. Some of the biotites is altering to chlorite.

With the exception of only one specimen, all of the granites include garnet which forms anhedral and subhedral grains of varying sizes. In the cordierite-bearing granites the garnet is sieved by quartz and commonly includes spinel and sillimanite. Alteration is limited to a minor development of biotite, chlorite and muscovite along fracture planes. In the sheared granites the garnet is pulled out into a granular lens.

Cordierite occurs in 6 of the 21 specimens in this suite, and in some it is a major component. It forms anhedral and euhedral grains which are fresh except for marginal pinitization. When it occurs in very small amounts it is pseudomorphed by pinite. The fresh cordierite is well twinned but a slight yellowing of the grains due to incipient pinitization provides the clue as to its identity. Rarely, included zircons are surrounded by pleochroic haloes.

Sillimanite typically occurs in association with cordierite. Minor sillimanite was noted in the sheared granites, but in the cordierite-bearing granites it occurs as well developed rods. Some of the sillimanite is intergrown with quartz, and some rims spinel. Well crystallised olive-green spinel (hercynite?) was noted in two of the cordierite-bearing granites. Accessory minerals include zircons, rare apatite and epidote, and an opaque mineral (ilmenite?) altering to leucoxene and sphene. A fresh, black opaque mineral (magnetite?) is associated with spinel.

The six cordierite-bearing granites included under "migmatite" occur with recognisable granulite so that they are not ordinary border-facies granite. These samples were collected from localities mapped as granite and I suggest that they represent granite with rafted granulite.

ASSORTED ROCKS FROM MIGMATITE

Quartzite

The quartzite specimens represent fragments of metamorphosed siliceous bands within the granulite which were caught up by the intruding granite to form migmatite.

They are composed in the main of irregular grains of quartz with sutured boundaries and distinct strain extinction. Sometimes the grain margins are recrystallized to a fine-grained mosaic. The quartz is typically crammed with two-phase inclusions, sagenite needles and rounded zircon grains. In one specimen the relict grain boundaries of well rounded, detrital quartz grains are preserved. Minerals occurring in minor quantities include red biotite with zircons rimmed by pleochroic haloes, kaolinized microcline and sericitized plagioclase. One specimen includes a trace of garnet and opaque grains replaced by sphene.

Pegmatite

Three specimens of pegmatite were collected from the migmatite unit. They are composed of large grains of pink microcline, quartz, and slightly sericitized plagioclase. One of the samples also includes large red garnets with ragged flakes of graphite, and an opaque mineral replaced by sphene. The presence of graphite indicates that this specimen was derived from the granulite unit.

Basic granulites

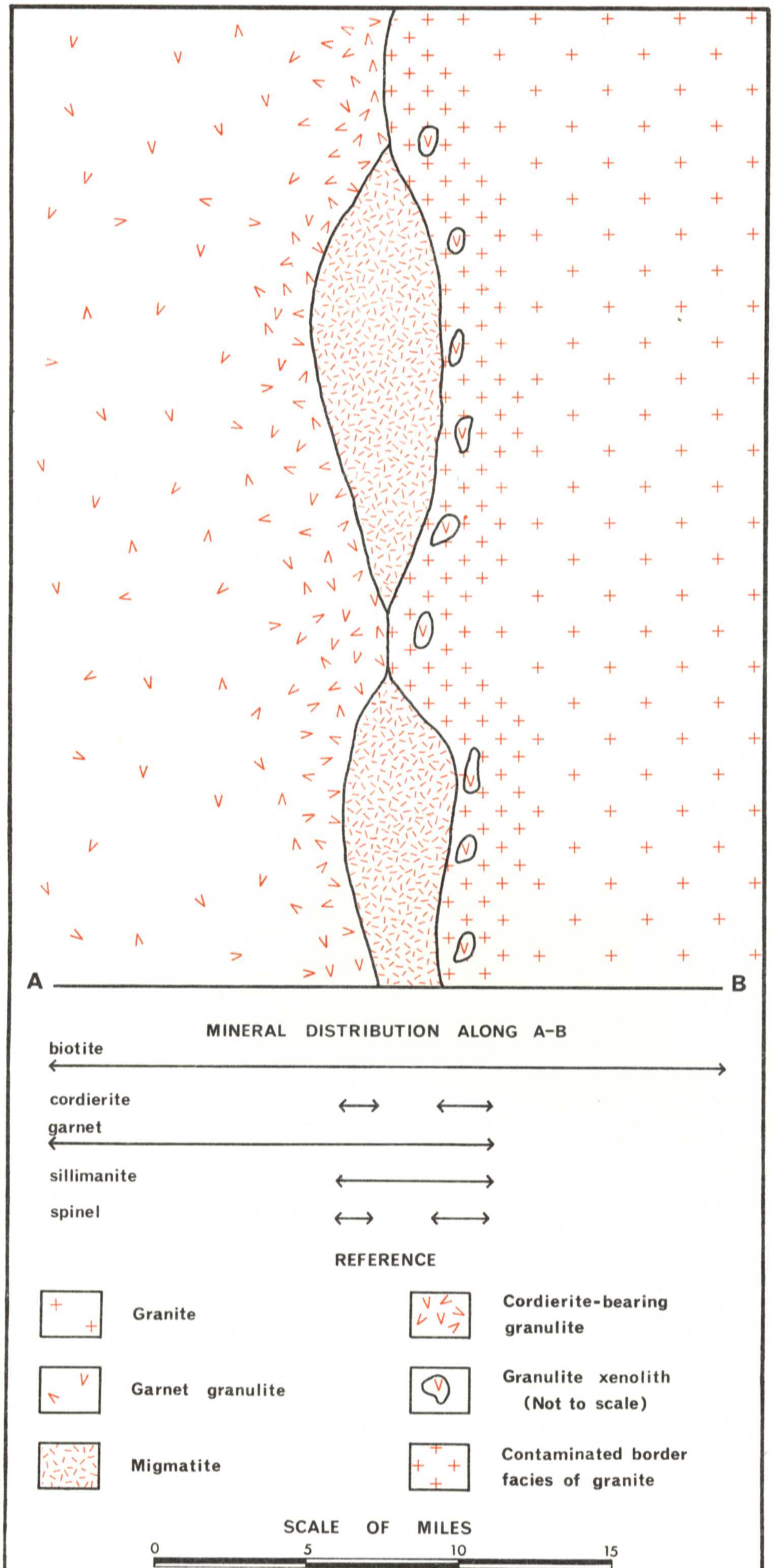
The two specimens included under this heading are both too rich in quartz to be metamorphosed gabbros and so must be interpreted as metamorphosed sediments which have been caught up in the migmatite.

The main minerals are plagioclase, clinopyroxene and quartz. Plagioclase forms well twinned, fresh, equant grains of labradorite. Quartz includes two-phase inclusions and has strain extinction. The clinopyroxene is colourless and is altering to tremolite. One specimen includes a trace of biotite and graphite(?). The other includes minor garnet, sphene and zircon and has secondary calcite developed along fractures.

DISCUSSION

Under this heading it is proposed to attempt an an explanation of the compositional variations within the three units described above, and to consider these variations as evidence for their genetic interrelationships (see Figure 5).

The granulites are the oldest rocks of the Northampton Block. They represent a pile of geosynclinal sediments of essentially greywacke conposition with intercalated siliceous bands (now quartzites), and intruded gabbroic sills (now basic granulites) which have suffered regional metamorphism to granulite facies grade. As suggested by Prider (1958) for the granulites of the Galena area, the graphite content of the granulites is a reflection of the slightly carbonaceous nature of the original sediments. The sedimentary origin of the granulites is indicated by their highly aluminous nature and the presence of layers of graphite, and relict detrital zircon grains. This is in agreement with the findings



SIMPLIFIED DIAGRAMMATIC PLAN OF THE ROCK RELATIONSHIPS IN THE PROTEROZOIC OF THE GERALDTON SHEET AREA

Fig. 5

12299

of Prider (1958), Wilson (1959) and Jones and Noldart (1962) for granulites from various parts of the Northampton Block.

The occurrence of cordierite-bearing granulites may be explained in several ways. As Mehnert (1968, p. 336) states, "the difficulty of a polygenetic interpretation of the same rock arises with many Mg-Fe-Al-rich metamorphites". These cordierite-rich rocks may represent metamorphosed sediments of the same chemical composition (probably pelitic sediments). In this case they are a response to a slightly lower grade of regional metamorphism than that which produced the garnet granulites. Alternatively they may be a product of some later metamorphic effect as an overprint on the granulite facies regional metamorphism.

Wilson (1959) considers there to be much evidence that the granulites of the Northampton Block have suffered more than one metamorphism. The co-existence of pyrope-almandine and cordierite in the granulites of greywacke composition, and the coexistence of the garnet-cordierite granulites with the hypersthene-augite-plagioclase granulites of gabbroic composition are regarded by him as evidence that the latest metamorphism was mainly thermal.

The general persistence of the cordierite-bearing granulites within a narrow band adjacent to the granite and migmatite suggests (perhaps circumstantially) a genetic relationship between the intrusion of the granite and the occurrence of cordierite. Detailed chemical data from the granulites would clarify this point but without it no definite conclusion can be drawn. However a likely possibility is that the granite was responsible at the time of intrusion for local magnesium metasomatism within the adjacent granulites. It is known that the granite was intruded as a sheet (Horwitz, in press) so the two anomalous specimens of cordierite-bearing granulite collected from localities away from the eastern margin may be related to small granite apophyses.

Layers of pegmatite and acid schlieren throughout the granulite unit are for the most part the result of local metasomatic activity, the bands having been "sweated" out of the country rock rather than intruded by an unrelated magmatic phase.

The porphyritic granite was intruded as a sheet into the granulites, with the development of a band of migmatite along the contact, and a narrow contaminated marginal facies within the granite itself. This contaminated zone is characterised by xenoliths of granulite rafted within the granite, and also by the occurrence of garnet and cordierite. With the possible exception of some granite pegmatites, cordierite is not a normal product of magmatic crystallization (Deer, Howie and Zussman, 1962, Vol. 1). Recorded accounts of cordierite-bearing igneous rocks, including granites, have without exception ascribed the cordierite to contamination by country rock such as argillaceous sediments, cordierite-bearing schists and gneisses which have enriched the magma in aluminium. The presence of garnet within the granite border facies also suggests that contamination by the intruded granulite has taken place. The production of garnets by contamination of the granite was first suggested by Horwitz (in prep.).

From both field and petrographic evidence the migmatite is a mechanical mixture of the granulite and the invading granite. In this case there is no question of the migmatite being of metasomatic origin. The absence of cordierite from the migmatite (as opposed to the granite contaminated by granulite xenoliths which were described with the migmatites) may be explained by the fact that this was an environment of tremendous stress, and therefore not conducive to cordierite formation, (Harker, 1950). The ubiquitous occurrence of almandine garnet is consistent with the migmatite being an area of high pressure.

CONCLUSIONS

The conclusions are best stated as a suggested genesis of the Northampton Block.

1. Geosynclinal sediments (carbonaceous greywackes, shales and intercalated siliceous sediments) were deposited and intruded by gabbroic sills.

2. Regional metamorphism (of which there was probably more than one episode) at granulite facies grade converted the sedimentary pile into garnet granulites with some quartzites and basic granulites. Metamorphic differentiation gave rise to pegmatite and aplite layers.

3. The granulites were intruded by granite. Formation of the granitic magma may have been concomitant with the latest regional metamorphism of the granulites, but the granite itself was not responsible for the metamorphism of the granulites. Migmatites were formed along the contact as the granite was intruded. Possible magnesium metasomatism of the marginal granulite by the granite resulted in the development of the cordierite-bearing granulites. Granulite contamination (especially the addition of aluminium) gave rise to the garnet and cordierite-bearing marginal facies of the granite.

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THE AGE OF THE GIDLEY GRANOPHYRE

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ABSTRACT

The Gidley Granophyre, which has been informally called the Dampier granophyre, is an intrusion of granophyre and associated gabbro along the basal unconformity of the Precambrian Fortescue Group. The main outcrop is in the Dampier Archipelago and adjacent mainland, between about 20° 30–45′ S and 116° 30–45′ E, with an area of about 52,000 km^2. Fourteen analysed samples yielded two Rb-Sr isochrons. The best interpretation of the younger isochron is argued to be 2,196 ± 26 m.y. The older age, of 2,612 ± 56 m.y., is thought to be unrealistic. The Gidley Granophyre is probably coeval and co-genetic with likely Fortescue Group lavas in the Yarraloola area, with a previously reported age of 2,190 ± 100 m.y., and is probably related to the Cooya Pooya Dolerite.

INTRODUCTION

This paper reports further results from a co-operative geochronological programme, initiated in 1968, between the Western Australian Institute of Technology and the Geological Survey of Western Australia (De Laeter and Trendall, 1970). The work reported is on a granophyre body intruded along the unconformity between the Archaean rocks of the Pilbara Block and the overlying rocks of the Fortescue Group, in the North West Division of the State.

ACKNOWLEDGEMENTS

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REGIONAL GEOLOGICAL AND GEOCHRONOLOGICAL SETTING

The Pilbara Block (Plate 32) is an area of Archaean granitic metasedimentary and metavolcanic rocks, between approximate latitudes 20° and 22° S and longitudes 116° and 121° E. It has a total extent of about 20,000 square miles (52,000 km^2), and its geological structure is typical of that of many Archaean shield areas, with metasedimentary and metavolcanic rocks forming steep, sinuous, synclinal "greenstone belts" separating broad domes of gneiss and granite.

To the north, the Pilbara Block is bounded by either the Indian Ocean or Phanerozoic rocks of the Canning Basin, but on its southern and eastern margins its limits are defined by the major regional unconformity at the base of the overlying Fortescue Group. This sequence, consisting mainly of basic lavas and associated pyroclastic rocks, is the lowermost of three groups which together constitute the Mount Bruce Supergroup. The Hamersley Group, which succeeds the Fortescue Group, is characterised by abundant and extensive iron formations, while the uppermost Wyloo Group contains mainly clastic sedimentary rocks, with locally important dolomite and basalt.

Although all three groups are locally folded, and the Wyloo Group is metamorphosed in the southernmost part of its outcrop, the Fortescue Group dips only gently away from the Pilbara Block at the unconformity, and is not metamorphosed in its vicinity. The resultant supposition that this unconformity represents a substantial interval of time is confirmed by the available geochronological data, which have been summarised by Compston and Arriens (1968, p. 566–7). Twelve granites from the Pilbara Block have yielded a Rb-Sr isochron of 3,050 ± 180 m.y., with acid lavas from one of the greenstone belts also between these limits. Separate minerals from a pegmatite had previously given ages of about 2,900 m.y., also by the Rb-Sr method, while De Laeter and Trendall (1970) reported an isochron age of 2,880 ± 55 m.y. for a late (post-folding) intrusive porphyry.

The age of the Fortescue Group is not well established. Compston and Arriens (1968) report 2,190 ± 100 m.y. for interbedded acid igneous rocks. These may be either lavas or sills, and, if the latter, this age is only a minimum one. However, ages of 2,000 ± 100 m.y. for the undoubtedly extrusive Woongarra Volcanics of the overlying Hamersley Group, and of 2,020 ± 165 m.y. for acid igneous rocks interstratified with the Wyloo Group, which is itself intruded by granite about 1,700 m.y. old, indicate the general credibility of 2,190 m.y. as a possible age of extrusion if the Fortescue Group rocks are lavas. Compston and Arriens (1968) conclude that the best age estimate for the lowermost Fortescue Group rocks is between 2,250 and 2,200 m.y., although the data for this estimate remain unpublished. Thus the unconformity below the Fortescue Group may represent a time gap of about 600 m.y.

THE GIDLEY GRANOPHYRE

Definition

Although it was mapped in 1962, as described below, the Gidley Granophyre was not formally named, and has been referred to as "granophyre in the Dampier Archipelago" (Kriewaldt, 1964) or informally as "Dampier granophyre" (Trendall, 1963). The following details are therefore set out for the purpose of formal definition in accordance with the requirements of the Australian Code of Stratigraphic Nomenclature (Geological Society of Australia, 1964). The name Gidley Granophyre is proposed for a stratiform intrusion of granophyre and associated quartz gabbro along the basal unconformity of the Fortescue Group over Archaean rocks of the Pilbara Block, in the Dampier Archipelago and adjacent mainland part of northwestern Western Australia. Gidley Island is an island of the archipelago (Plate 33). No type section is specified, since much of the outcrop, as represented by Kriewaldt (1964) and more generally in Plate 33 of the present paper, between the limits 20° 24′ and 20° 44′ S and 116° 26′ and 116° 53′ E, has good exposure. In its thickest part the sheet probably reaches a thickness of about 10,000 feet (3,000 m). The Gidley Granophyre is Precambrian, its exact age being the main topic of this present paper.

Outcrop, form and field relationships

The outcrop of the Gidley Granophyre falls entirely within the Dampier and Barrow Island 1 : 250,000 sheet, which was mapped in 1962 by four Geological Survey geologists (Kriewaldt, 1964). The appropriate part of this map is here reproduced, with slight modifications, as Plate 33.

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Kriewaldt (1964, p. 9) summarised the field relationships of the granophyre as follows. It "is intruded at the unconformity between Archaean granitic rocks and overlying gently dipping basaltic lavas of the Proterozoic. At the top of the granophyre, metasomatised by it, are small lenses of altered arkose, basal to the lava. The marginal granophyre is light coloured. Small dykes, apparently offshoots of the granophyre, intrude the overlying basalt on Enderby Island". The relationship between the granophyre and the gabbros and dolerites of the same general area is not clear, and Kriewaldt (1964) regards some of the basic rocks as "possibly contemporaneous with the granophyres, others with the younger dolerite dykes" which cut the granophyre. These dykes are omitted from Plate 33; on the published 1 : 250,000 map they appear as two intersecting sets, with bearings of about 045° and 160°, which cut all the Precambrian rock units.

Structural information is also omitted from Plate 33. Northerly and northwesterly dips recorded from Enderby, West Lewis, Malus and East Lewis Islands lie mainly between 5° and 10°, and although the base of the granophyre is not exposed it may be assumed that it forms an open syncline with a gentle northerly plunge, as suggested by the possible lines of top and base marked on the map. In this interpretation the extensive belt of gabbro extending southward from the eastern part of Dolphin Island appears as a basal part of the intrusion.

Petrography

In hand specimen the granophyre is normally a massive, homogeneous, dark green, dark blue, purple or black rock, sometimes with a false impression of coarse granularity imparted by a patchy mottling of two contrasted colours. One local variant has red and green mottling with an apparent "grain size" of about 3 mm, to give a general purple colour.

This two-fold division corresponds to one which is normally discernible in thin section (Plate 34 A) whether or not it is macroscopically visible. In the red and green mottled rocks the green material consists mainly of an irregular intergrowth of quartz and alkali feldspar. The texture of the intergrowth is complex. It consists partly of irregular patches, about 0·1–0·2 mm across, of barely resolvable micropegmatitic intergrowth in which the individual quartz and feldspar bodies are 5–20 μ across, and partly of alternating strips of these two minerals about 10 μ wide and as long as 2 mm. The longer of such quartz strips consist of several optically distinct sections, and are interpreted as paramorphs after tridymite (Ray, 1947; Wager and others, 1953). The red material consists also of a close intergrowth of quartz and alkali feldspar, but here subhedral to euhedral feldspars, often with a tendency to skeletal growth and about 0·1–0·2 mm across, lie in an even quartz mosaic of average grain diameter about 0·5 mm. The feldspar is cloudy with dusty (possibly hematite) inclusions which are absent along the clear cleavage lines, which are thus rendered conspicuous. These two types of material are irregularly and closely intergrown, with vaguely defined intergradational margins; there is, however, a preference of that first described to have convex margins against the second, so that the latter appears interstitial to the former. This impression is heightened in some rocks by a spherulitic tendency in the first. The exact nature of the alkali feldspar involved in both types of intergrowth remains uncertain. Trendall (1963) gave reasons for regarding some as high albite, but subsequent total rock analyses suggest that such is potassic, and the vague and irregular extinction often present seems indicative that unmixing may have led to a fine-scale association of sodic and potassic feldspar.

Although the textural details of the quartz-feldspar intergrowth in these rocks vary from sample to sample, there is no indication from the material studied of any divisibility into distinctly definable textural types. One such textural detail is the occasional presence, in the cores of spherulites, of subhedral low albites up to 0·5 mm across. Other minerals present in subordinate amounts in the granophyre include small rounded opaque grains, and irregular patches of epidote, sphene and chlorite. These sometimes form aggregates, rectangular in section, suggesting derivation from an original ferromagnesian mineral. Chlorite, in some of the granophyres, also fills abundant intersecting cracks.

The gabbro sample analysed (15604) comes from the basal part of the intrusion (Plate 33) and is illustrated in Plate 34 B. Groups of subhedral, somewhat altered, clinopyroxenes up to 5 mm across, lie in a matrix consisting mainly of an aggregate of subhedral laths of andesine-labradorite generally about 1 mm long. Some orthopyroxene is also present. The cores of the plagioclase laths often have dense saussurite, and they are marginally zoned to albite. The interstices between the plagioclase laths are occupied variously by pyroxene, quartz or, most commonly, a micrographic intergrowth of quartz and albite. Irregular areas of chlorite are probably derived from the alteration of pyroxene, and a few scattered flakes of red-brown biotite are also present.

Other gabbros within the Gidley Granophyre, as defined in this paper, are more classically gabbroic in thin-section appearance. An example from Dolphin Island, shown in Plate 34 C, is noritic, with an approximately equigranular mosaic of hypersthene, augite and labradorite. Some petrographic resemblance to 15603 is, however, provided by a few interstitial pockets of quartz or of micrographic albite/quartz intergrowth.

A rock closely associated with the granophyre, and whose petrography is conveniently described here, is 15603. This rock was collected as a granite just below the gabbro (Plate 33; Plate 34 D), and was analysed in this study. It consists of a coarse (2–5 mm) anhedral mosaic with three components: clear quartz, plagioclase and potassic feldspar. The plagioclase is probably albite, and occurs in single equant grains so crowded with small sericite flakes as to make its exact determination impossible. The potassic feldspar forms smaller grains and has characteristics closely similar to the alkali feldspar of the granophyre. It is crowded with dark dusty inclusions, whose absence conspicuously defines the cleavage, and has a patchy, complex extinction. This feldspar also occurs as rims, about 0·1 mm thick, separating most contacts between quartz and plagioclase. The rock has evidently been markedly altered by the overlying intrusion.

PLATE 34 (opposite)

A R152, typical thin section appearance of the Gidley Granophyre (PPL). An area of coarser micropegmatitic intergrowth runs downwards and to the right from the centre of the photograph. The remainder of the photograph is occupied by irregular and finer grained quartz-feldspar intergrowth. A quartz paramorph after a tridymite plate appears to the upper left.

B 15605, a gabbro from about 2 miles (3.2 km) south of Dampier (crossed nicols). A twinned orthopyroxene lies at the top of the photograph. To the left of it, and also extending downwards from its lower end towards the left lower corner, are fine-grained areas of micropegmatitic intergrowth. There is white quartz along the lower edge. The dark area on the right is saussurite, white, less altered plagioclase appears to the upper left.

C R665, gabbro from Angel Island (oblique nicols). This noritic rock contains only scattered patches of micropegmatite; none are visible here.

D 15603, an altered granite (PBL). The clear quartz is cracked and rimmed by dark alkali feldspar separating it from pale grey albite. The darker grey feldspar to the lower left is entirely alkali feldspar, as is the patchy material to the upper right.

MATERIAL USED

The work reported here took place in two stages. In the first stage all samples of granophyre and associated rocks collected in 1962 during 1 : 250,000 scale mapping were assembled. Obviously weathered samples were discarded, and preliminary XRF determinations of Rb and Sr were carried out on the remainder. On the basis of these results the samples with highest and lowest Rb/Sr, and four distributed between, were analysed isotopically, in the hope that a single isochron of high quality would appear. This hope was disappointed, both initially and after analysis of two additional samples.

In the second stage, 13 further samples were collected from the vicinity of the town of Dampier, by Mr. J. G. Blockley, and were similarly dealt with. The resultant total of 14 analyses appeared to give a pattern capable of rational interpretation, presented farther below. In our judgement, a more positive result is unlikely without the addition of more extensive work than could be justified at present.

Of the 14 samples finally analysed 12 are granophyres (all numbers preceded by R, and 15602, 15610, 15612 and 15613), one a gabbro (15604) and one a contact altered granitic rock (15603). The petrography of these has already been described, and their locations appear on Plate 33.

EXPERIMENTAL PROCEDURE

Sample preparation

About 100g of each sample were reduced to —100 mesh using a jaw crusher and a Kurt Resch hammer mill. After splitting, about 10g were further ground for about 15 minutes in a Kurt Resch automatic mortar grinder.

Chemistry

An accurately weighed sample of each rock selected for analysis was placed in a teflon dish. For a 0·5g sample approximately 10 mls of 48 per cent HF and 1·5 mls of 70 per cent $HClO_4$ were required for the dissolution, the mixture finally being taken to dryness on a hotplate. The residue was then dissolved in 30 mls of 2·5N HCl and the solution taken to dryness. Approximately 10 mls of 2·5N HCl were then added and the solution transferred to a quartz ion exchange column containing 20g of wet Dowex 50W-X8, 200–400 mesh cation exchange resin. Strontium was eluted using 2·5N HCl, the cut being taken between 40 mls and 50 mls. The eluted sample was taken to dryness, redissolved in a minimum of 2·5N HCl, and placed on a micro column containing 1g of cation resin. The strontium was then eluted as before and the eluant taken to dryness ready for mass spectrometric analysis.

Mass spectrometry

Isotopic analyses were carried out on a 12-inch radius, 90° magnetic sector, solid source mass spectrometer. The source and collector slits were set to 0·004 in. and 0·020 in. respectively to provide a resolution of approximately 400. The sample was mounted as the chloride on the side filament of a conventional triple filament surface ionization source. Rhenium filaments, which were outgassed prior to use, were employed throughout. No evidence of rubidium or strontium contamination from the filaments or ion source could be detected. New filament buttons were used for each sample and the source was cleaned between successive analyses.

The usual operating currents for strontium, loaded as the chloride, are 4·0 amps for the centre ionising filament, and approximately 1·0 amps for the side filaments. For rubidium chloride, slightly lower currents were used. For a strontium analysis the filament currents were initially adjusted to a value where strontium emission was minimal. These conditions were retained for about 1 hour to enable the alkali beam, which was invariably present, to be reduced to a level where it no longer had a serious suppressing effect on the production of strontium ions. After the rubidium beam was reduced to a negligible size, the side filament temperature was gradually increased until an Sr^{88} ion beam of the order of 10^{-12} amps was obtained. For a r μg sample this beam could be maintained over several hours of operation without a marked decrease in intensity.

An electron multiplier with a gain of about 10^4 was used as the ion detector. The resulting signals were amplified in a vibrating reed electrometer with a 10° 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 calibrated for scale factors, linearity and speed of response.

The isotopic peaks were scanned from the lowest mass to the highest mass and then back again, this operation constituting one sweep. Ten sweeps usually comprised a mass spectrometer "run". The sweep speed was adjusted so that at least 5 counts of 1 second each were recorded across the top of each peak, whilst a minimum of time was spent on the baseline between the peaks. The computer was programmed to select a number representative of the height of each peak immediately after sweeping through the peak. This information was then stored in memory until the mass spectrometer run was finished, after which a complete statistical analysis of the isotopic ratios was carried out. The final results could thus be presented at a teletype, situated in the mass spectrometer laboratory, within a minute of the end of run.

Sr isotope ratios were also measured for unspiked Sr extractions. The mass range 84 to 88 was scanned on a sensitive scale during the analysis in order to detect the presence of any Rb at mass 85. The isobaric contribution of Rb^{87} to the Sr^{87} ion beam was always less than 0·01 per cent.

Replicate analyses of M.I.T. standard strontium carbonate were made over a period of time to give a mean value of Sr^{88}/Sr^{86} of 8·2850 rather than 8·3752 as determined by other authors (Faure and Hurley, 1963). The difference is largely due to the influence of electron multiplier-induced mass discrimination. After correcting the measured Sr^{88}/Sr^{86} ratio to 8·3752, the actual value found for the M.I.T. standard Sr^{87}/Sr^{86} ratio was 0·70. The Sr^{87}/Sr^{86} ratios contained in Table 1 have likewise been normalised to Sr^{88}/Sr^{86} equal to 8·3752.

X-ray Fluorescence

This technique was used to select rocks with favourable Rb-Sr ratios for mass spectrometric analysis and also to determine precise values of the Rb-Sr ratio for the selected samples. A Siemen's SRS-1 fluorescence spectrometer, equipped with a molybdenum tube, a lithium fluoride (200) crystal and a scintillation detector, was used for the Rb-Sr analyses. Finely ground samples (–200 mesh) were pressed with a boric acid backing and were then in a form suitable for X-ray fluorescence analysis.

Rubidium was read at a 2 θ position of 26·56° and strontium at a 2 θ position of 25·09°. Before selecting the background positions, consideration was given to possible interference effects, and the profile of the background in the vicinity of the RbKa and SrKa peaks was carefully observed. The most satisfactory background positions for this spectrometer were found to be at 2 θ positions of 27·06° and 25·81° for rubidium and 25·59° and 24·59° for strontium.

A preset count of 2 x 10^5 was used for each position and a dead-time correction was then made. Each sample was measured a number of times depending on the concentrations of rubidium and strontium in the particular sample.

A conversion factor from intensity to weight ratios was determined by analysing a number of standard rocks, with a wide range in Rb-Sr ratio, in which the concentration of rubidium and strontium was accurately known.

The values of the concentration of rubidium and strontium in the standard rocks were determined by isotope dilution as discussed by De Laeter and Abercrombie (1970), and these values have been used in determining the calibration curve for X-ray fluorescence.

This calibration curve allowed for matrix effects and the variable fluorescent response between rubidium and strontium. Machine drift during an analysis was obviated by analysing a reference sample between each run. In addition an appropriate standard rock was analysed with each suite of samples.

Isotope dilution

The Rb/Sr ratios of three of the samples listed in Table 1 were also determined by isotope dilution. This enables a minor adjustment to the X-ray fluorescence values to be made, if necessary, for differences in matrix between the standard rocks and the samples representing the Gidley Granophyre. However the results were identical within experimental error and thus no adjustment was made.

Weighed quantities of Rb^{87} and Sr^{84} spikes were added to the rock samples prior to dissolution. Each sample was dissolved as discussed above in a $HF\text{-}HClO_4$ mixture, and the rubidium and strontium separated by cation exchange chemistry. Blank determinations showed that the Rb and Sr contamination introduced by the chemical processing was less than 10^{-8}g and 10^{-7}g respectively. Full details of the isotope dilution technique used in this laboratory are given by De Laeter and Abercrombie (1970).

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 at the 95 per cent confidence level, in Table 1, for each of the 14 samples analysed. Ages which may be computed from selected groups of these samples are discussed in the following section. All computations employ the method of Williamson (1968), which minimises the weighted sum of squared residuals. All age calculations are based on a Rb^{87} decay constant of 1·39 x 10^{-11} $year^{-1}$. The errors associated with the age and initial Sr^{87}/Sr^{86} ratio (R_i) are calculated from the standard deviation of the slope and intercept respectively.

TABLE 1. ANALYTICAL DATA FOR SAMPLES OF THE GIDLEY GRANOPHYRE

Sample	Rb/Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
R 152	5·67	17·30 ± 0·24	1·2760 ± 0·0023
R 153	2·77	8·25 ± 0·08	1·0275 ± 0·0020
R 154	3·24	9·64 ± 0·10	1·0226 ± 0·0007
R 155	2·12	6·27 ± 0·06	0·9615 ± 0·0025
R 156	2·57	7·64 ± 0·09	1·0100 ± 0·0023
R 157	1·47	4·32 ± 0·04	0·8848 ± 0·0006
R 159	5·49	16·66 ± 0·22	1·2295 ± 0·0010
R 664	0·17	0·49 ± 0·006	0·7171 ± 0·0005
15602	5·328 (5·237)*	15·97 ± 0·32	1·1878 ± 0·0025
15603	1·011	2·95 ± 0·06	0·8053 ± 0·0010
15604	0·322 (0·320)	0·93 ± 0·018	0·7391 ± 0·0009
15610	2·984 (2·969)	8·83 ± 0·18	0·9867 ± 0·0018
15612	4·773	14·36 ± 0·28	1·1360 ± 0·0024
15613	2·024	5·96 ± 0·12	0·9078 ± 0·0012

* Values in parenthesis were determined by isotope dilution; all others in this column by X-ray fluorescence.

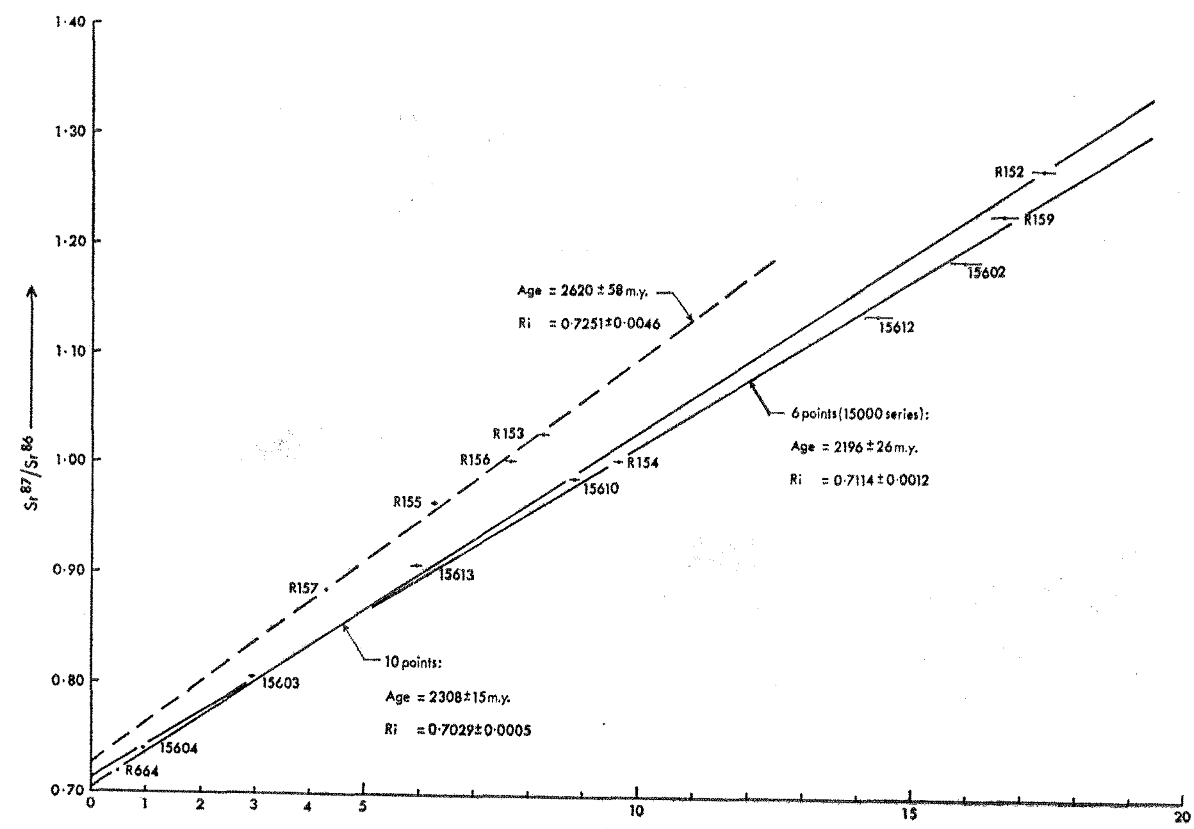

Fig. 6 Isochron plot of the 14 analysed samples. See text for discussion 12300

DISCUSSION

The data of Table 1 are plotted in Figure 6. Inspection indicates an apparent distribution along two possible isochrons, an older one defined by R153, R155, R156, and R157, and a younger one defined by the remaining rocks. The validity and significance of each can be discussed separately.

There are 10 points on the possible younger isochron, and a computation of these gives an age of 2,307 ± 15 m.y., with an R_i of 0·7032± 0·0005. This isochron appears on Figure 6. However, 7 of the 10 defining points depart from it by greater than experimental error, and it is likely both that "geological effects" control the positions of at least some of these rocks, which require explanation, and also that the computed age may be a spurious one.

Subsequent discussion of this rather poor isochron is conveniently carried out in three stages, represented by the following three questions:

1. What are the upper and lower age limits which could be defined by selective exclusion of points, and are there rational grounds for such selection?

2. What apparent limits to the age are set by data already available, combined where necessary with geological interpretation?

3. Is there a hypothesis which inter-relates more geological and geochronological data, both new and previously reported more satisfactorily than any other?

An isochron defined by six of the samples from the immediate vicinity of Dampier (2,196 ± 26 m.y. with R^i 0·7114 ± 0·0012) is also shown on Figure 6. It is clear, without computation, that extreme limits of approximately 2,150 and 2,350 m.y. may be obtainable by exclusion of chosen points. There are, however, no clear grounds for any exclusion. Only 15603 and 15604 are petrographically distinct types, and their exclusion would probably not improve the statistical reliability of any resultant isochron obtained from the remaining rocks, all of which are petrographically uniform granophyre. Possible exclusions on other grounds than petrographic dissimilarity are discussed farther below.

We may now consider the second of the enumerated questions. Although the intrusive status of granophyre has been questioned (Holmes, 1960) there seems little doubt, from Kriewaldt's (1964) descriptions, that the Gidley Granophyre originated by the injection of magma, whatever the origin of this. To be consistent with available data the granophyre must therefore be younger than the lowermost part of the Fortescue Group.

Exactly how much younger it might be is speculative, on two counts. Firstly, the thickness of Fortescue Group cover at the time of intrusion is not known. Kriewaldt (1964, p. 8) gives the thickness of this group in the Dampier Archipelago as 4,000 feet (1,200 m), increasing to 7,000 feet (2,100 m) at Cape Preston, where the Fortescue Group crosses the mainland coast about 40 miles (64 km) to the west. Granophyric textures are assumed to relate to the fairly rapid cooling of the magma, and high-level intrusion is therefore a preferred hypothesis, but there is little published information on which to set a depth limit; Davies (1959, p. 212) has estimated a roof thickness of 1,700–2,000 feet (510–610 m) for a thinner granophyre sill in Wales, 1,600–2,000 feet (480–610 m) thick.

Secondly, even if the depth of intrusion were known, the time interval represented by, say, 2,000 feet (610 m) of Fortescue Group lava is also unknown. Trendall and Blockley (1970, p. 298) have suggested, with several qualifications, possible limits of 2,000 and 6,000 years per foot for the subsidence rate of the Hamersley Basin, in which the Fortescue Group accumulated. If the general order of these speculative estimates is correct then 10 m.y. may have been more than adequate for the extrusion of a sufficient thickness of Fortescue Group lavas to provide cover for the intrusion of the Gidley Granophyre.

On the other hand, the lowermost few thousand feet of the Fortescue Group *may* have taken several hundreds of millions of years to accumulate, and the lowest feasible limit of basal Fortescue Group age is an age younger than the latest igneous event in the Pilbara Block, by the time necessary for erosion to set the scene for Fortescue Group deposition. This period can only be guessed at, but in round terms, 80 m.y. after the age of the Copper Hills Porphyry would give a maximum possible age of 2,800 m.y.

There is, however, an available argument which makes the age of the Fortescue Group irrelevant. The material for Compston and Arriens' (1968) age of 2,190 ± 100 m.y. for acid igneous rocks of the group came from the Nallanaring Volcanic Member of the Jeerinah Formation in the Yarraloola 1 : 250,000 sheet area (Williams, 1968: approximate locality 20° 30′ S, 116° 15′ E), and lie the same order of thickness above the base of the group as is likely to have covered the Gidley Granophyre at the time of intrusion. Whatever estimate for rate of Fortescue Group accumulation is used in the one case must clearly also be used in the other, so that from existing data 2,190 ± 100 becomes a likely older limit for the Gidley Granophyre regardless of the basal age of the Fortescue Group. On the other hand there is no useful younger age limit for the granophyre from existing data, since the transecting basic dykes have not been dated.

Thus, in this discussion so far, we have for the Gidley Granophyre a youngest possible isochron limit of about 2,150 m.y. by irrational discarding of inconvenient points, and an argued older limit of 2,190 ± 100 from existing data. It remains to consider the third question, and to propose a hypothesis which is both geologically and isotopically plausible, and which takes into account the widest possible range of information.

For the genesis of the Gidley Granophyre two extreme hypotheses are available: either it is a differentiate from basic magma during this period, or it results from the regeneration of older crustal material. In the first case a simple isochron with a low R_i would be expected, and in the latter, assuming that "regeneration" produced isotopic uniformity, a simple isochron with a high R_i. These two isochrons are represented diagrammatically by A and D in Figure 7.

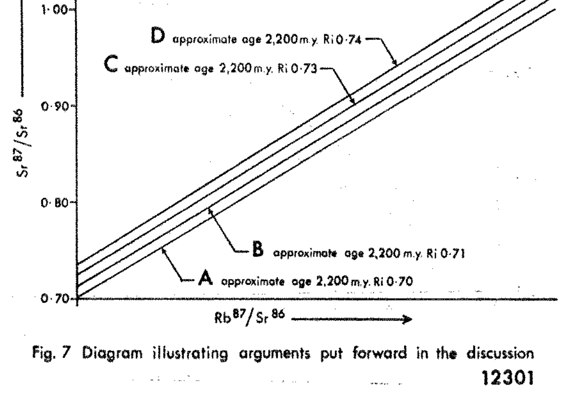

Fig. 7 Diagram illustrating arguments put forward in the discussion

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Since the results are more complex it may be examined whether the complexity is explicable in terms of a combination of the two extremes. Suppose the Gidley Granophyre to have been generated primarily by direct differentiation of mantle-derived material, and secondarily by concurrent digestion of older crust; and suppose that the proportion of digested material in the magma varied slightly in different parts. Such a situation would result in the potential local existence now of a family of parallel isochrons intermediate between A and D of Figure 7, of which two, B and C, are there represented. In such a situation, a very large number of Gidley Granophyre samples would be expected to define a broad "isochronal zone", having A and D as limits.

But suppose now that the *minimum* contamination with older crust is in fact close to B, and take into account the fact that the granophyre appears largely to have digested the underlying *granitic* rocks. In this situation, the more digested material in the magma, the higher the total Rb/Sr ratio may be expected to become, so that, with random sampling, while isochron B may appear in practice, only the upper (right-hand) parts of the higher parallel isochrons (C and D) may appear. In this situation the "real" isochron, B, may become steepened by the inadmissible inclusion of points from higher isochrons, with complementary depression of the ordinate intercept, or R_i.

We suggest that such may be the origin of the difference between the two plotted isochrons of Figure 6, and that the data of that Figure may incorporate a real isochron represented by the six points provided by the samples close to Dampier. It can now be examined whether any other geochronological or geological evidence supports this. Taking the latter first there are indications that at least some differentiation has taken place: there exists a basal gabbro layer whose petrographic affinity with the granophyre argues against its separate intrusion in that position as a later (or earlier) unrelated body. The ratio of granophyre to gabbro (possibly about 3 : 1), and the comparatively clear dichotomy between these two components of the intrusion, do indicate, however, that differentiation could not have occurred entirely in place.

A possible solution to this point may lie in the Cooya Pooya Dolerite, whose position is shown in Plate 32. Both this dolerite and the Gidley Granophyre may be the remaining north and south parts of a major intrusion in the crest of the gentle anticlinal arch whose axis follows the east-west trend of the Archaean outcrop now lying between. This extensive, mainly basic sheet was intruded at or close above the basal Fortescue Group unconformity in the Yarraloola and Pyramid 1 : 250,000 sheet areas (Williams, 1968; Kriewaldt and Ryan, 1967).

Until further data become available we therefore suggest that:

1. The age of 2,196 ± 26 m.y. derived from the six samples close to Dampier is probably the most acceptable present estimate for the age of the Gidley Granophyre.

2. The acceptance of this figure involves a preferred hypothesis that the granophyre originated by the differentiation of acid magma from mantle material at about this time, and that variable digestion of older granitic crust took place at some stage before emplacement.

3. Emplacement may have taken place in more than one stage, with continuing differentiation.

4. The Gidley Granophyre is probably both coeval and cogenetic with the stratiform acid rock within the Fortescue Group from which Compston and Arriens' (1968) age of 2,190 ± 100 m.y. was derived.

We have no ready explanation for the older (2,612 ± 56 m.y.) isochron of Figure 6. The four defining rocks (R153, R155, 6, 7) are not locally grouped, but are petrographically similar, and the isochron cannot be invalidated on petrographic grounds. A common feature of all four samples of possible significance, is that they lie near the top of the intrusion. At present, we prefer to regard these samples as a group properly belonging to 2,196 m.y. isochrons of even higher R_i than D of Figure 7, which accidentally define a meaningless age; the problem requires further work for its final elucidation.

Further work on both the Cooya Pooya Dolerite and Gidley Granophyre would be useful to consolidate and extend the results here reported. It could advantageously include analyses of the Bamboo Creek Porphyry, which was intruded at the same stratigraphic position at the other extremity of the main northern unconformity of the Fortescue Group; it is shown on Plate 32.

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AGES OF GRANITIC ROCKS IN THE POONA-DALGARANGA AREA OF THE YILGARN BLOCK, WESTERN AUSTRALIA[1]

by P. C. Muhling[2] and J. R. de Laeter[3]

ABSTRACT

The ages of granitic rocks in the area bounded by longitude 117° and 118° E and latitude 27° and 28° S have been determined using the total -rock Rb-Sr method. Ages indicated are 2,590 ± 23 m.y. for a large granitic complex about 72 miles long and 36 miles wide, in the Poona-Dalgaranga area, and 2,605 ± 51 m.y. for several disconnected granitic masses on the eastern edge of the complex. The granites of this area have about the same age and initial Sr^{87}/Sr^{86} ratio as those of the Kalgoorlie area.

INTRODUCTION

This is the second report resulting from a programme of Rb-Sr isotope geochronology on the Precambrian of Western Australia which was initiated in 1968 jointly by the Western Australian Institute of Technology and the Geological Survey of Western Australia (de Laeter and Trendall, 1970).

ACKNOWLEDGEMENTS

Mr. W. W. Thomas and Mr. I. D. Abercrombie, of the Western Australian Institute of Technology, were responsible for the X-ray fluorescence analyses and the chemical work respectively. The Director of the Geological Survey of Western Australia gave permission to publish this work.

GEOLOGY

Regional environment

The Yilgarn Block (Prider, 1965; Daniels and Horwitz, 1969) has a roughly rectangular shape with irregular northern and eastern boundaries and is the largest area of Archaean rocks in Australia. It is located between latitudes 25° to 34° S and between longitudes 117° to 125° E. The west side of the Block is faulted against the Phanerozoic sediments of the Perth and Carnarvon Basins and is bounded on the northwest side by the Gascoyne Mobile Belt (Daniels and Horwitz, 1969) and on the southern and southeastern sides by the Albany-Fraser Province (Daniels and Horwitz, 1969). The northern and northeastern edges are bounded by unconformities with younger Precambrian sediments of the Bangemall Basin (Daniels and Horwitz, 1969) and with Phanerozoic sediments of the Officer Basin.

The Yilgarn Block comprises elongate remnants of folded, metamorphosed volcanic and sedimentary rocks embayed and distorted by intrusive granitic rocks. Most of these areas of metamorphic rocks trend northwesterly, although some in the northwest corner of the Yilgarn Block trend north-east.

The granitic rocks include gneissose and migmatitic types, broadly conformable with the structures of the metamorphic rocks, and discordant types with primary flow structures or massive texture.

Cue Granites

A feature of the northwest corner of the Yilgarn Block is a batholith of granitic rocks, first described by Johnson (1950). Recent mapping (Muhling, 1969; Baxter, in prep.) has enabled sub-division of much of this batholith. The Poona-Dalgaranga area (Figure 8) is part of the western half of the Cue 1 : 250,000 sheet area (SG/50-15) and is enclosed between latitudes 27° 00′ to 28° 00′ S and longitudes 117° 00′ to 117° 45′ E. It includes the eastern part of the batholith defined by Johnson.

The area consists of disconnected areas of rocks metamorphosed to the greenshist facies, folded about axes trending between north and east-northeast and concordantly intruded by intensely foliated granodiorites and adamellites, which in turn have been intruded discordantly by later adamellites and granites.

For the purposes of the age determinations, the granitic rocks were divided simply into "inner granites" (i.e. border facies and internal facies, groups 1 and 2) and "outer granites" (group 3).

Previous age estimates

The only age determinations available for this part of the Archaean of the Yilgarn Block are reported by Compston and Arriens (1968). They indicate ages of 2,615 ± 40 m.y. for granite and 2,920 ± 220 m.y. for the granitic gneiss which it intrudes in the Koolanooka Hills; these are about 100 miles southwest from the Poona-Dalgaranga area. Although no ages had been determined for granitic rocks in the Cue Sheet area, it was thought that possibly the younger granites could have been about the same age as the granite at Koolanooka Hills.

MATERIAL USED

Sampling

The Cue 1 : 250,000 sheet was the only area in the Murchison Goldfield mapped by the Geological Survey in the current mapping programme, by the end of 1968. The radiometric age project was to determine separately the ages of the different textural units of the granitic rocks and thus derive both the ages of the rocks and some clue to the source of magma.

Weathering poses sampling problems in the area and among the granitic rocks few specimens could be collected fresh enough for age determination. Sixteen samples were submitted to check their chemical suitability and to provide a guide for further sampling. Ten samples were selected finally and their locations are shown in Figure 8.

Petrography

All the rocks contain quartz, plagioclase (ranging in composition from albite to andesine) and microcline (often perthitic). The mafic mineral is biotite. Textures range from porphyritic to medium grained with one rock being fine grained. The texture of the even-grained varieties, or in the groundmass of the porphyritic rocks, is allotriomorphic granular.

The "outer granites" (group 3) consist of four granodiorites and one trondhjemite. They have a distinct foliation shown by aligned flakes of biotite and c-axes of quartz and feldspar grains. Evidence of strain indicated by bent and fractured twin planes is present in some grains. Accessory minerals are present in greater quantities than in the "inner" granitic rocks, though the constituent minerals are about the same for both groups (magnetite, apatite, zircon, sphene, allanite and epidote).

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[1] This paper was presented at the Geological Society of Australia Symposium on the Archaean Rocks, held in Perth in May 1970, and is therefore also published in an abridged form in Special Publication No. 3 of the Society.

[2] Geological Survey of Western Australia.

[3] Physics Department, Western Australian Institute of Technology.

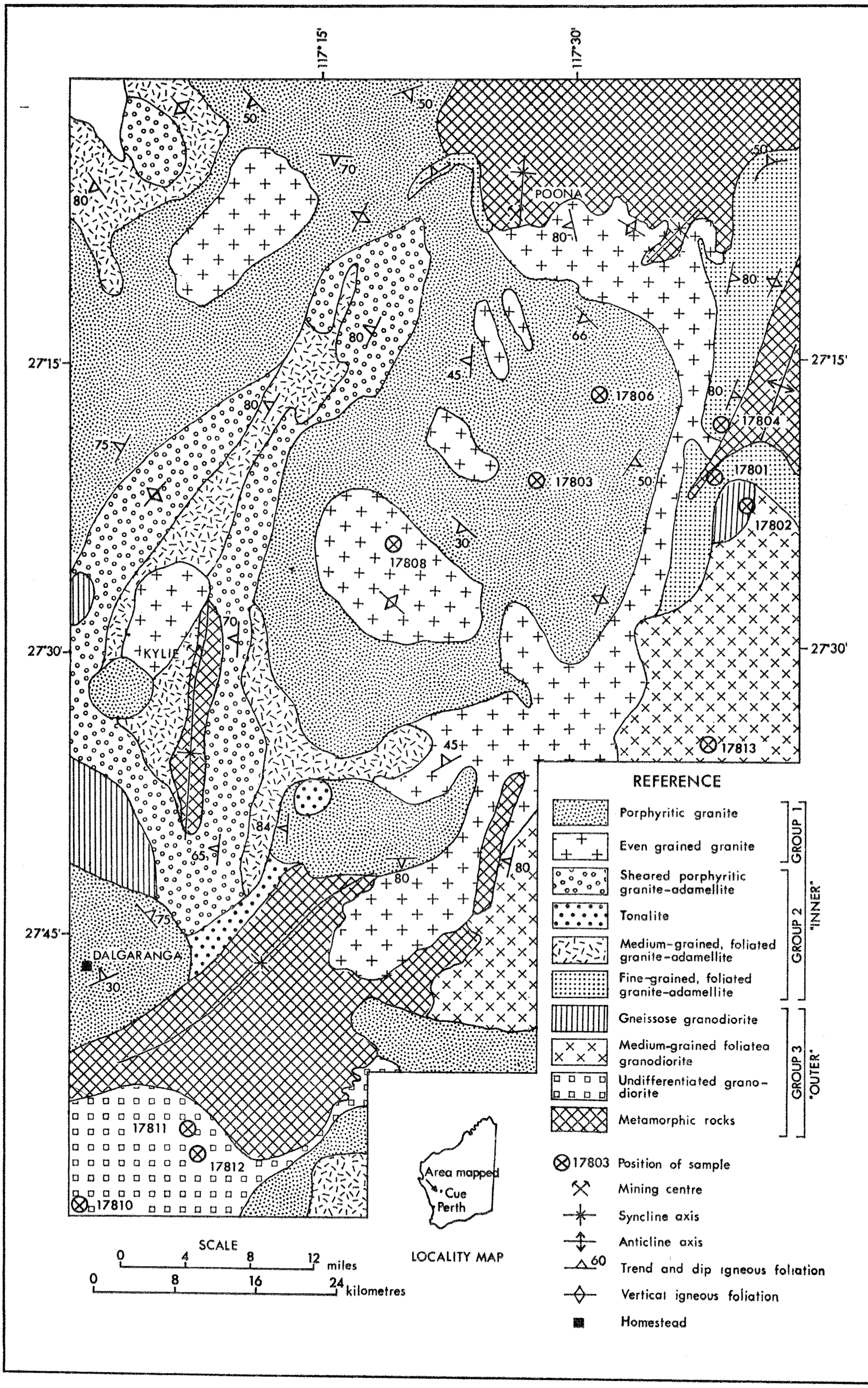

Fig. 8 Geological map of the Poona-Dalgaranga area

The "inner" granitic rocks (from the internal and border facies rocks) are granites or adamellites in which foliation is poor or absent and much of the biotite is altered to chlorite. Microcline has tended to include or replace earlier minerals, rather than lie interstitial to them, as in the first group. The porphyritic granite of specimen 17803 is unusually rich in potassium feldspar compared with the other granites.

A summary of the petrographic characteristics of these rocks is set out in Table 1 and the modes are shown in Table 2.

TABLE 1. SUMMARY OF CHARACTERISTICS OF TYPES OF GRANITIC ROCKS ON THE CUE 1 : 250,000 SHEET AREA

Groups and Subdivisions			Summary of Characteristics
"INNER"	INTERNAL FACIES OR GROUP 1	Porphyritic granite	Pale pink, medium to coarse-grained granite with phenocrysts ½ to 5 inches long. A platy flow foliation parallels contacts with other rocks. Intrusive into medium-grained granite
		Medium-grained granite	Some porphyritic margins, gradational to even-grained granite. Platy foliation of schlieren, feldspar crystals or biotite crystals. Other parts of granite massive. Intrusive into all border facies rocks
	BORDER FACIES OR GROUP 2	Sheared, porphyritic granite-adamellite	Square or rectangular feldspar phenocrysts (some distorted) set in an intensely foliated groundmass (with quartz lenticles). Intrusive into medium-grained, foliated granite-adamellite
		Medium-grained foliated granite-adamellite	Light grey to white, some parts with streaks of biotite. A distinct foliation of quartz and feldspar grains
		Foliated, micro-granite-adamellite	Contact is conformable with country rock. Locally intrusive into country rock. Most of this rock is foliated, but some is massive
		Contaminated granitic rocks	(a) Grey tonalite ; xenoliths of quartz ; feldspar and biotite (b) Lenses and flakes of biotite with microline phenocrysts in a pale pink, medium-grained groundmass
"OUTER"	GROUP 3	Medium-grained, foliated granodiorite	A mixture of medium-grained and coarse-grained, foliated rocks with sheared porphyritic granodiorite. A distinct foliation of quartz, feldspar and biotite. Very few pegmatites
		Gneissose granodiorite	A mixture of fine-grained, foliated and medium-grained foliated granodiorites. Banded textures with bands of biotite and pegmatites cut by foliation

TABLE 2. MODES OF SAMPLES (VOLUME BY PER CENT)

Classification : OUTER (Group 3)

Sample No.	17802	17810	17811	17812	17813
Quartz	35	26	18	41	17
Plagioclase	51	56	66	40	66
K-Feldspar	3	13	7	11	6
Biotite	11	5	9	8	9
Magnetite	x	x	x	x	2
Apatite	x		x	x	x
Zircon	x	x	x	x	x
Sphene					x
Allanite		x	x		x
Epidote			x		

Classification : INNER (Groups 1 and 2)

Sample No.	17801	17804	17806	17808	17803 (a)	17803 (b)
Quartz	28	27	26	30	15	25
Plagioclase	39	27	19	21	18	5
K-Feldspar	30	32	52	45	57	60
Biotite	3	14	2	4	10	10
Magnetite	x	x	1	x	x	x
Apatite	x	x	x	x		
Zircon	x		x	x		
Sphene						x
Allanite				x		
Epidote	x			x	x	x

NOTE : 17803 (a) is a fine-grained granite
17803 (b) is a porphyritic granite from the same specimen
x Mineral present

RESULTS

The experimental procedures used were essentially the same as those described by de Laeter and Trendall (1971).

The measured Rb-Sr and Sr^{87}/Sr^{86} ratios, as well as the Rb^{87}/Sr^{86} ratio calculated from them are given in Table 3 for the Cue "inner" and "outer" granitic rocks. Errors in both groups are at the 95 per cent confidence level.

TABLE 3. ANALYTICAL DATA FOR THE CUE SHEET GRANITIC ROCKS

CUE "INNER" GRANITIC ROCKS

Sample No.	Rb-Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
17801 B	0·223 ± 0·003	0·645 ± 0·006	0·7258 ± 0·0009
17801 A	0·965 ± 0·008	2·81 ± 0·03	0·8070 ± 0·0014
17808	1·672 ± 0·017	4·91 ± 0·05	0·8890 ± 0·0025
17804	2·665 ± 0·020	7·91 ± 0·08	0·9938 ± 0·0028
17806 A	4·76 ± 0·05	14·43 ± 0·15	1·2206 ± 0·0028
17803 A	3·29 ± 0·03	9·76 ± 0·10	0·9832 ± 0·0020
17803 B	4·69 ± 0·05	14·12 ± 0·14	1·1438 ± 0·0014
Composite	3·99	11·94	1·0635

Age 2,590 ± 23 m.y. Initial Sr^{87}/Sr^{86} = 0·7028 ± 0·0010

CUE "OUTER" GRANITIC ROCKS

Sample No.	Rb-Sr	Rb^{87}/Sr^{86}	Sr^{87}/Sr^{86}
17813	0·0735 ± 0·001	0·212 ± 0·002	0·7108 ± 0·0008
17811	0·279 ± 0·003	0·808 ± 0·008	0·7356 ± 0·0020
17810	0·330 ± 0·003	0·956 ± 0·010	0·7368 ± 0·0025
17802	0·583 ± 0·006	1·69 ± 0·02	0·7630 ± 0·0023
17812	0·931 ± 0·009	2·71 ± 0·03	0·8035 ± 0·0014

Age 2,605 ± 51 m.y. Initial Sr^{87}/Sr^{86} = 0·7031 ± 0·0009

The isochrons for each group (Figure 9) were derived by the method of Williamson (1968), which minimises the weighted sum of the squared residuals. Age calculations are based on an Rb^{87} decay constant of $1 \cdot 39 \times 10^{-11}$ $year^{-1}$. The errors associated with the age and initial Sr^{87}/Sr^{86} ratio are calculated from the standard deviation of the slope and intercept respectively.

The age for the Cue "inner" granites is 2,590 ± 23 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0·7028 ± 0·0010. The points representing samples 17803A and B do not lie on the isochron. Mapping has suggested these granites to be the same age as the surrounding rocks and therefore a leakage of Sr^{87} or a late addition of Rb may be responsible for this result.

The Cue "outer" granites have an age of 2,605 ± 51 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0·7031 ± 0·0009. The combined age of the Cue "inner" and "outer" granitic rocks was computed to be 2,590 ± 20 m.y. with an initial Sr^{87}/Sr^{86} ratio of 0·7031 ± 0·0006.

DISCUSSION

The division of the Cue Sheet granitic rocks into "inner" and "outer" groups appears to reflect a general difference in Rb-Sr ratios, with the "inner" group having higher ratios than the "outer". No consistent relationship is evident between the present Sr^{87}/Sr^{86} ratios and the composition of the rocks within each group. Both groups include a wide range in texture and composition (granite-granodiorite), yet with the exception of 17803 the analyses of the members of each group plot on or near their respective isochrons.

The outer granites, which appear from mapping to be older than the inner group of granites, also have a slightly older indicated age. However, because of the errors associated with the methods used, both groups are essentially coeval on the isotopic evidence.

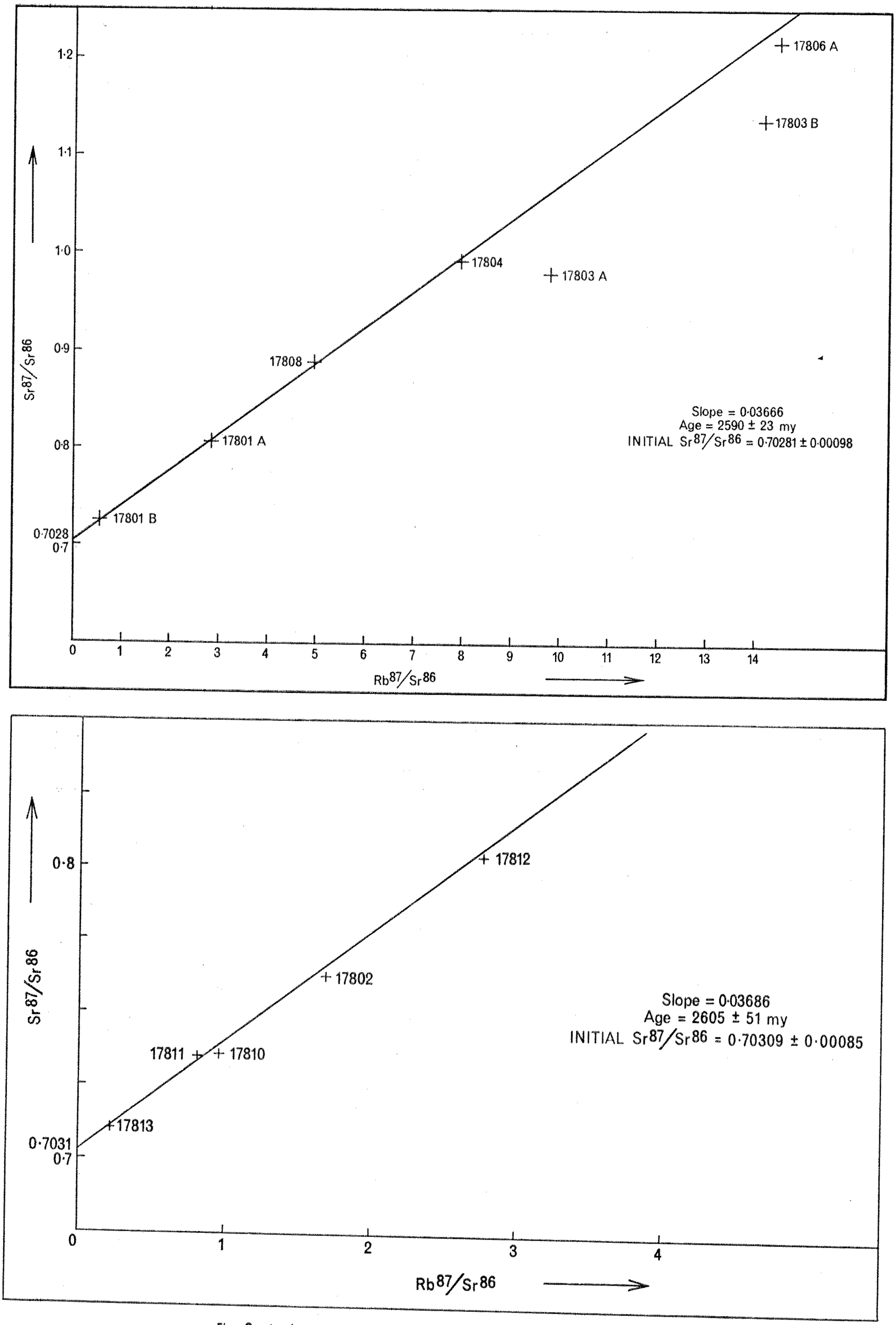

Fig. 9 Isochron plots for the data of Table 3. The top diagram is for the Cue "inner" granitic rocks; the bottom diagram for the "outer" granitic rocks.

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Compston and Arriens (1968) distinguish two main episodes of granite emplacement for Western Australia: "3,050 m.y. to 2,900 m.y. and from 2,750 m.y. to 2,600 m.y.; the time range of the younger is definitely real. Isolated granitic rocks were emplaced a little later than 2,600 m.y. or have been updated slightly by later metamorphism". The Cue Sheet granitic rocks appear to belong to this younger period of granite emplacement in the Archaean of Western Australia.

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APPENDIX 1

PETROGRAPHY OF SAMPLES

GROUP 3—THE "OUTER" GRANITIC ROCKS

17802:

This specimen is from an area of gneissic textured rocks. It is a medium-grained granodiorite with a distinct foliation of biotite grains. The texture is allotriomorphic granular. Plagioclase has little twinning though a few grains have albite and Carlsbad twins. Most grains are mildly zoned and the average composition is oligoclase (An_{24}). The average grain diameter is 1·37 mm. Microcline has poor twinning and a few grains have myrmekite borders against plagioclase. About half of the biotite has been altered to chlorite. Irregular grains of quartz are interstitial to all other minerals and some grains have a shadowy extinction.

17810:

It is one of the third group (Table 1): a medium-grained granodiorite with an allotriomorphic granular texture. A foliation is defined by biotite grains. Fine-grained aggregates of quartz, microcline and plagioclase (with myrmekite) are interstitial to, or enclosed by, medium-grained crystals of the same minerals. Plagioclase (oligoclase An_{25}) is anhedral and in two sizes: 1·8 x 1·0 mm to 3·0 x 2·5 mm and 0·2 x 0·2 mm. It is fresh, has curved albite twinning and a zoned extinction. Anhedral perthitic microcline crystals are bounded by aggregates of fine-grained plagioclase and myrmekite. Long, sinuous aggregates of quartz (with uniform optical orientation) fill interstices and are approximately parallel to the trend of biotite flakes.

17811:

Specimen 17811 is a porphyritic granodiorite with a foliation shown by biotite grains (not all aligned). Phenocrysts of both microcline and plagioclase range up to 5·2 x 7·7 mm. The groundmass grains vary from an average grain diameter of 0·4 mm to 0·9 mm and are of two elements: patches of medium-grained quartz and plagioclase as well as fine-grained interstitial patches of myrmekite and untwinned plagioclase. Myrmekite is confined to the areas of fine-grained crystals. The plagioclase is zoned but most seems to be oligoclase (An_{15}). Perthitic microcline occurs mainly as very poorly twinned anhedral phenocrysts. Signs of stress are: slip along biotite cleavage planes, extinction shadows in quartz, curved twin planes in plagioclase, and trains of fine-grained crystals around plagioclase phenocrysts. There are more accessory minerals than in 17801, 17802 or 17810.

17812:

This is a porphyritic granodiorite. A foliation is shown by quartz and biotite. Grains range in size from 4·2 x 2·6 mm (phenocrysts) to 0·1 x 0·1 mm (groundmass). This rock has been sheared more than any other described here. Anhedral phenocrysts of poorly twinned microcline and oligoclase (An_{18}), with lenticular aggregates of quartz grains are set in a groundmass of microcline, oligoclase and quartz with trains of biotite crystals. The aggregates of quartz are elongated parallel to the foliation, range from 0·9 x 0·4 mm to 0·4 x 0·2 mm, and show a moderately undulose extinction.

17813:

This was collected from an area of medium-grained, foliated granodiorite, east of Mount Charles. The texture is allotriomorphic granular with a foliation of aligned quartz, feldspar and biotite. Anhedral, oval plagioclase grains (oligoclase An_{21}), rounded microcline crystals and aggregates of quartz are separated from each other by short trains of fine-grained quartz, feldspar and myrmekite. Most grains have few inclusions. Oligoclase grains range in size from 3·0 x 2·5 mm to 0·3 x 0·3 mm, have a mildly zoned extinction and poor twinning. Microcline crystals have a zoned extinction and poorly developed twinning which is seen only on crystal edges. Lenticular aggregates of quartz whose individual grains have rounded edges are oriented parallel to the foliation.

GROUPS 1 AND 2—THE "INNER" GRANITIC ROCKS

17801:

This is a porphyritic adamellite from a narrow migmatite zone on the east side of the metamorphic rocks at Big Bell. A foliation visible in both hand specimen and thin section is formed by aligned biotite, plagioclase crystals and lines of quartz grains with shadowy extinction. Anhedral phenocrysts of plagioclase (ranging from 4·9 x 2·6 mm to 1·9 x 1·9 mm) are set in an allotriomorphic granular groundmass of plagioclase, microcline-perthite, quartz and biotite. The phenocrysts are equidimensional and are not aligned parallel to the foliation in the groundmass. The plagioclase is oligoclase (An_{14}), zoned to rims of albite (An_6), where next to microcline perthite; it has albite twinning and has been replaced in patches by microcline. The twin planes of some grains are curved. Perthitic microcline occurs as phenocrysts, but mainly in the groundmass. Cross-hatched twinning is well developed. Quartz forms lines of anhedral grains (4 mm in diameter) or occurs as single elongate grains up to 1·9 mm long. Biotite is interstitial to all other minerals and some is altered to chlorite.

17803:

This specimen was taken from a contact between a porphyritic granite rock, rich in biotite, and a fine-grained granite.

(a) *Fine-grained granite:* The texture is allotriomorphic granular. Anhedral well twinned fresh grains of albite (An_3) have an average size 0·9 x 0·6 mm. Some twin planes are bent or displaced along shears. Anhedral microcline grains (with very few albite inclusions) are fresh and poorly twinned. Their size varies from 0·6 x 0·4 mm to 1·4 x 0·8 mm. Quartz occurs as irregular grains up to 1·4 mm long, with ragged edges. Biotite has formed lines and clusters of crystals.

(b) *Porphyritic granite:* Closely packed phenocrysts of microcline are separated from each other by quartz, biotite, plagioclase and large irregularly shaped areas of quartz up to 11·2 mm long. The groundmass grains vary from 0·4 x 0·4 mm to less than 0·05 x 0·05 mm. Anhedral microcline grains range from 5·6 x 2·8 mm (phenocrysts) down to 0·8 x 0·4 mm. Anhedral grains of accessory plagioclase (andesine An_{33}) show fractured twin planes. A foliation is present, marked by lines of biotite crystals parallel to the contact with the fine-grained granite.

17804:

This specimen is a well foliated, porphyritic adamellite from a lens enclosed in the fine-grained, foliated granite. Square and rectangular phenocrysts of microcline, with short tails and stringers up to 11·0 mm long of optically continuous quartz are set in a groundmass of quartz, plagioclase, microcline and biotite. The plagioclase crystals are anhedral, about half the grains are twinned and some twin planes are bent. Some grains, where next to microcline, are zoned from a core of oligoclase (An_{14}) to a rim of albite (An_5). The microcline is a string and replacement type perthite with phenocrysts up to 11·2 x 5·6 mm with irregular edges, or as groundmass crystals (0·4 x 0·4 mm). It is well twinned in the quadrille pattern. The long stringers of quartz show little undulose extinction, and parallel the foliation together with biotite and some of the microcline-perthite phenocrysts. The biotite is interstitial to all other minerals. The texture shows evidence of stress but little granulation.

17806:

This porphyritic granite was collected from near the Wolfram prospect at Callie Soak. Anhedral phenocrysts of perthitic microcline and oligoclase (An_{28}) are set in a groundmass of both of the feldspars, biotite and quartz. The microcline-perthite ranges from 3·5 x 3·0 mm to 0·4 x 0·3 mm and has good cross-hatched twinning. The largest grains of oligoclase are 1·9 x 1·5 mm but most are 0·6 mm in diameter, have poor albite twinning and have been partially replaced by microcline parallel to 010. Most crystals show reverse zoning to rims of andesine (An_{33}). Quartz forms large irregular blobs filling areas between feldspar crystals.

17808:

It is a medium-grained granite. The texture is allotriomorphic granular, with a poorly developed foliation shown by alignment of biotite flakes. Anhedral grains of oligoclase are zoned to rims of albite, where against microcline, and these rims are wider than those seen in other specimens. The grain size ranges up to 5·4 x 2·7 mm though the average size is 2·0 x 2·0 mm and there is a little faint albite twinning. Perthitic microcline (with bands and stringers of plagioclase) ranges in size from 7·4 x 3·0 mm to 0·6 x 0·6 mm. Quartz grains have a very irregular shape and undulose extinction.

INDEX

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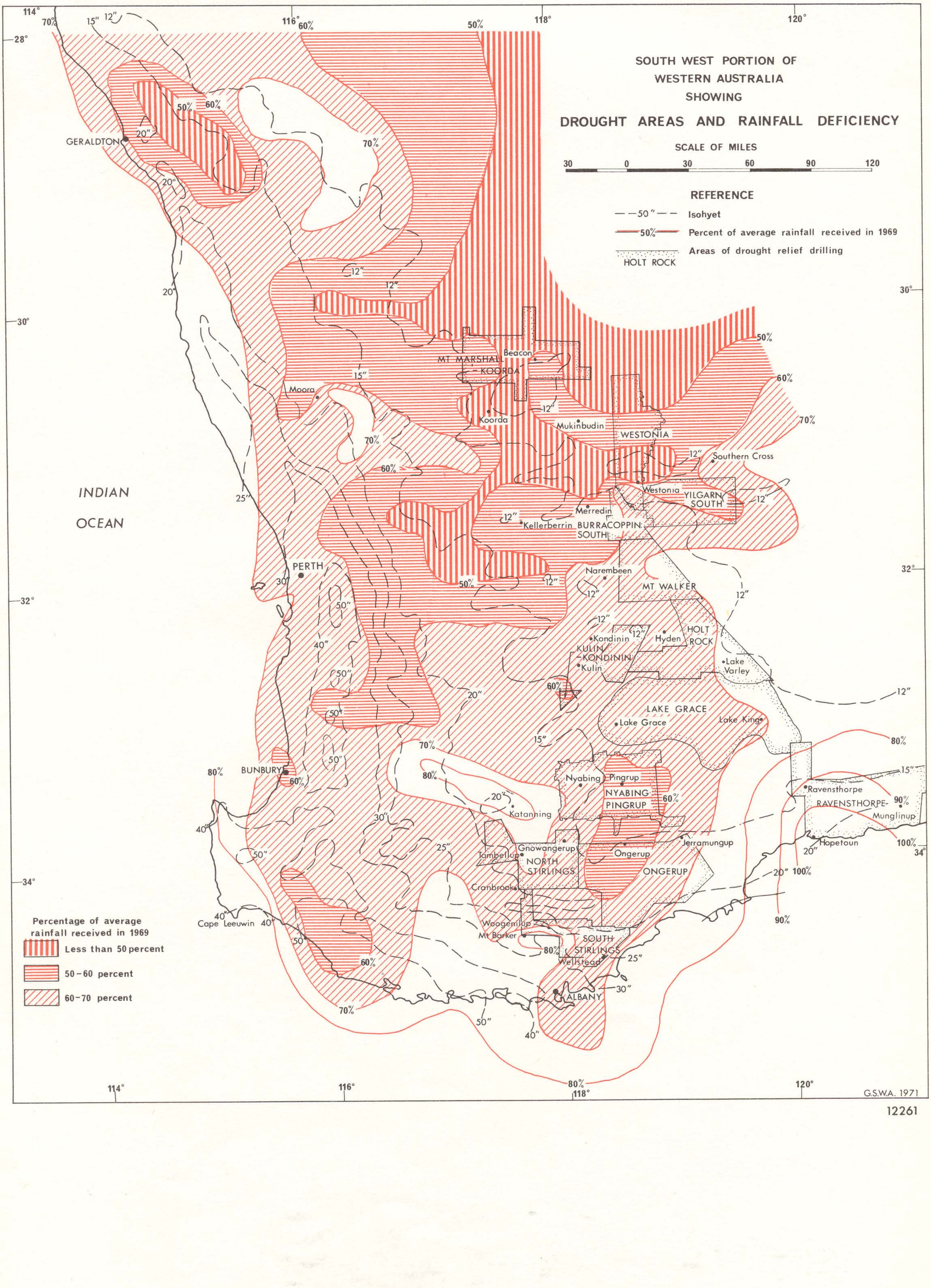
PLATE 1



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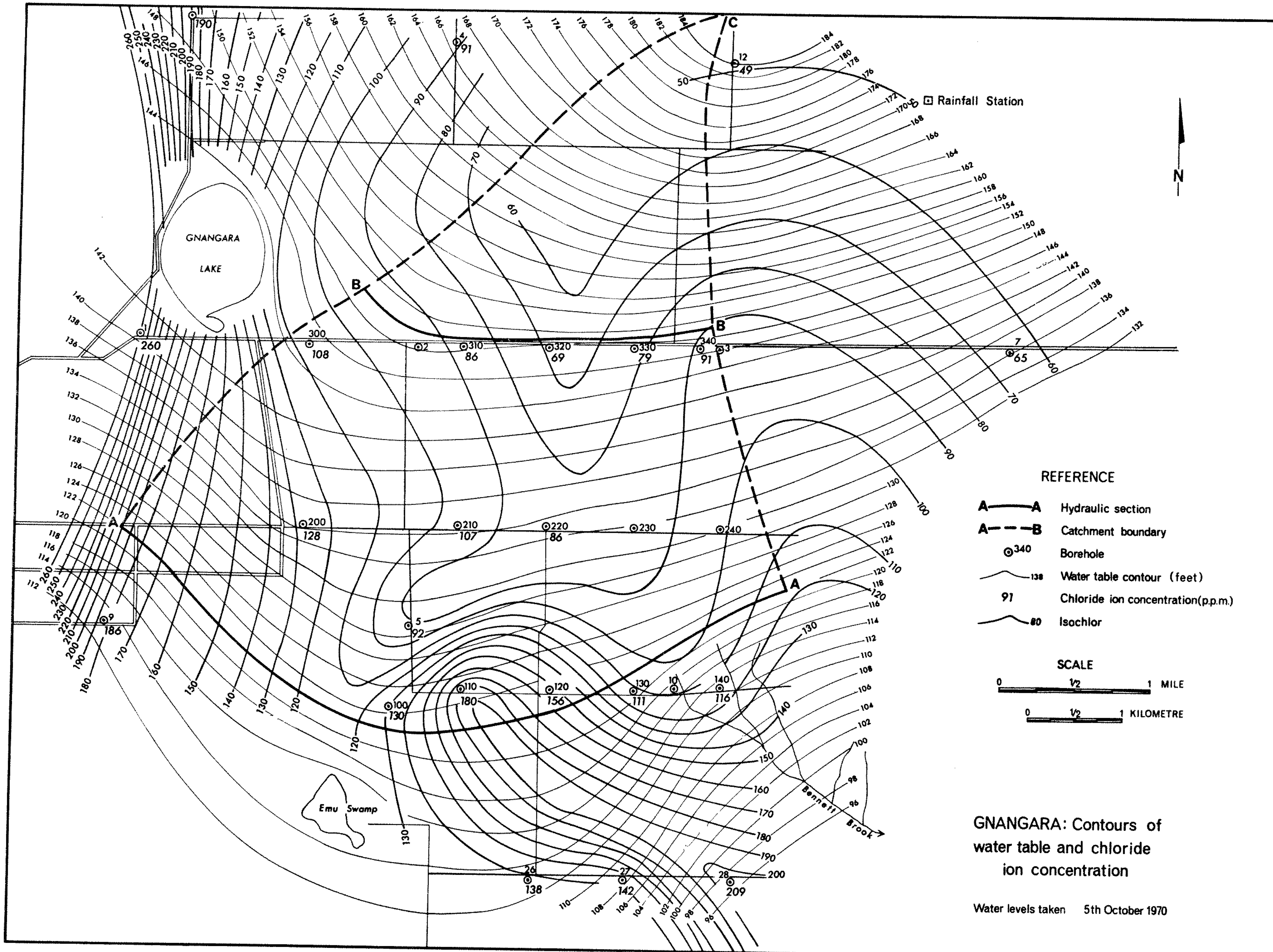

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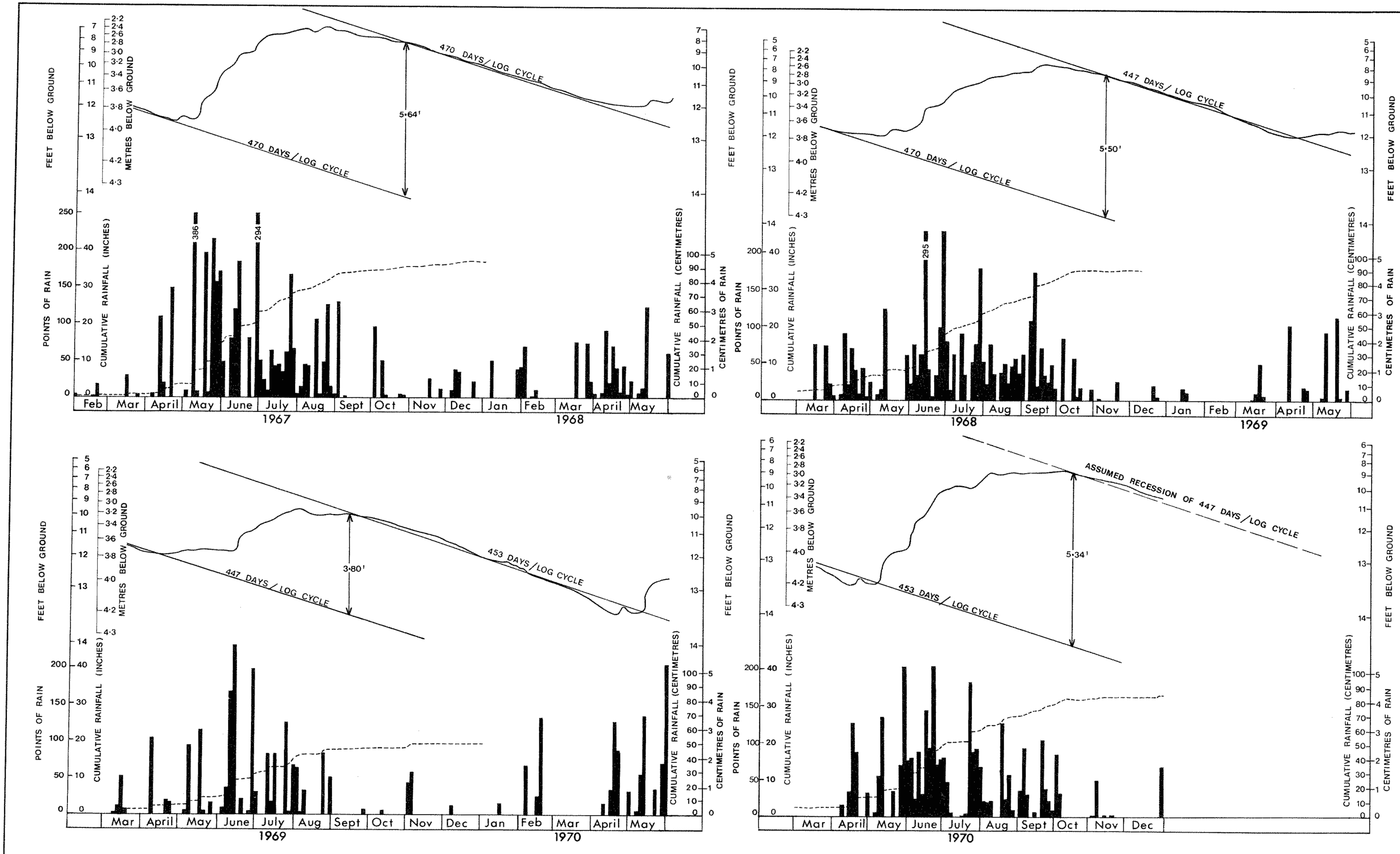

PLATE 3

GNANGARA NO 5 BOREHOLE: HYDROGRAPHS FOR 1967 – 1970 AND RAINFALL HYPSOGRAMS

12266

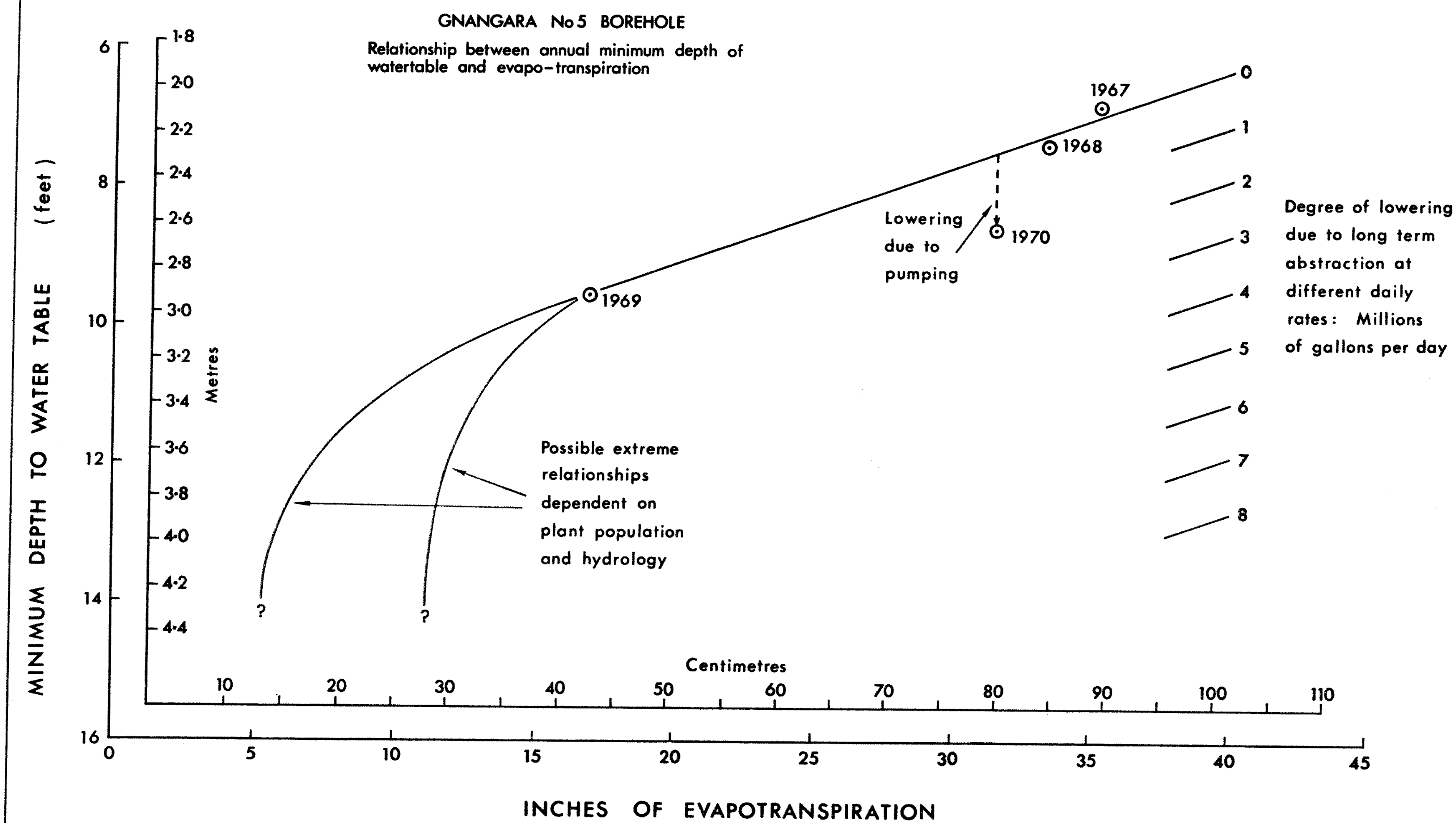

PLATE 4

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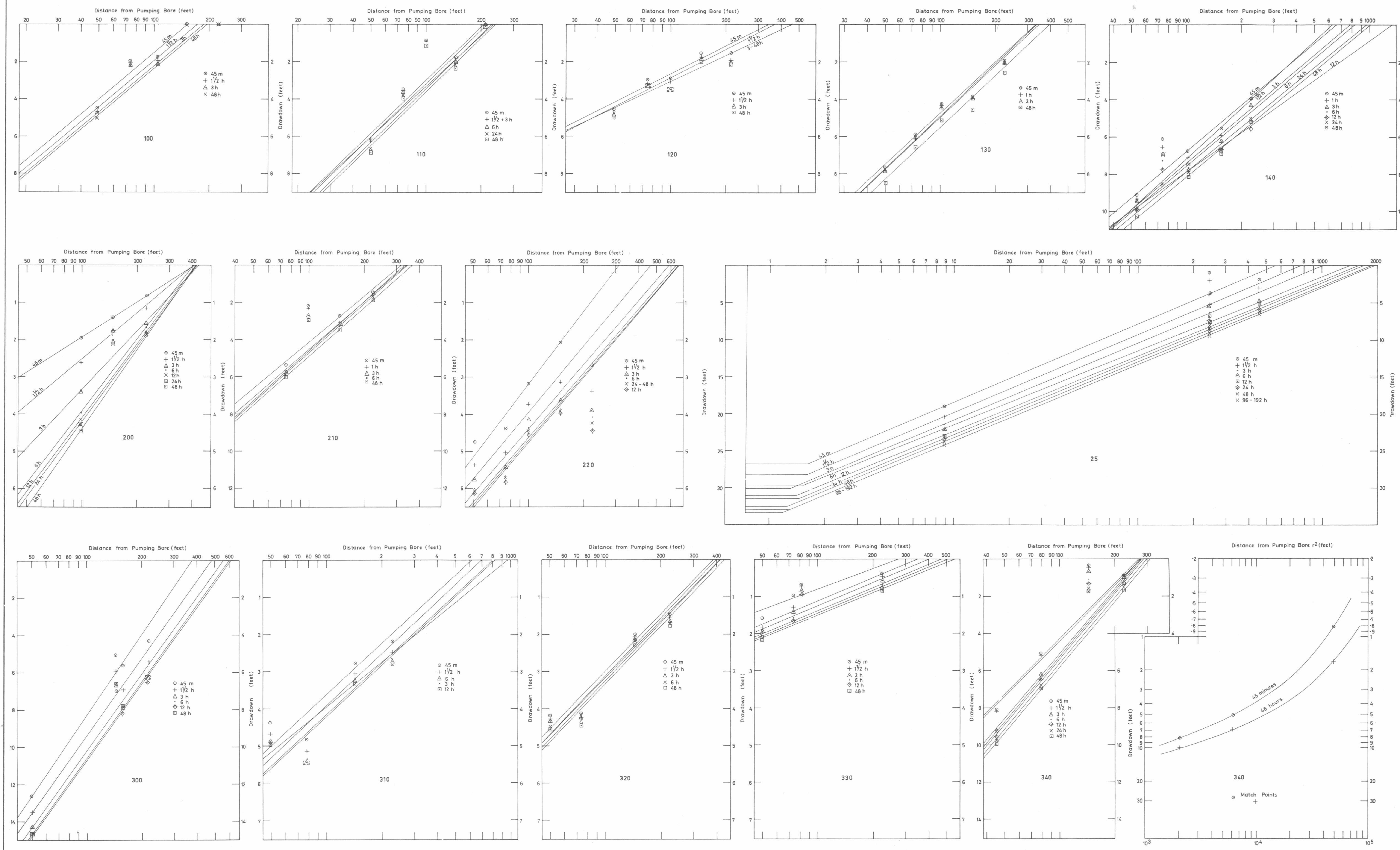
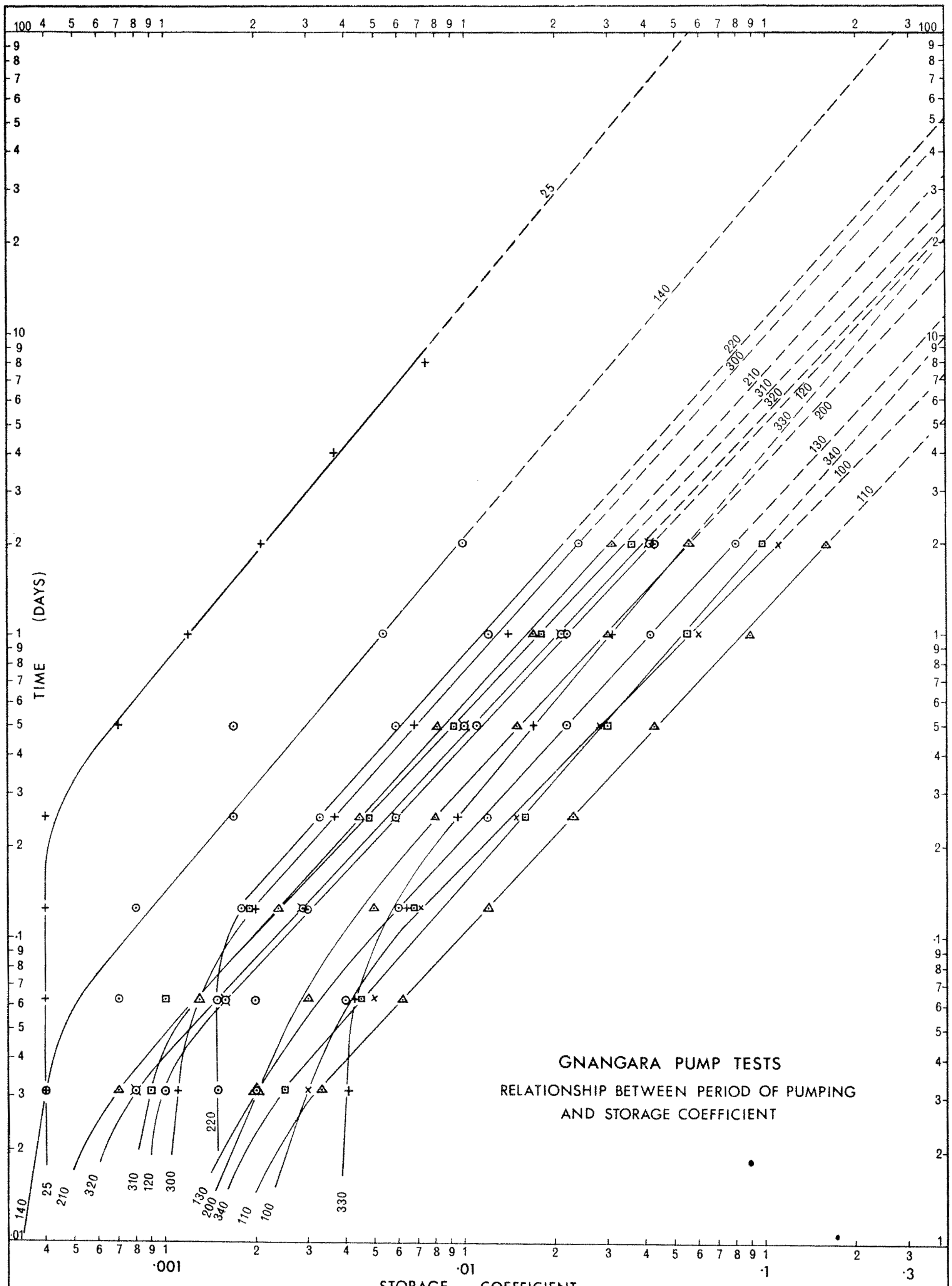


DISTANCE - DRAWDOWN PLOTS FOR GNANGARA BOREHOLES


GNANGARA PUMP TESTS
RELATIONSHIP BETWEEN PERIOD OF PUMPING
AND STORAGE COEFFICIENT
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STORAGE COEFFICIENT
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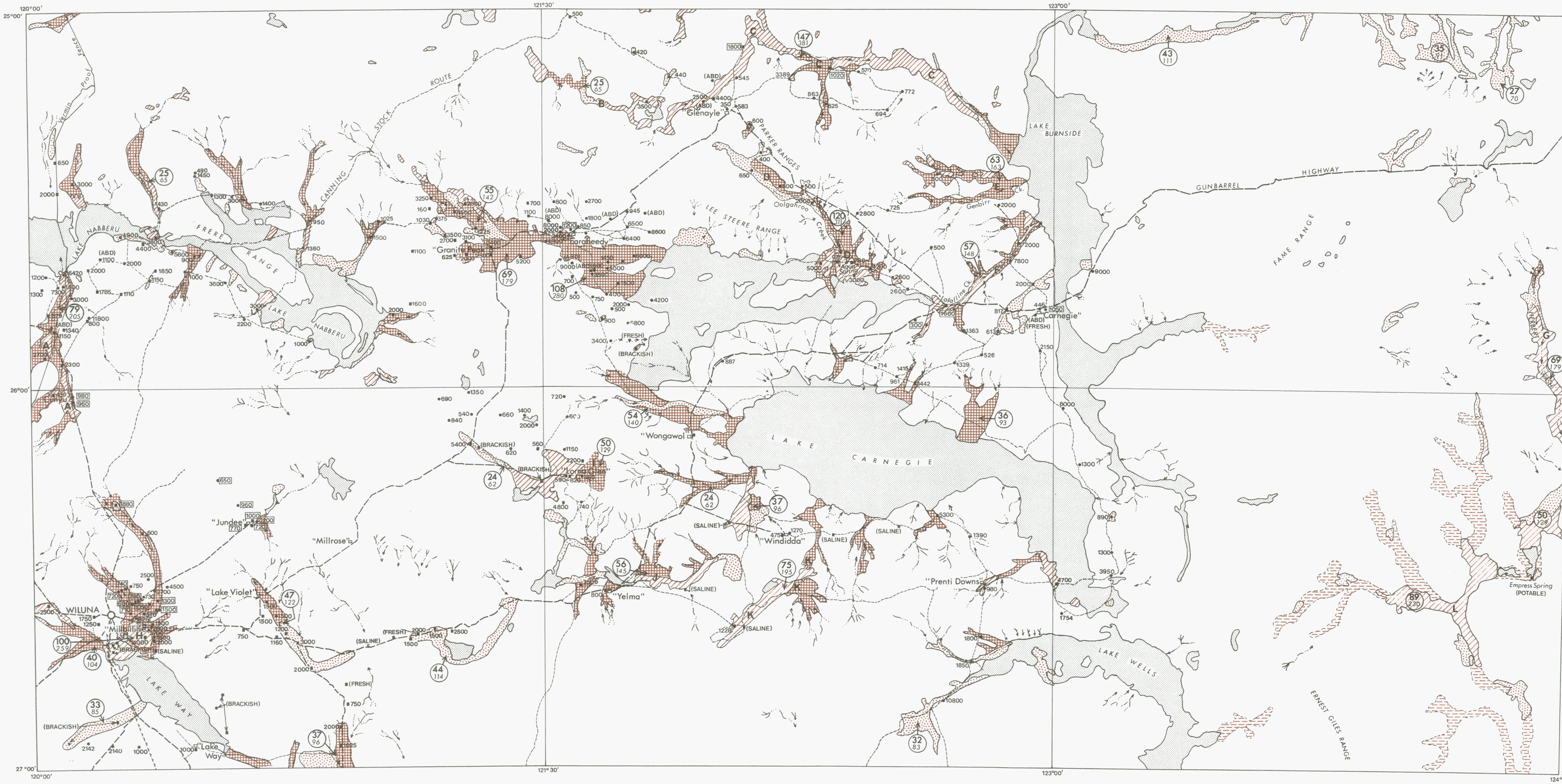
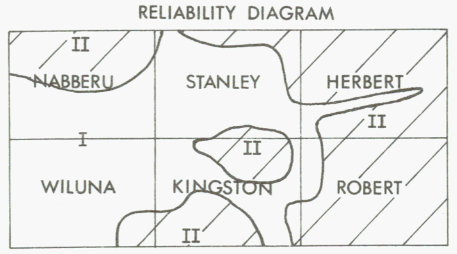


RELIABILITY DIAGRAM



I. Compiled from mapping, hydrological census and reconnaissance traverses.

II. Compiled from photo-geological interpretation and few reconnaissance traverses.

INDEX TO ADJOINING SHEETS

COLLIER	BULLER	TRAINOR	MADLEY	WARRI
PEAK HILL	NABBERU	STANLEY	HERBERT	BROWNE
GLENGARRY	WILUNA	KINGSTON	ROBERT	YOWALGA
SANDSTONE	SIR SAMUEL	DUKETON	THROSSELL	WESTWOOD

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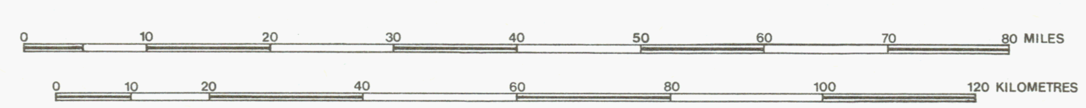


GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ALLUVIAL AND CALCRETED DRAINAGES

EAST MURCHISON AND MT. MARGARET GOLDFIELDS

NABBERU MINING DISTRICT

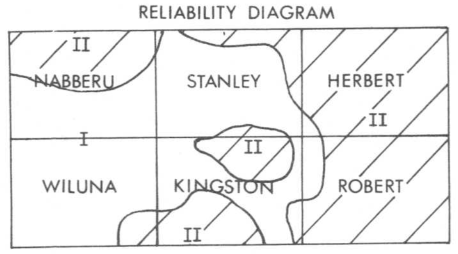
To accompany report by C.C.Sanders and A.S.Harley. 1970

REFERENCE

- Alluvium
- Probable Alluvium
- Interpreted Desert Drainage Lines
- Massive Calcrete
- Minor and patchy calcrete with alluvium
- Lacustrine deposits (mainly saline)
- 56/145 — Areal extent of calcrete and alluvium catchment in square miles (square kilometres) over 25 square miles (65 square kilometres)
- "Jundee" — Homestead
- Major road
- Minor road
- Drainage trend
- O — Town
- 740 — Well, salinity (ppm. T.D.S.) by conductivity. Govt. Chem. Labs.
- 230 — Bore, salinity (ppm T.D.S.) by conductivity. Govt. Chem. Labs.
- 1740 — Well, field salinity (ppm. T.D.S.)
- 1390 — Bore, field salinity (ppm. T.D.S.)
- E — Major catchment area. For potential recharge estimate (table I)

LOCALITY DIAGRAM

RELIABILITY DIAGRAM



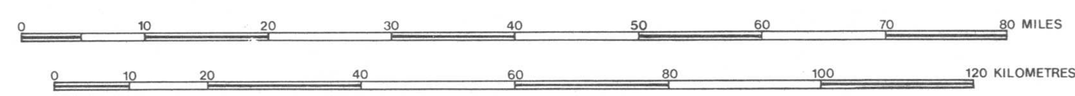
I. Compiled from mapping, hydrological census and reconnaissance traverses.

II. Compiled from photo-geological interpretation and few reconnaissance traverses.

INDEX TO ADJOINING SHEETS

COLLIER	BULLER	TRAINOR	MADLEY	WARRI
PEAK HILL	NABBERU	STANLEY	HERBERT	BROWNE
GLENGARRY	WILUNA	KINGSTON	ROBERT	YOWALGA
SANDSTONE	SIR SAMUEL	DUKETON	THROSSELL	WESTWOOD

SCALE 1:1,000,000



REFERENCE

Undifferentiated Permian and Mesozoic
Ordovician
Dolerite intrusion
Proterozoic
Archaean

"Jundee" Homestead
Major road
Minor road
Drainage trend
Town

LOCALITY DIAGRAM

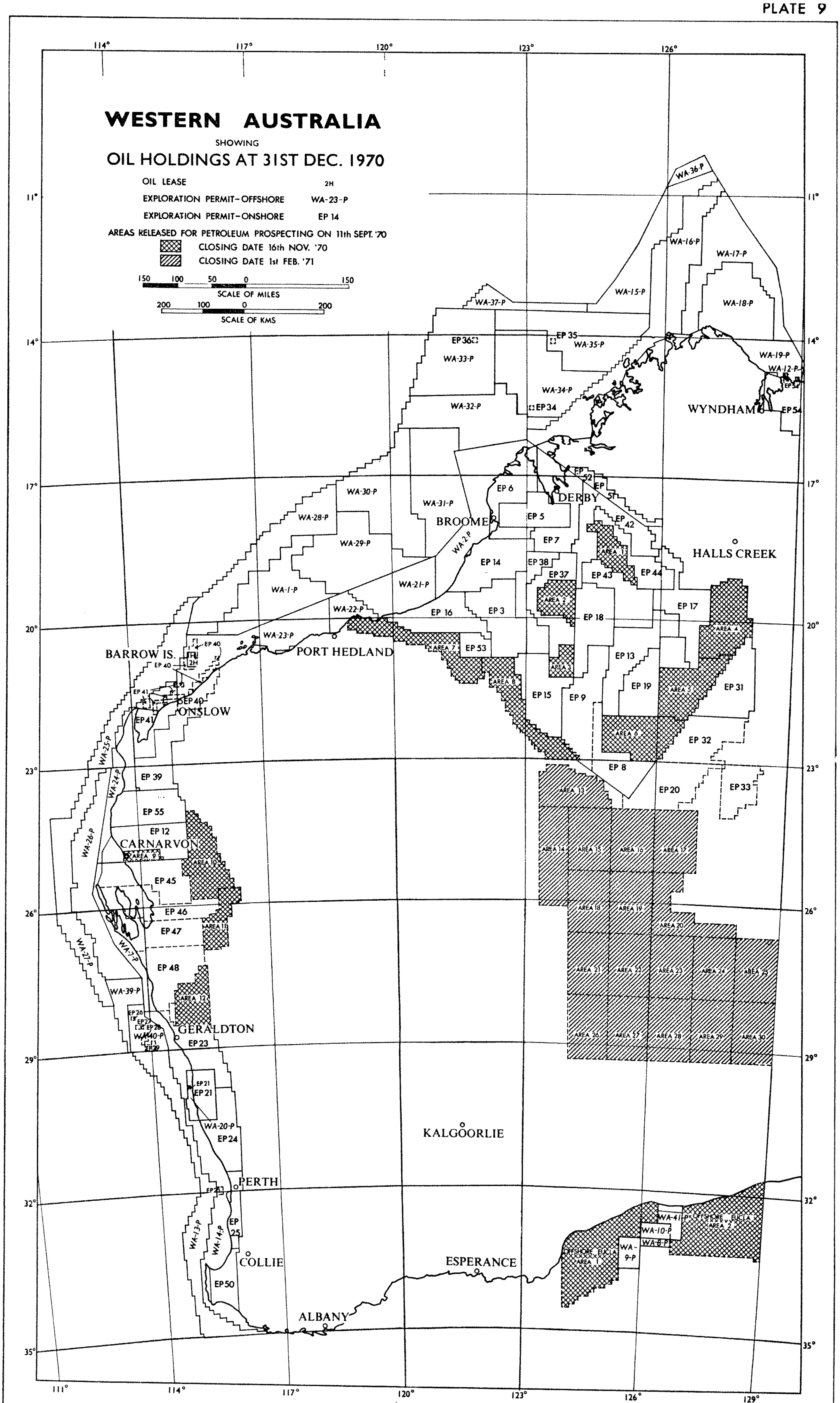
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

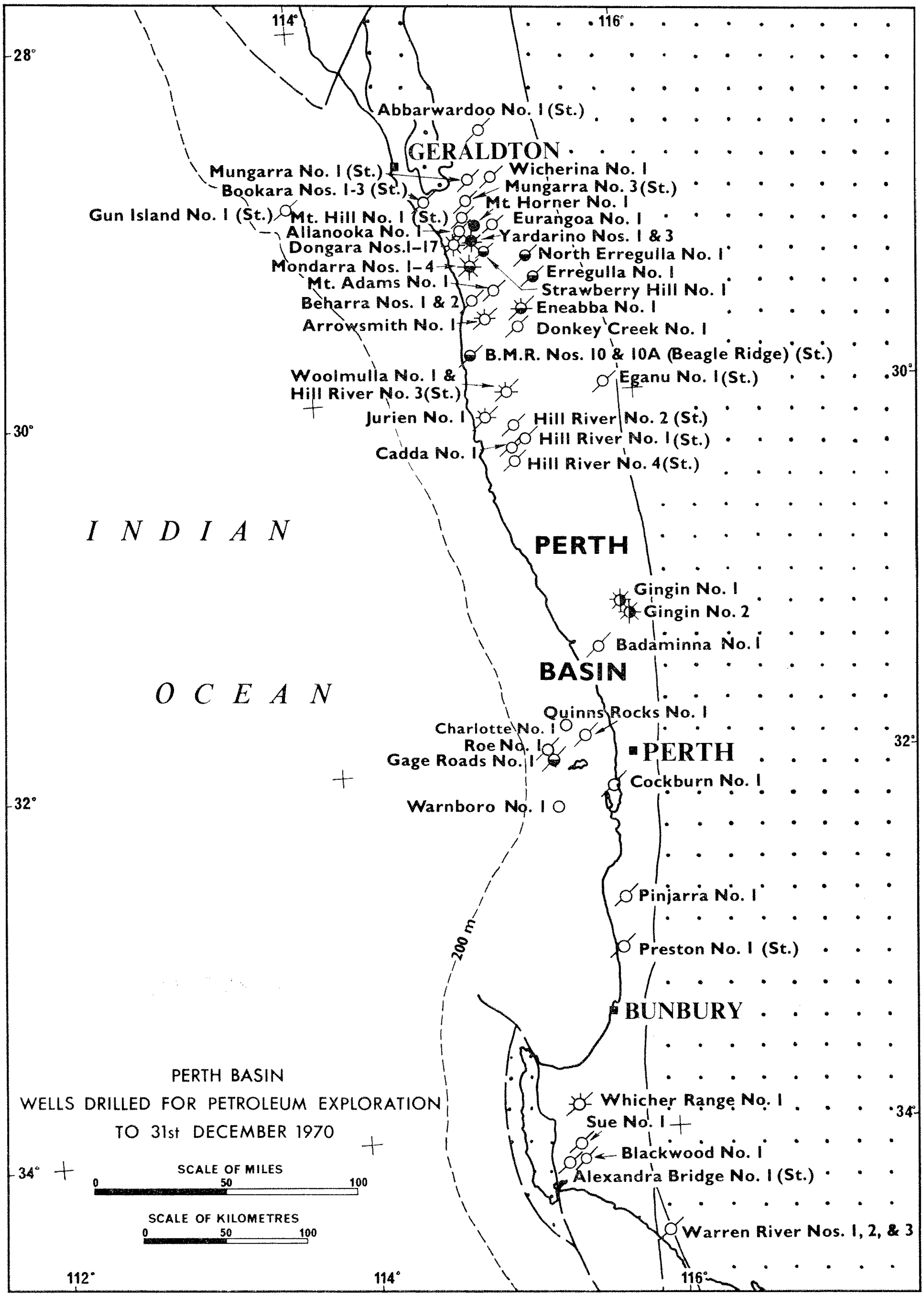
PRE-CAINOZOIC SOLID GEOLOGY

EAST MURCHISON AND MT. MARGARET GOLDFIELDS
NABBERU MINING DISTRICT

To accompany report by C.C. Sanders and A.S. Harley. 1970

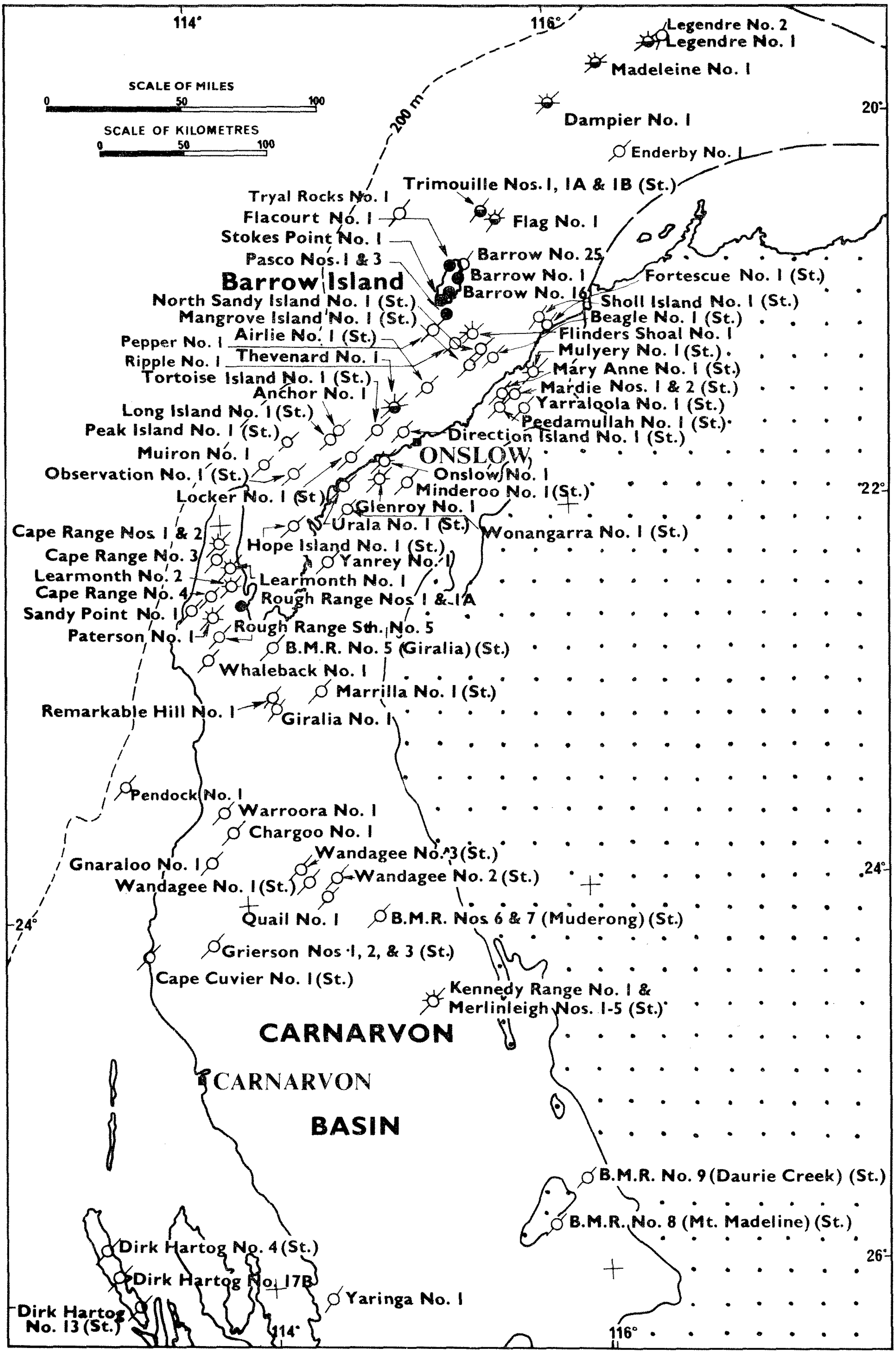
12268


WESTERN AUSTRALIA
SHOWING
OIL HOLDINGS AT 31ST DEC. 1970
OIL LEASE 2H
EXPLORATION PERMIT-OFFSHORE WA-23-P
EXPLORATION PERMIT-ONSHORE EP 14
AREAS RELEASED FOR PETROLEUM PROSPECTING ON 11th SEPT. '70
CLOSING DATE 16th NOV. '70
CLOSING DATE 1st FEB. '71
SCALE OF MILES
SCALE OF KMS
WYNDHAM
DERBY
BROOME
HALLS CREEK
PORT HEDLAND
BARROW IS.
ONSLOW
CARNARVON
GERALDTON
KALGOORLIE
PERTH
COLLIE
ESPERANCE
ALBANY



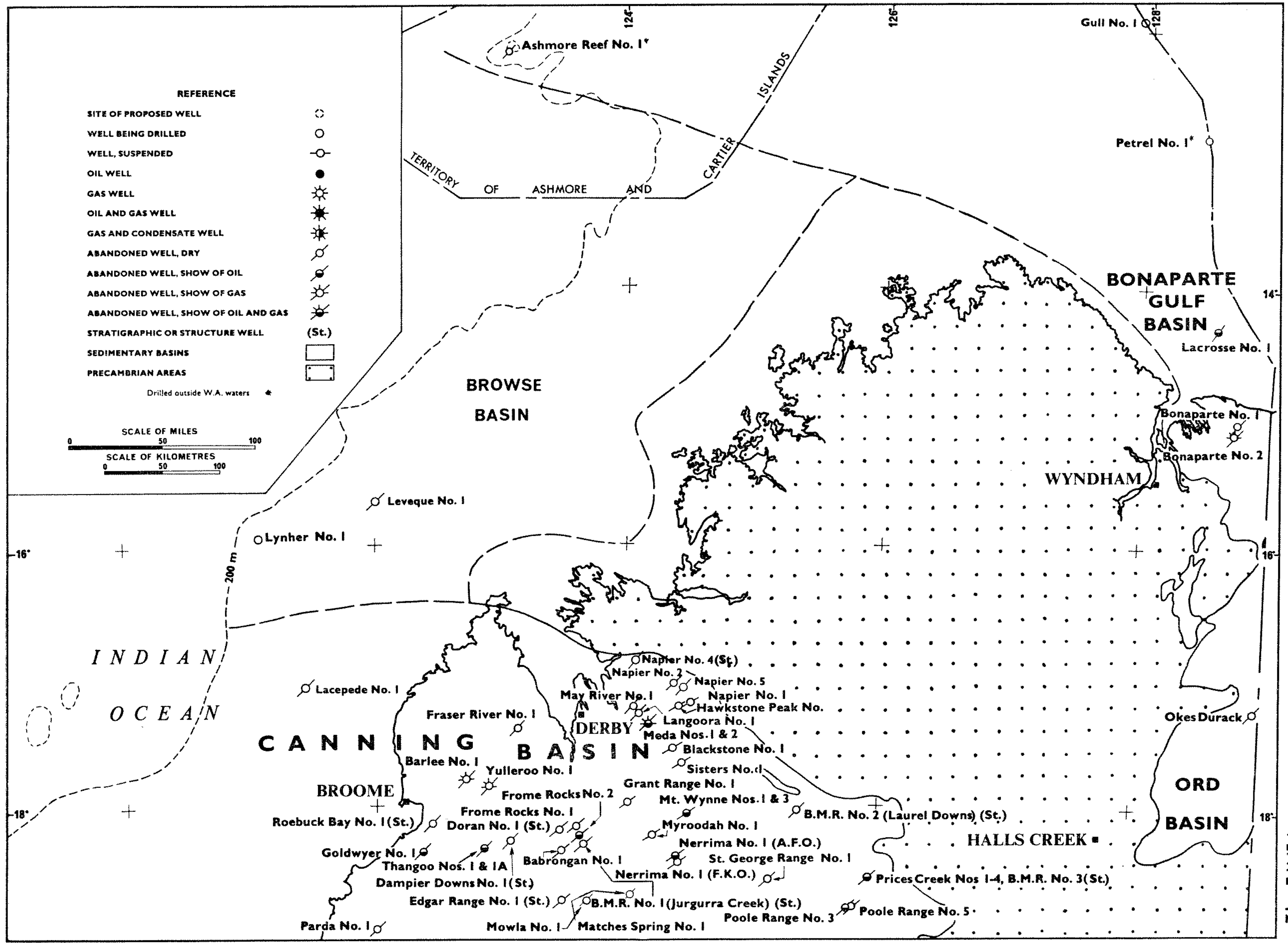
PERTH BASIN
WELLS DRILLED FOR PETROLEUM EXPLORATION
TO 31st DECEMBER 1970

12270

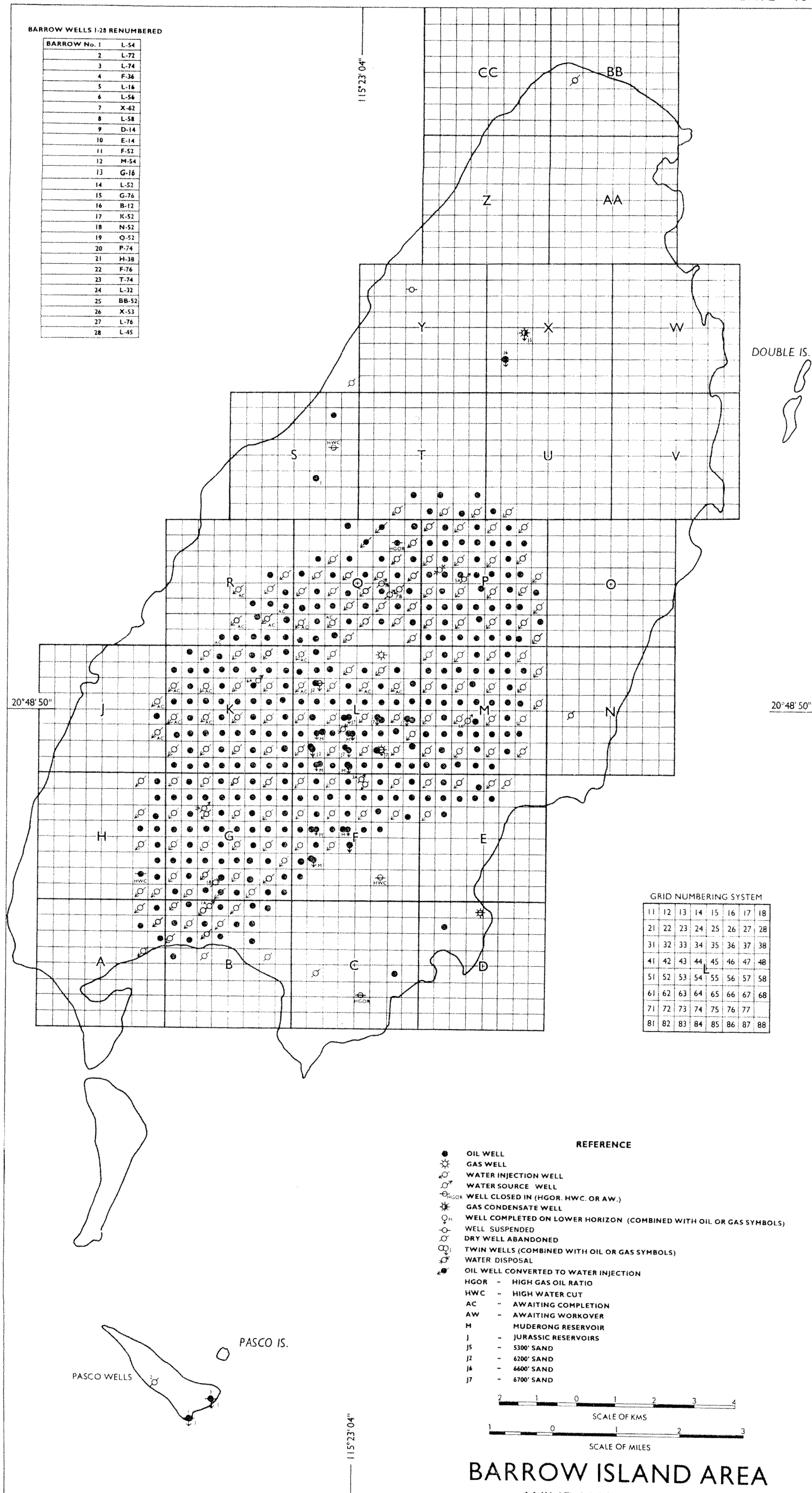


CARNARVON BASIN : WELLS DRILLED FOR PETROLEUM EXPLORATION TO 31st DECEMBER 1970

12271



NORTHERN CANNING, BROWSE AND SOUTHERN BONAPARTE GULF BASINS; WELLS DRILLED FOR PETROLEUM TO 31st DEC 1970. 12272



BARROW WELLS 1-28 RENUMBERED

BARROW No. 1	L-54
2	L-72
3	L-74
4	F-36
5	L-16
6	L-56
7	X-62
8	L-58
9	D-14
10	E-14
11	F-52
12	M-54
13	G-16
14	L-52
15	G-76
16	B-12
17	K-52
18	N-52
19	Q-52
20	P-74
21	H-38
22	F-76
23	T-74
24	L-32
25	BB-52
26	X-53
27	L-76
28	L-45

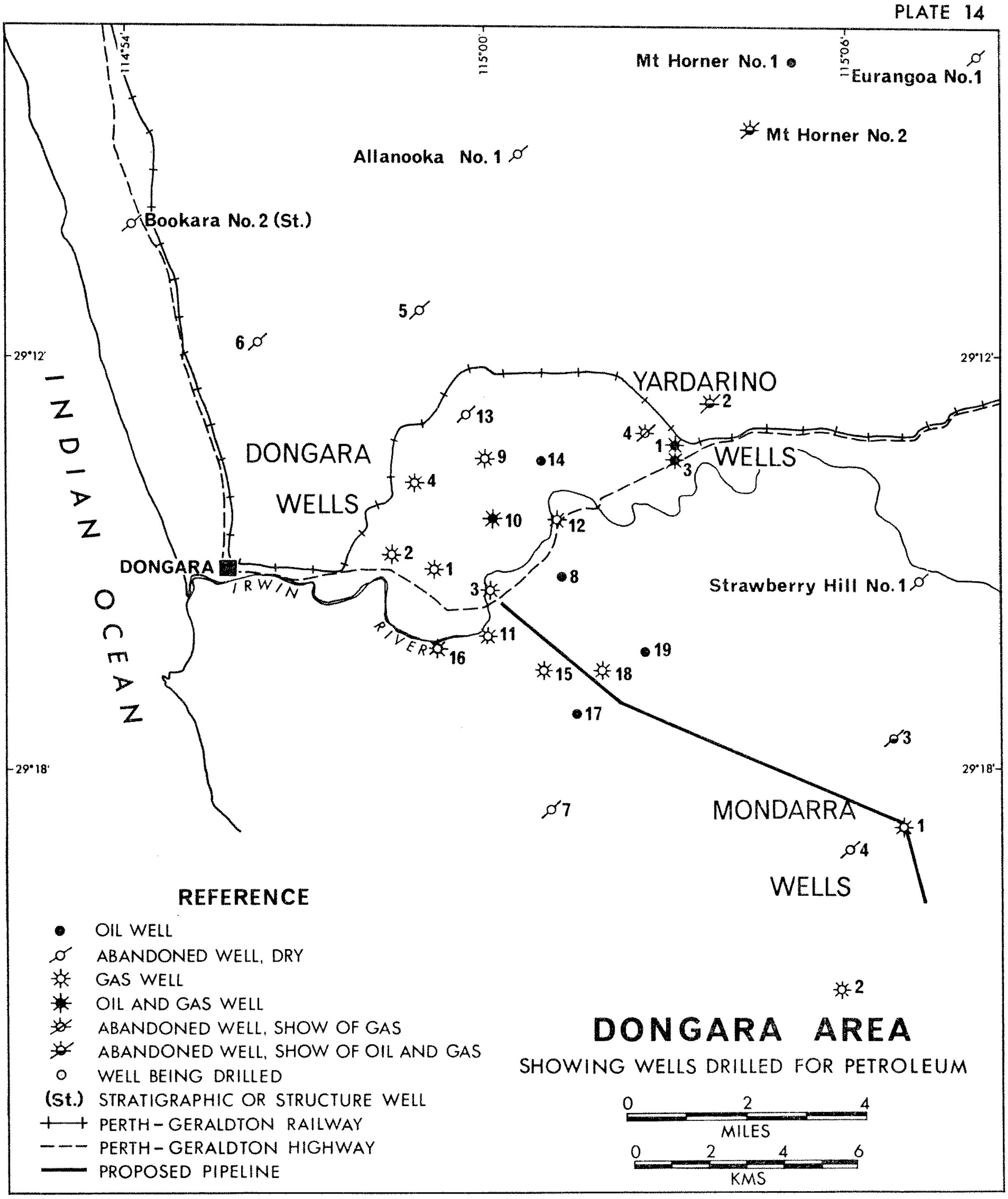
GRID NUMBERING SYSTEM

11	12	13	14	15	16	17	18
21	22	23	24	25	26	27	28
31	32	33	34	35	36	37	38
41	42	43	44	45	46	47	48
51	52	53	54	55	56	57	58
61	62	63	64	65	66	67	68
71	72	73	74	75	76	77	
81	82	83	84	85	86	87	88

BARROW ISLAND AREA
WINDALIA RESERVOIR

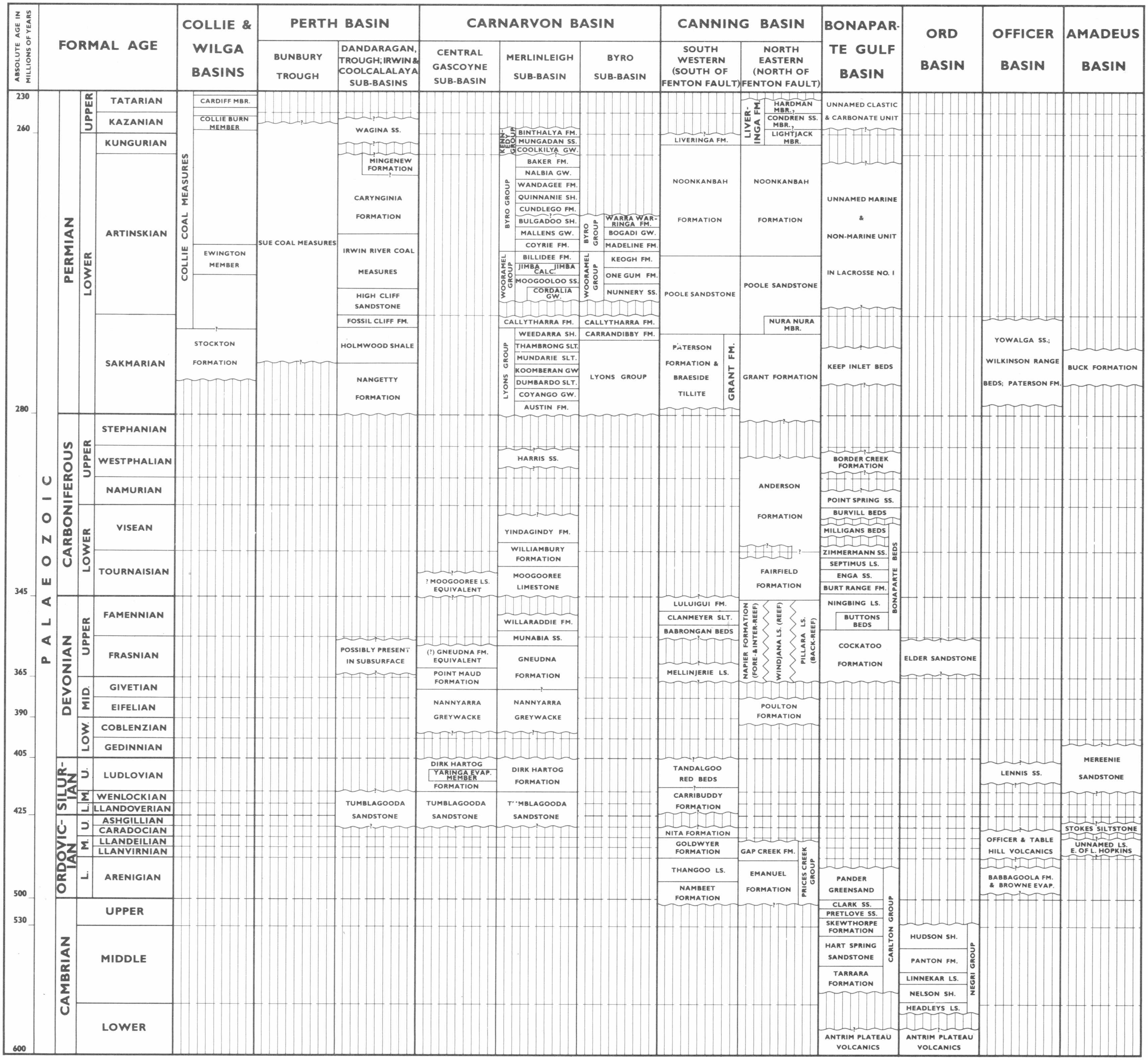
31-12-70

12273



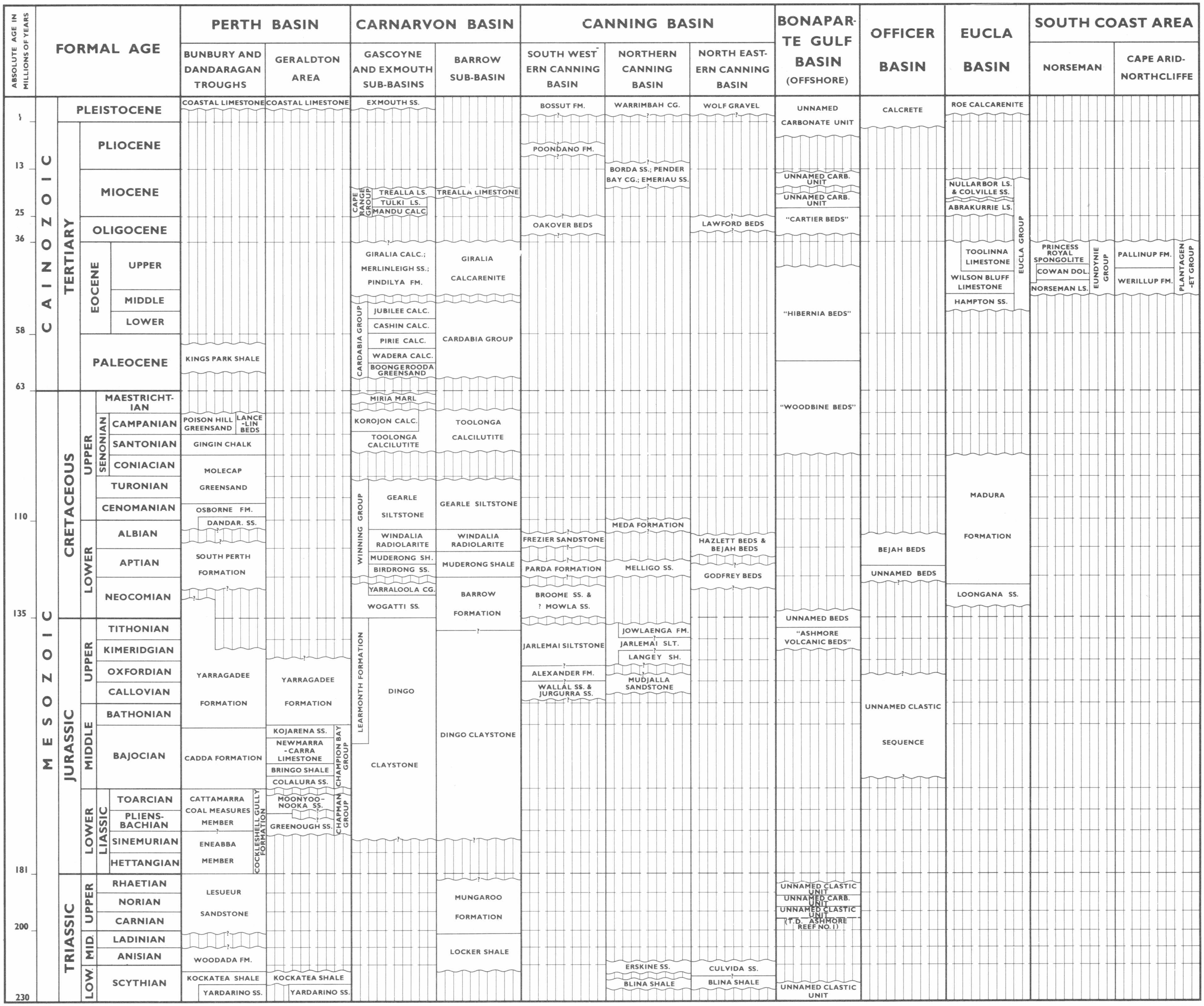
DONGARA AREA

SHOWING WELLS DRILLED FOR PETROLEUM



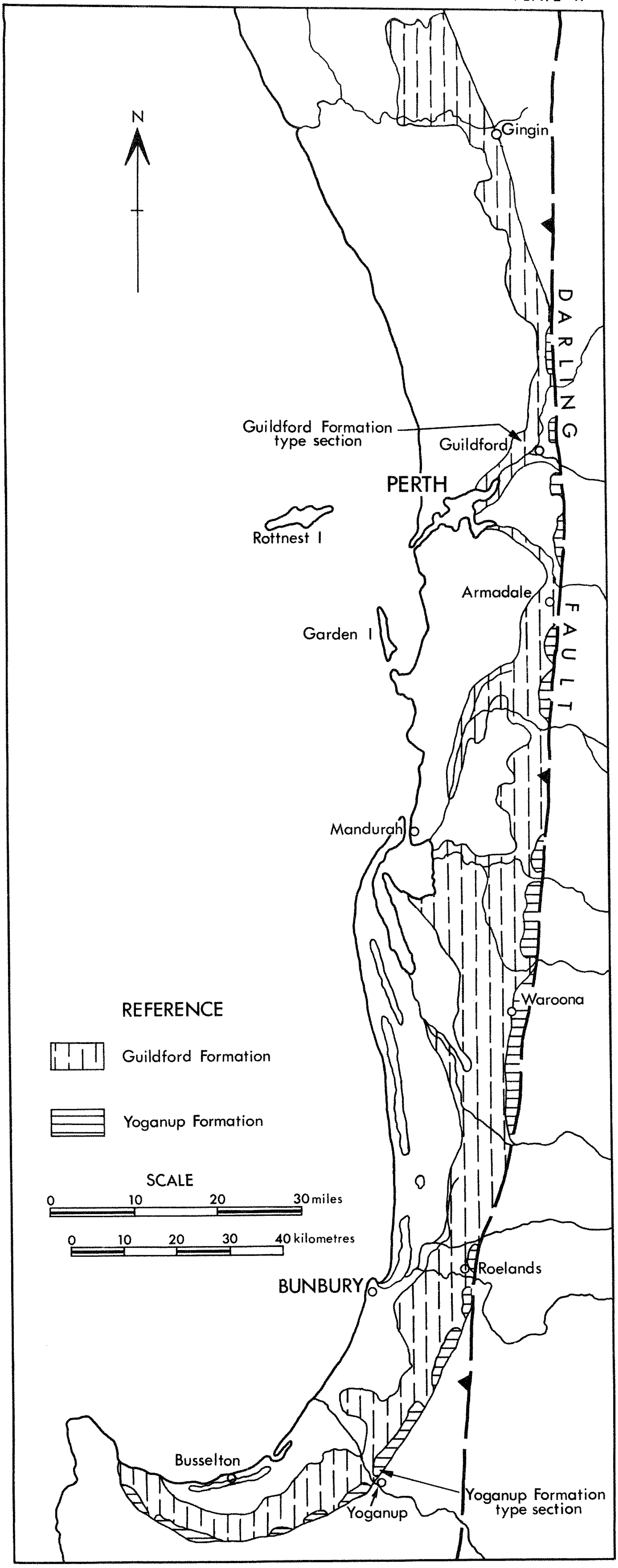
12275

PHANEROZOIC STRATIGRAPHY OF WESTERN AUSTRALIA, CORRELATION CHART.
PART I CAMBRIAN TO PERMIAN



12276

PHANEROZOIC STRATIGRAPHY OF WESTERN AUSTRALIA, CORRELATION CHART.
PART II TRIASSIC TO CAINOZOIC



DISTRIBUTION OF GUILDFORD AND YOGANUP FORMATIONS IN THE PERTH BASIN

12277

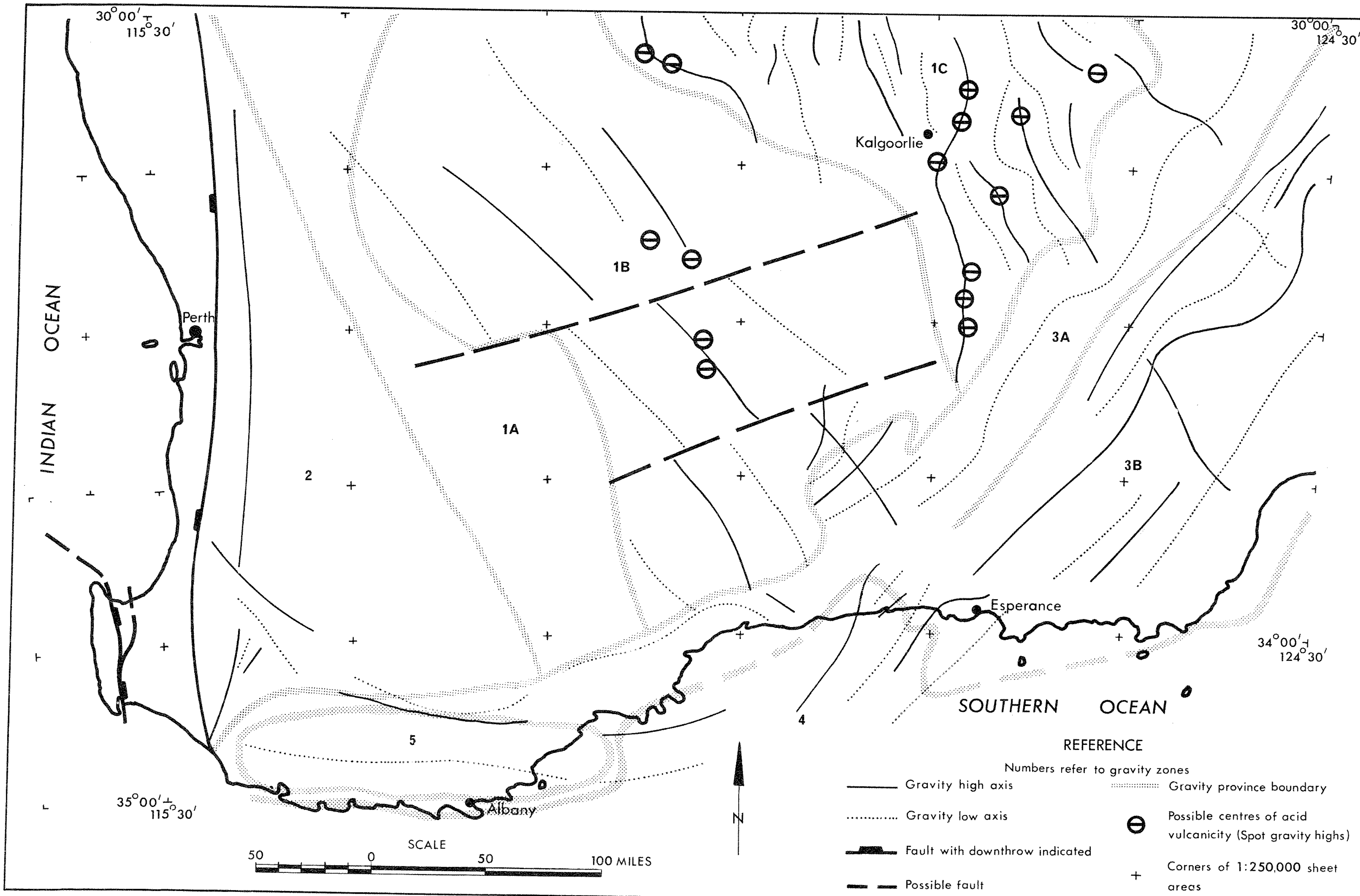


PLATE 18

TECTONIC DOMAINS DEDUCED FROM THE BMR GRAVITY MAP OF SOUTHWESTERN AUSTRALIA

12278

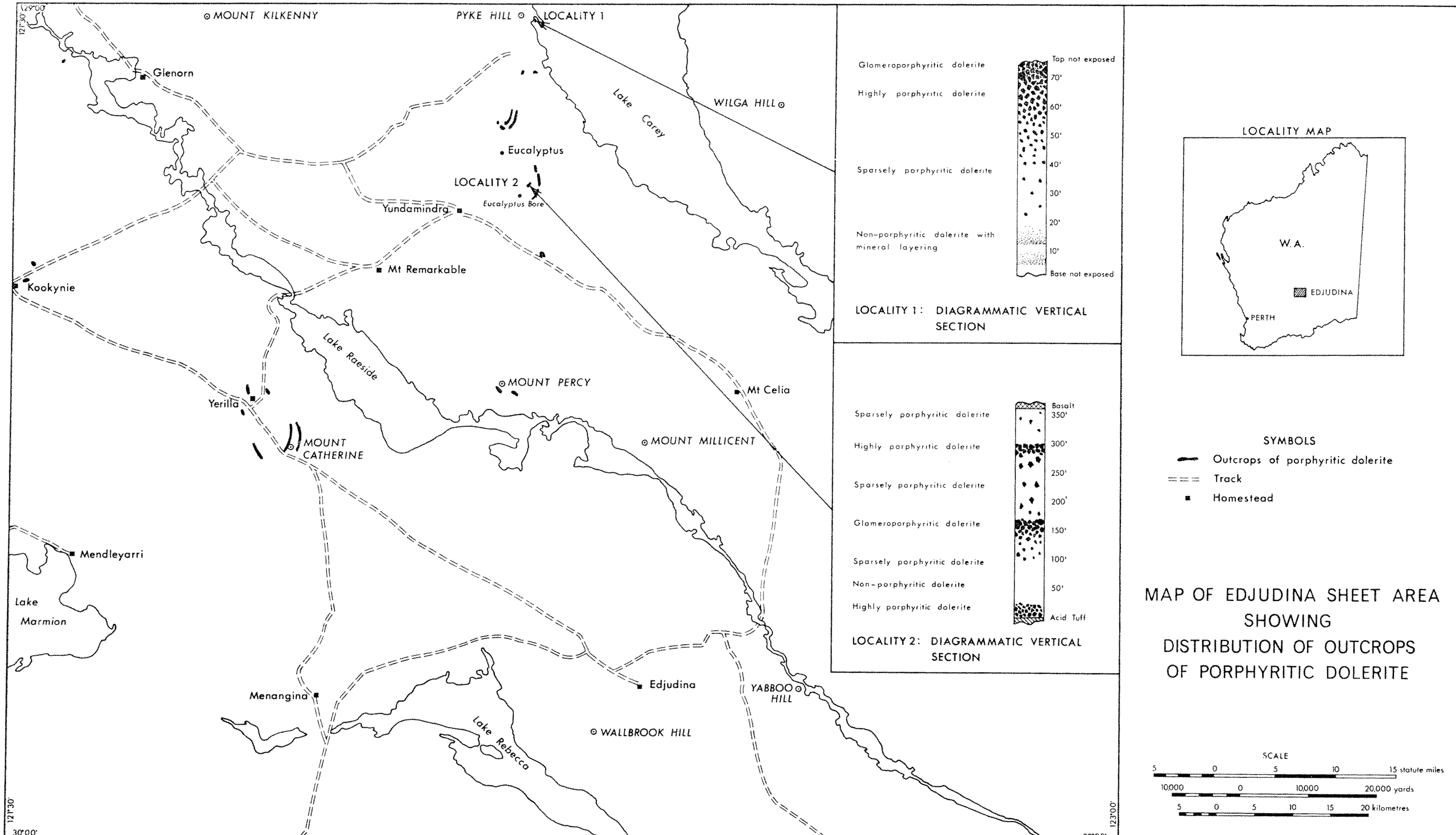
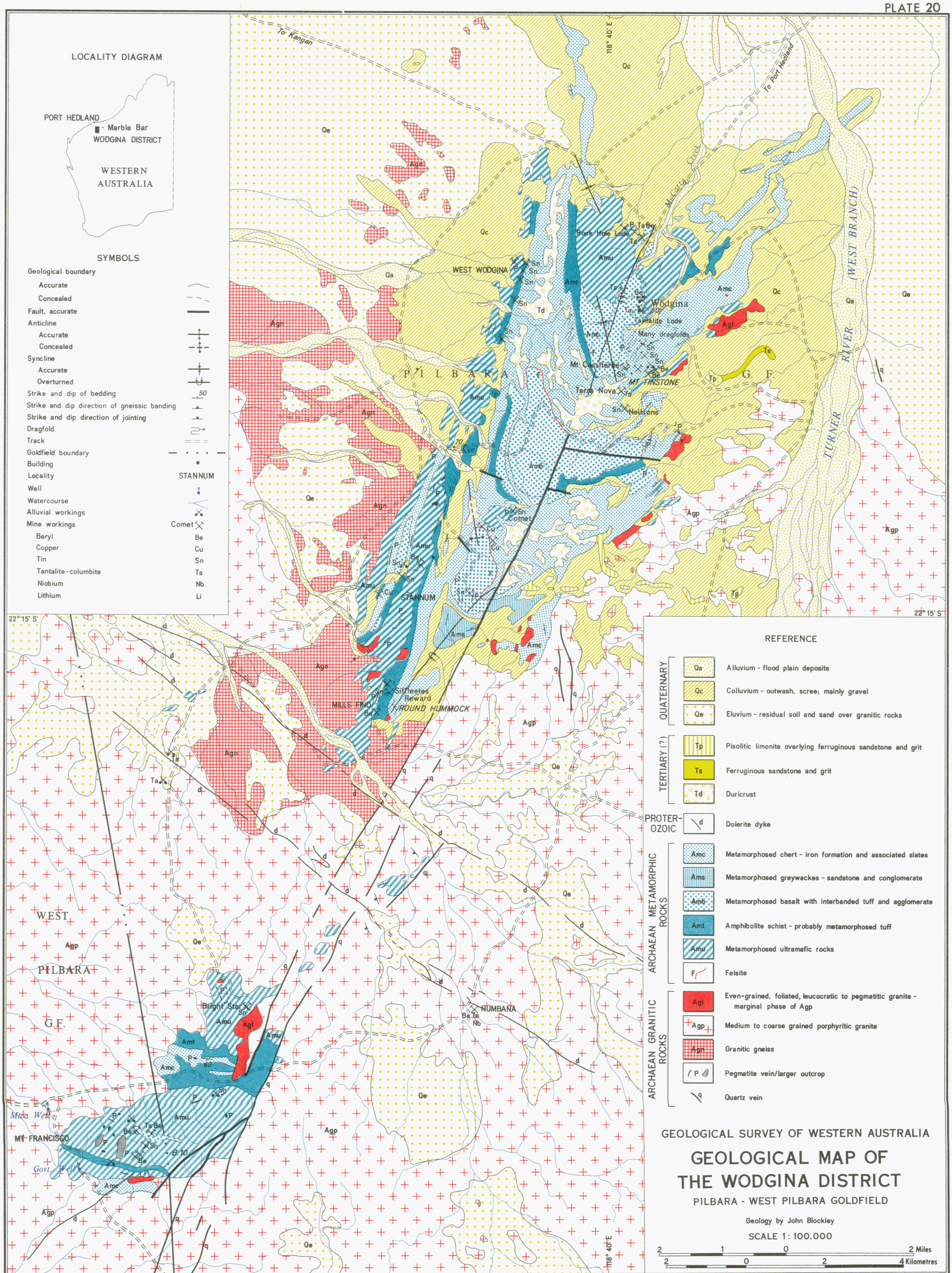


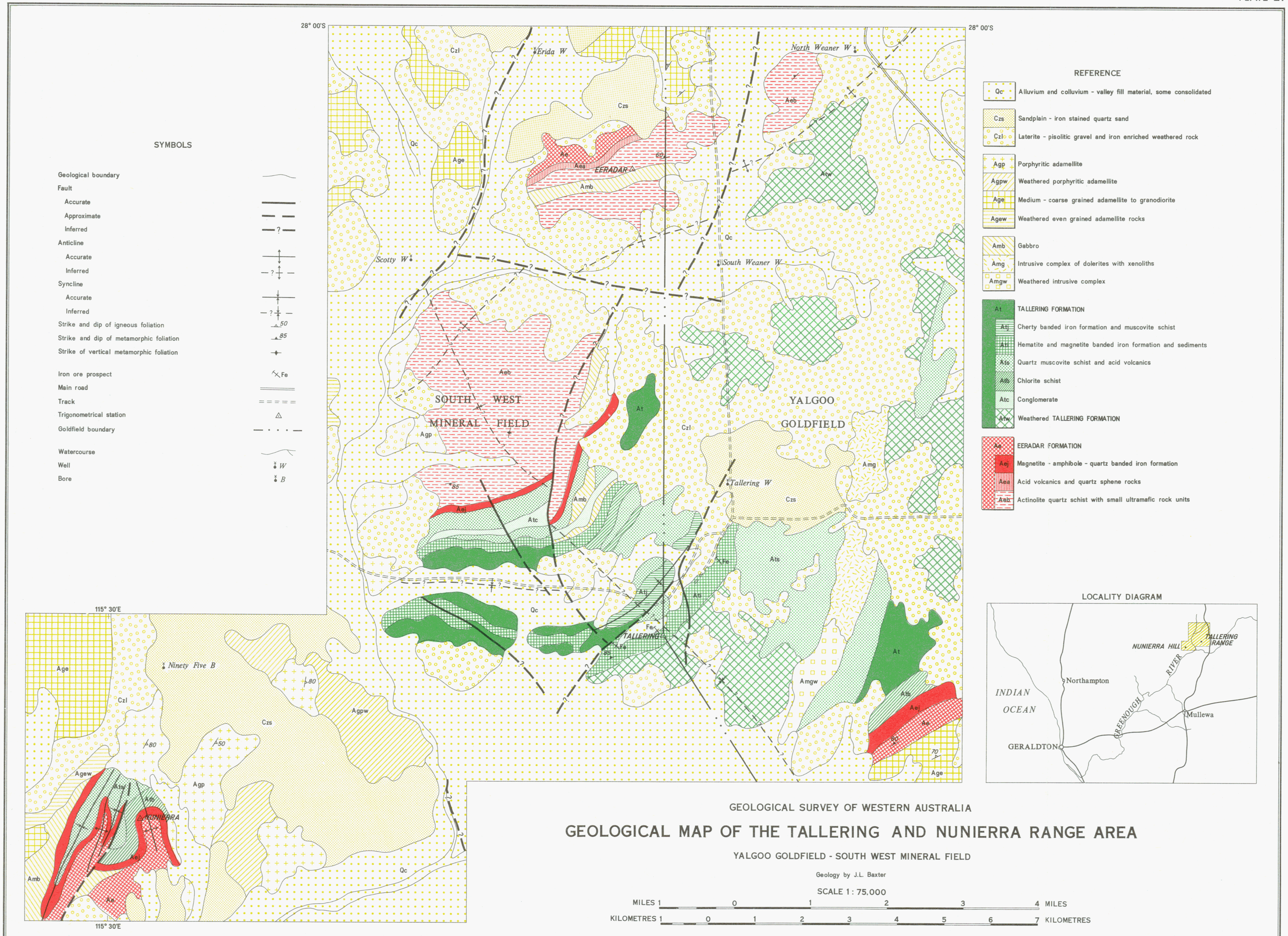
PLATE 19

12279

PLATE 20



12280



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL MAP OF THE TALLERING AND NUNIERRA RANGE AREA

YALGOO GOLDFIELD - SOUTH WEST MINERAL FIELD

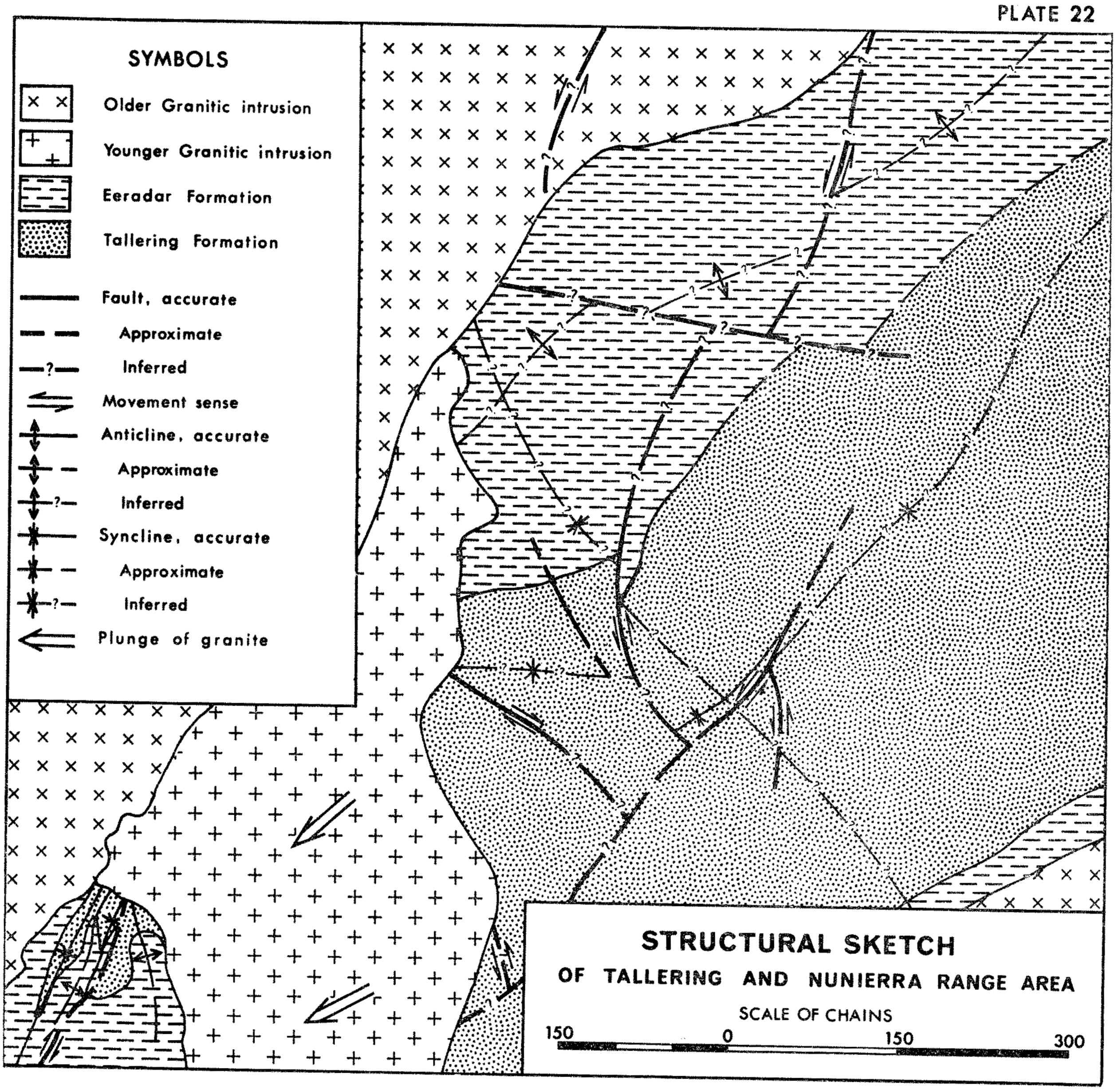
Geology by J.L. Baxter

SCALE 1 : 75,000

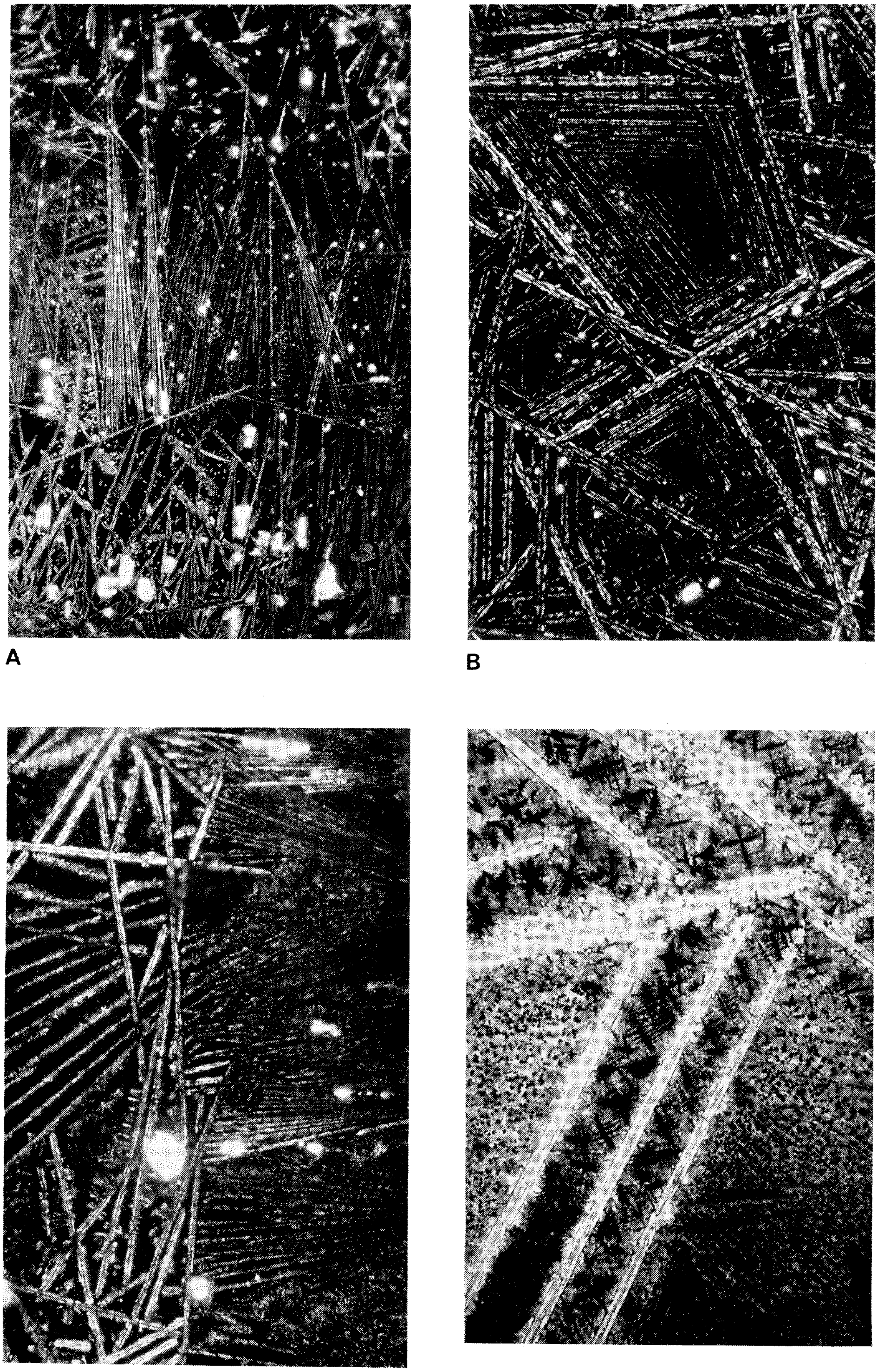
MILES 1 0 1 2 3 4 MILES

KILOMETRES 1 0 1 2 3 4 5 6 7 KILOMETRES

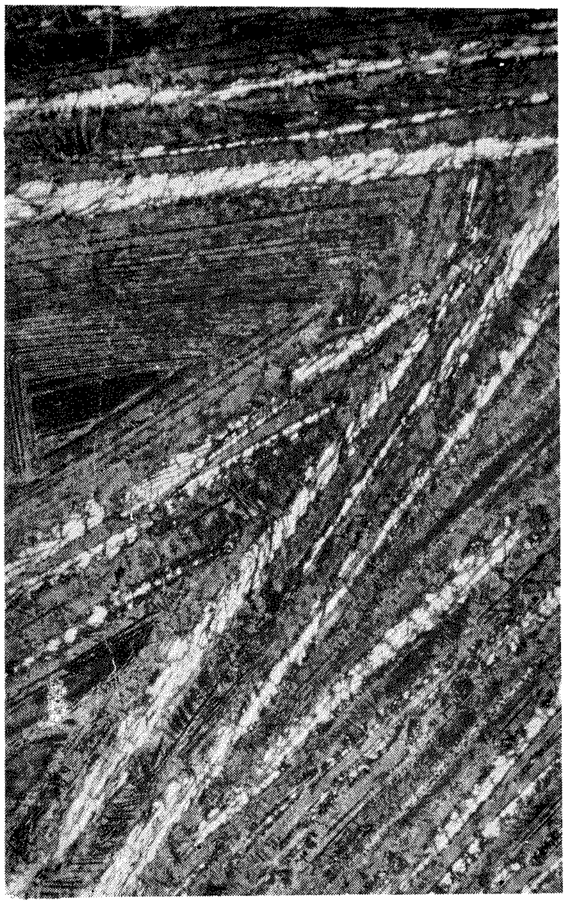
12281


SYMBOLS
Older Granitic intrusion
Younger Granitic intrusion
Eeradar Formation
Tallering Formation
Fault, accurate
Approximate
Inferred
Movement sense
Anticline, accurate
Approximate
Inferred
Syncline, accurate
Approximate
Inferred
Plunge of granite
STRUCTURAL SKETCH
OF TALLERING AND NUNIERRA RANGE AREA
SCALE OF CHAINS
150
0
150
300

12282

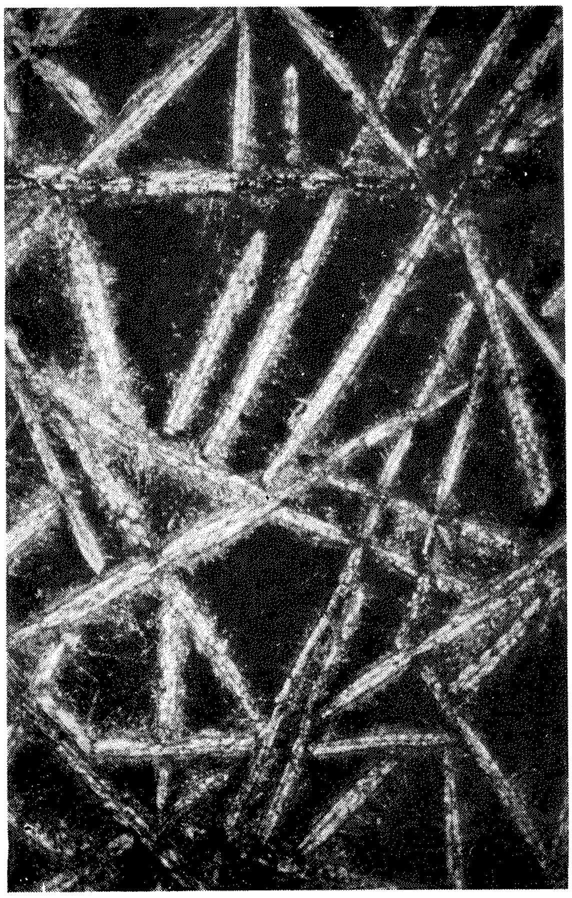


A B C D

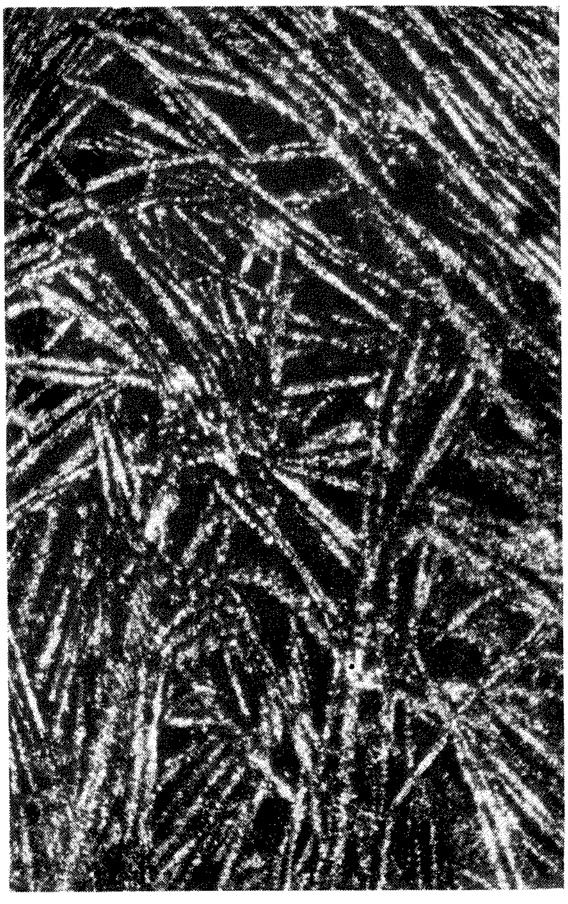


A

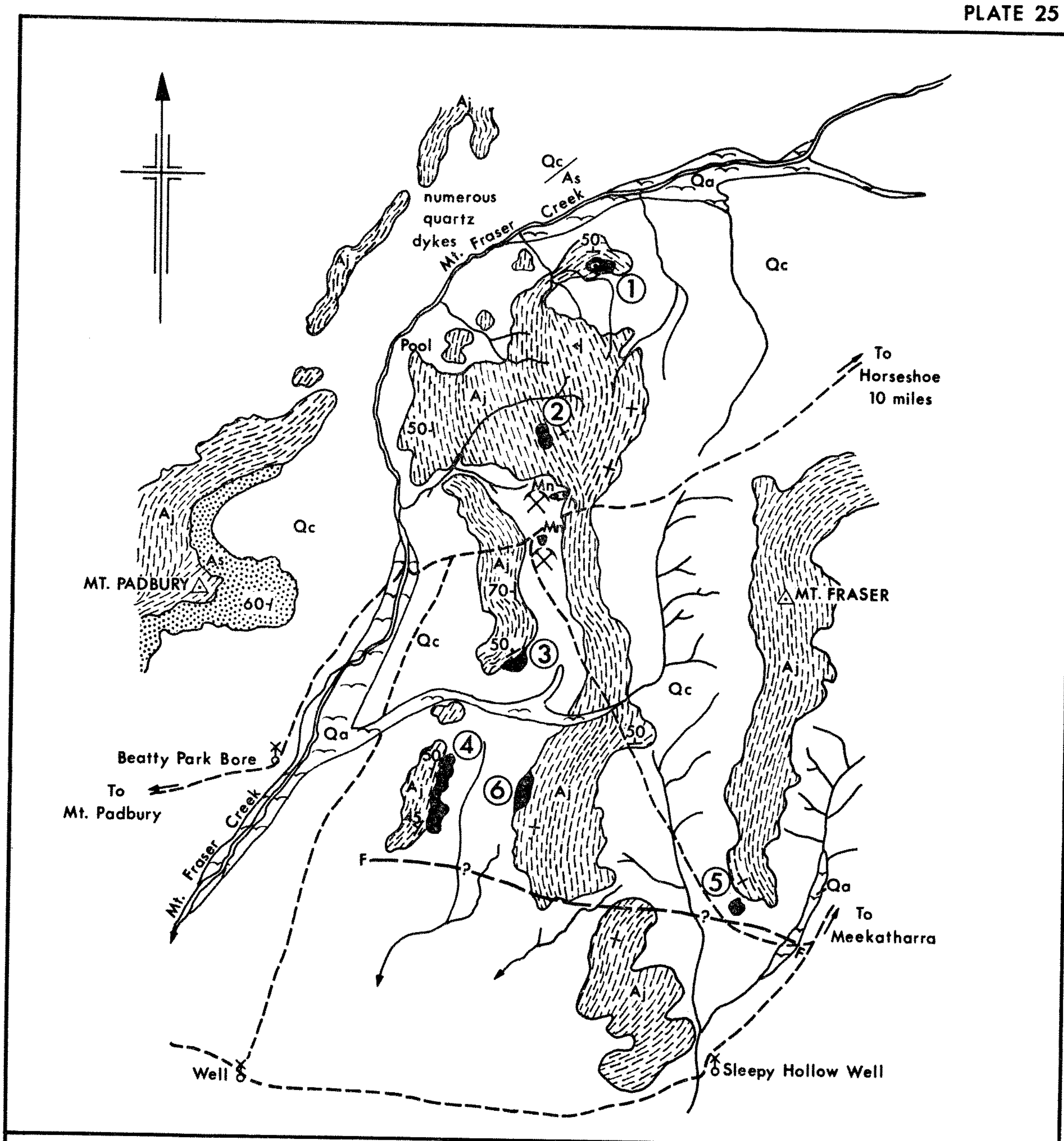
B

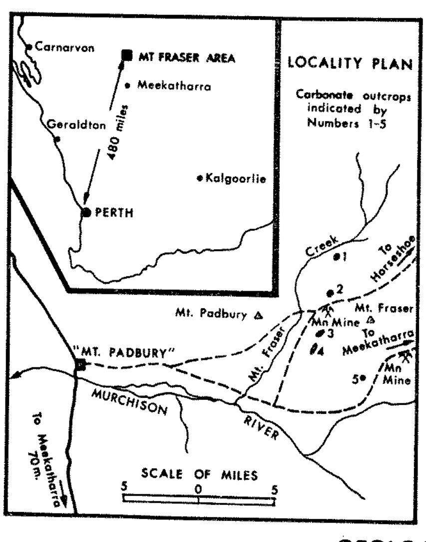


C



D





REFERENCE

- Qa — River alluvium
- Qc — Colluvium. Rock scree and soil cover
- Aj — Banded iron formation and shale
- As — Sandstone, siltstone
- Carbonate and associated intrusive rocks
- Manganese deposit

SYMBOLS

- Vertical strike and dip of bedding
- Strike and dip of bedding
- 50 — Strike and dip of bedding, measured
- F —?— Fault, inferred

GEOLOGICAL SKETCH MAP OF THE
MOUNT FRASER AREA

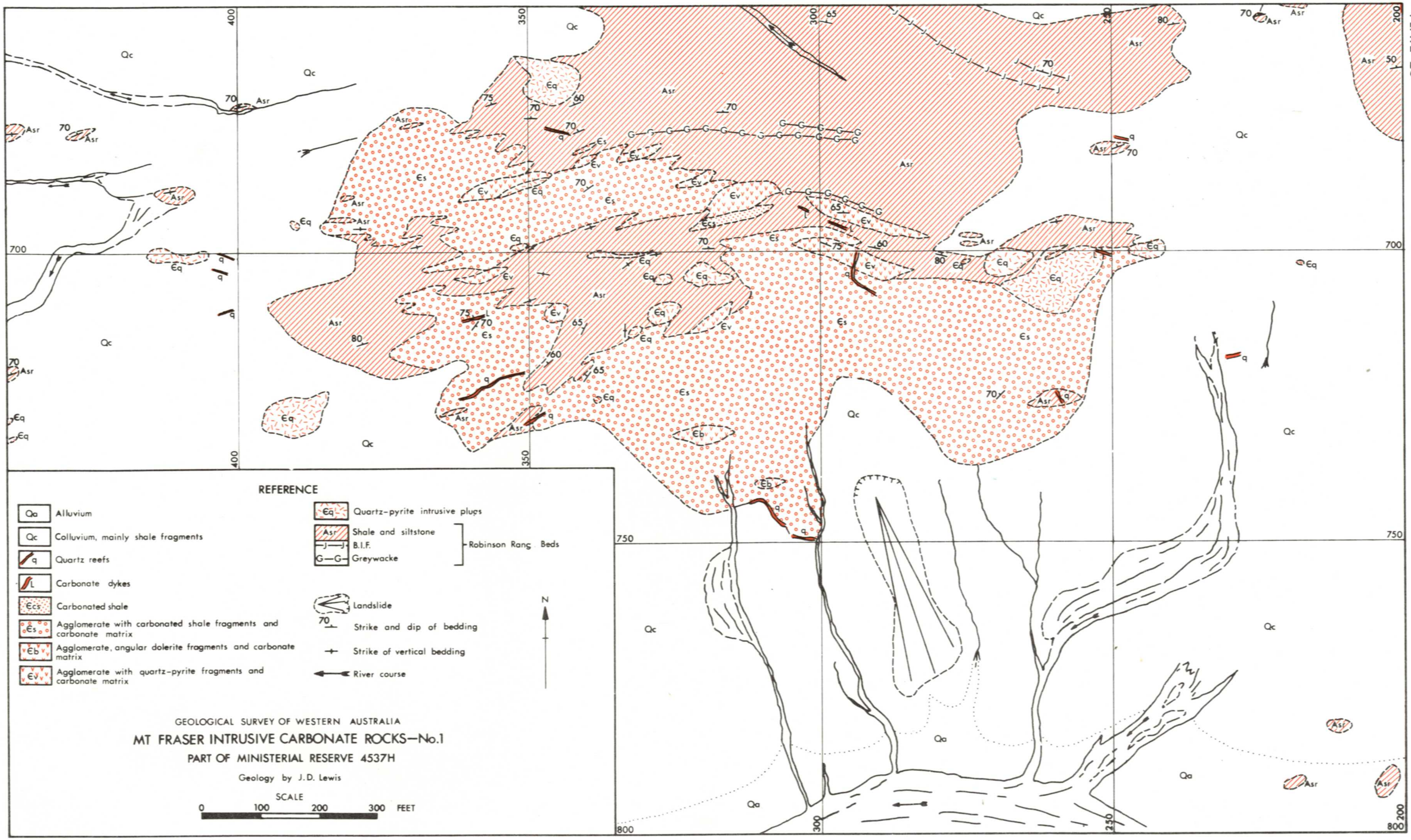
SCALE

2 0 2 4 miles

2 0 2 4 6 kms

12285

PLATE 26



12286

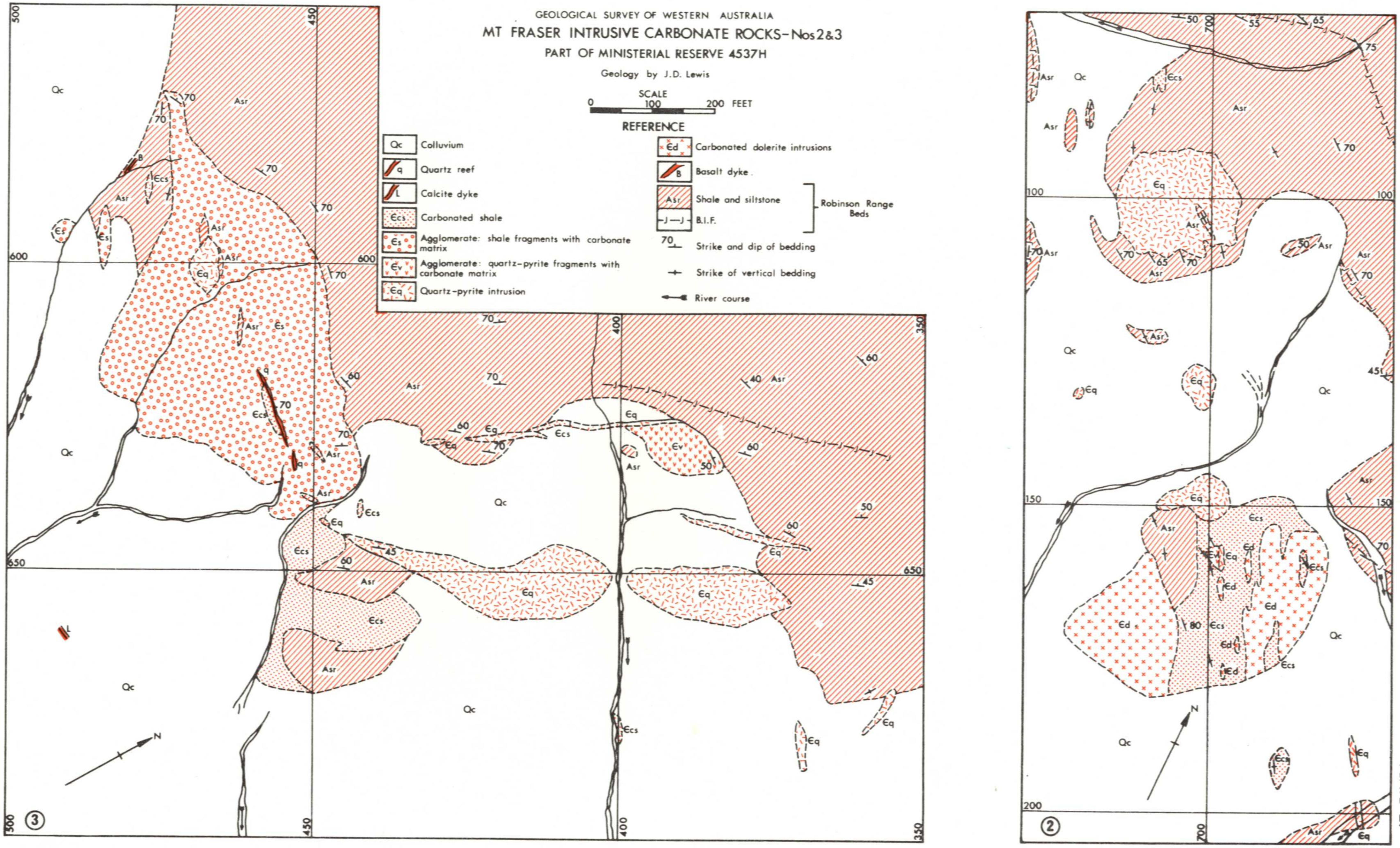
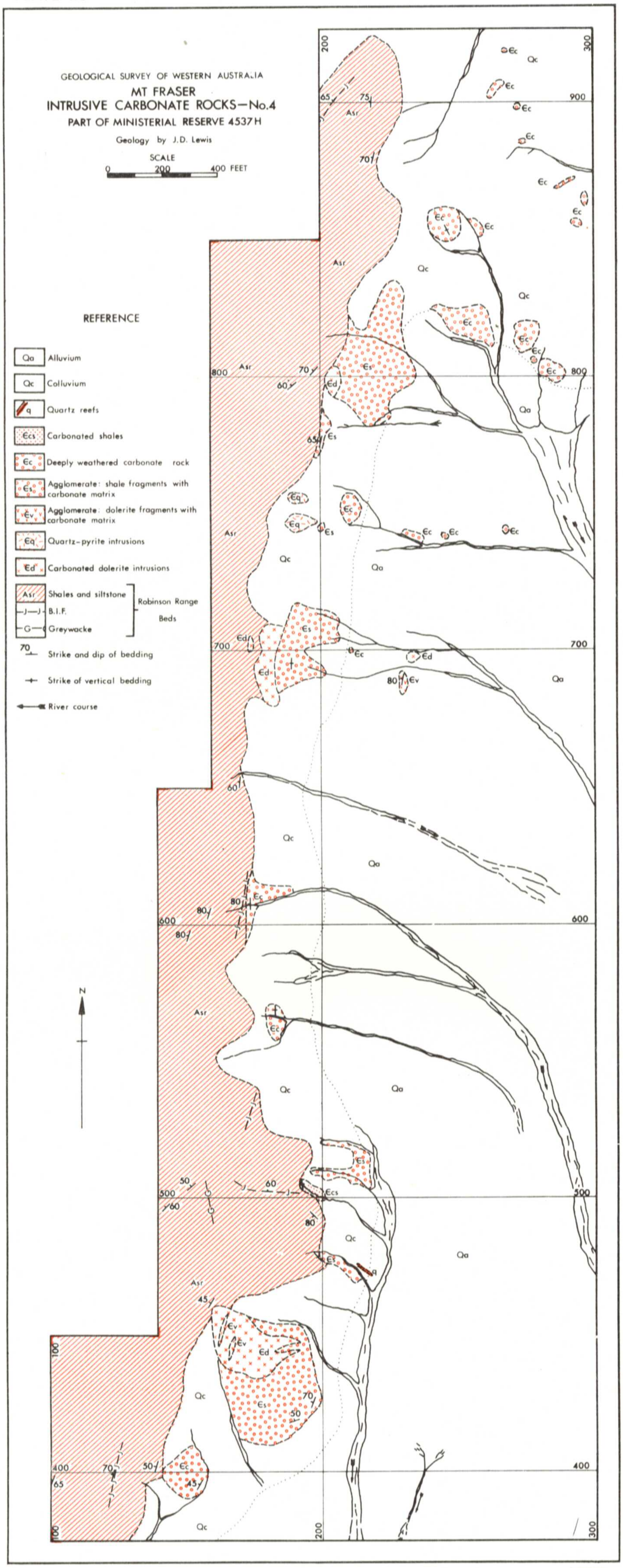


PLATE 27

12287


GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MT FRASER
INTRUSIVE CARBONATE ROCKS—No.4
PART OF MINISTERIAL RESERVE 4537H
Geology by J.D. Lewis
SCALE
0 200 400 FEET
REFERENCE
Qa Alluvium
Qc Colluvium
q Quartz reefs
Ꞓcs Carbonated shales
Ꞓc Deeply weathered carbonate rock
Ꞓs Agglomerate: shale fragments with carbonate matrix
Ꞓv Agglomerate: dolerite fragments with carbonate matrix
Ꞓq Quartz-pyrite intrusions
Ꞓd Carbonated dolerite intrusions
Asr Shales and siltstone
J—J B.I.F.
G— Greywacke
Robinson Range Beds
70 Strike and dip of bedding
Strike of vertical bedding
River course
N

12288

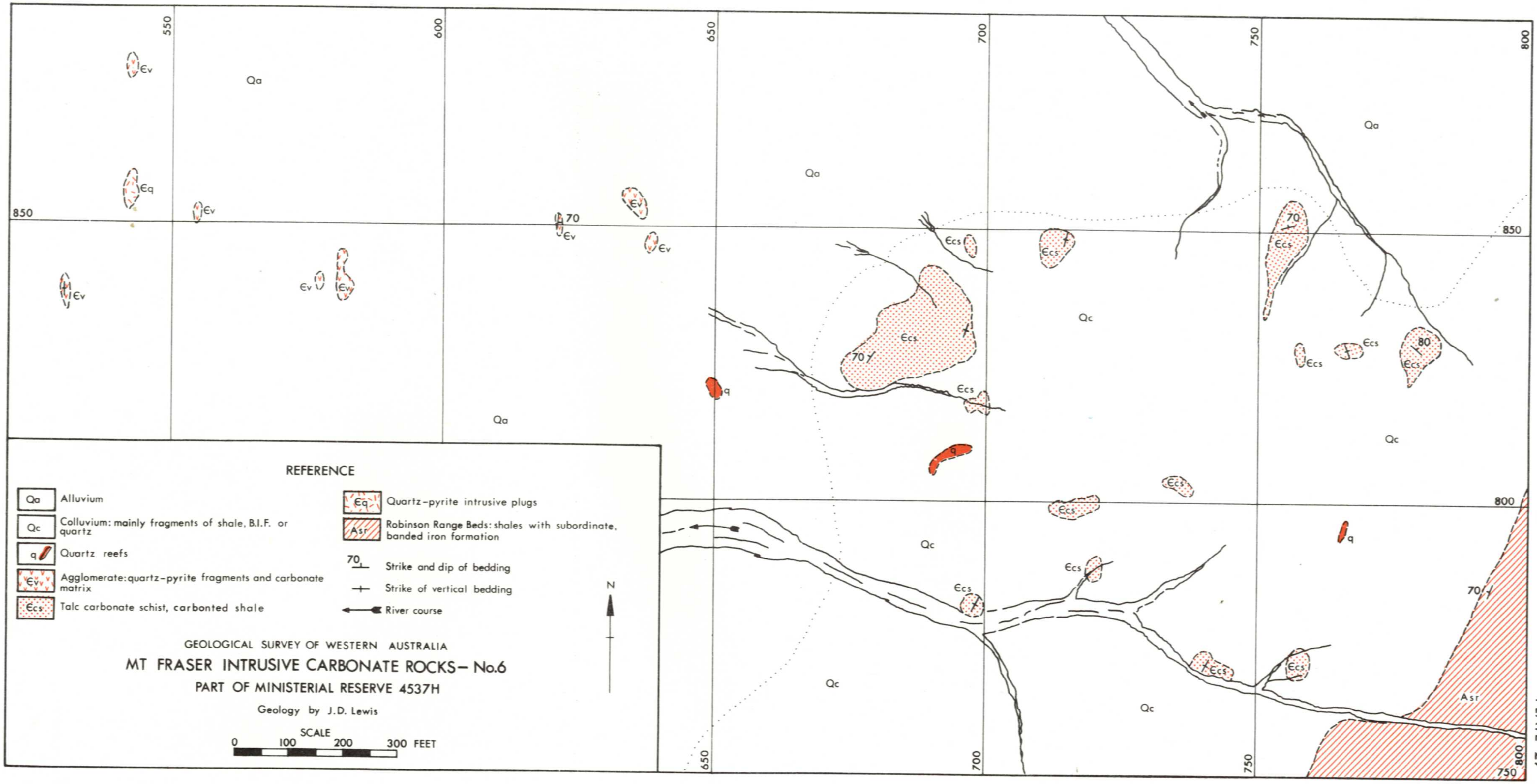
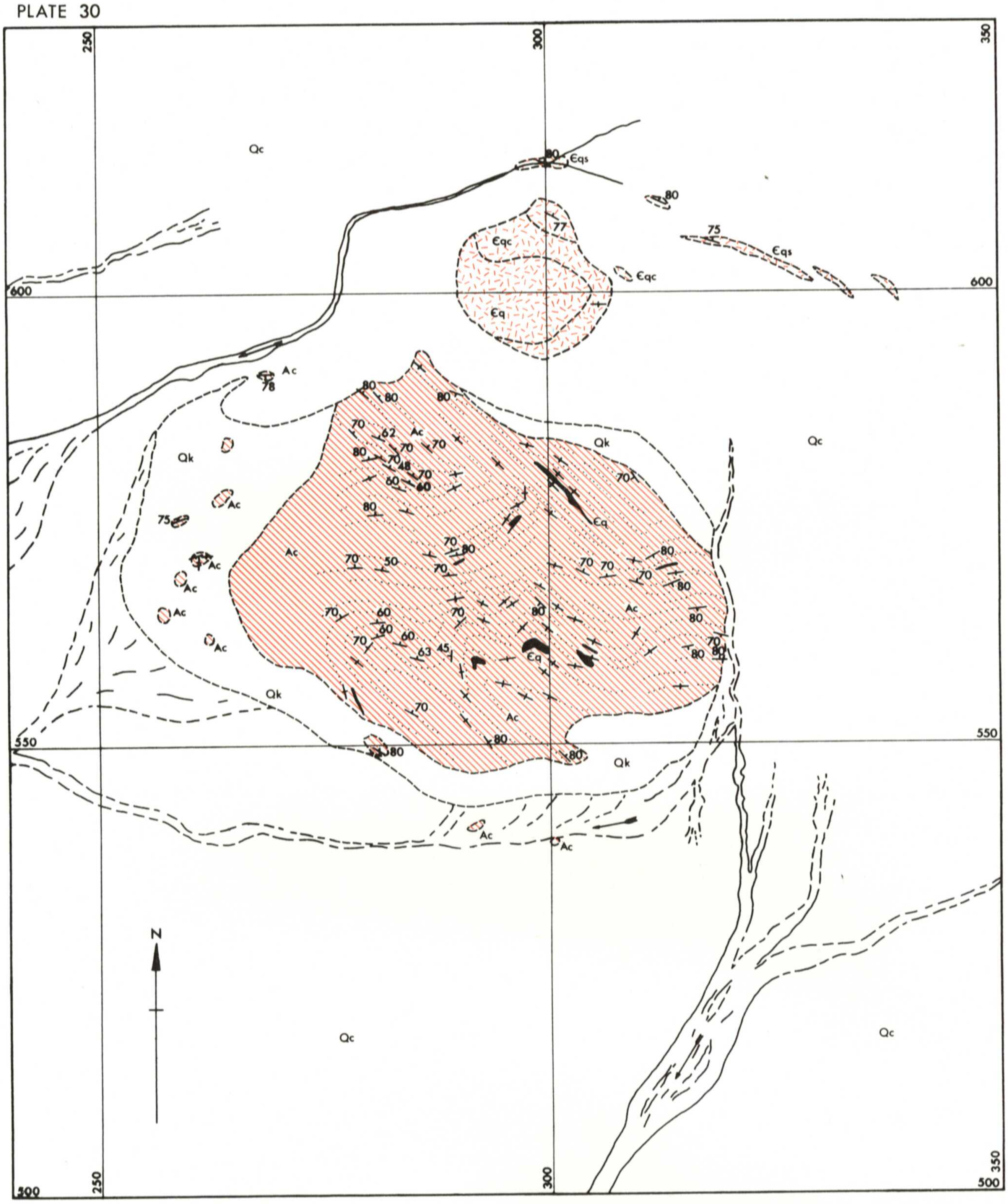


PLATE 29

12289

PLATE 30



REFERENCE

Qc — Colluvium: fragments of shale, B.I.F. and hematite.

Qk — Kankar overlying remobilised sediments.

Ac — Remobilised and carbonated sediments, showing trend lines of bedding. Thinly laminated quartzite and shale.

70 — Strike and dip of bedding

Strike of vertical bedding

Єq — Quartz-pyrite-chloritoid intrusive plug.

Єqc — Carbonated quartz-pyrite rock.

Єqs — Silicified quartz-pyrite rock.

Єq — Dykes and pods of quartz-pyrite-chloritoid rock.

River course

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MT FRASER
INTRUSIVE CARBONATE ROCKS—No.5

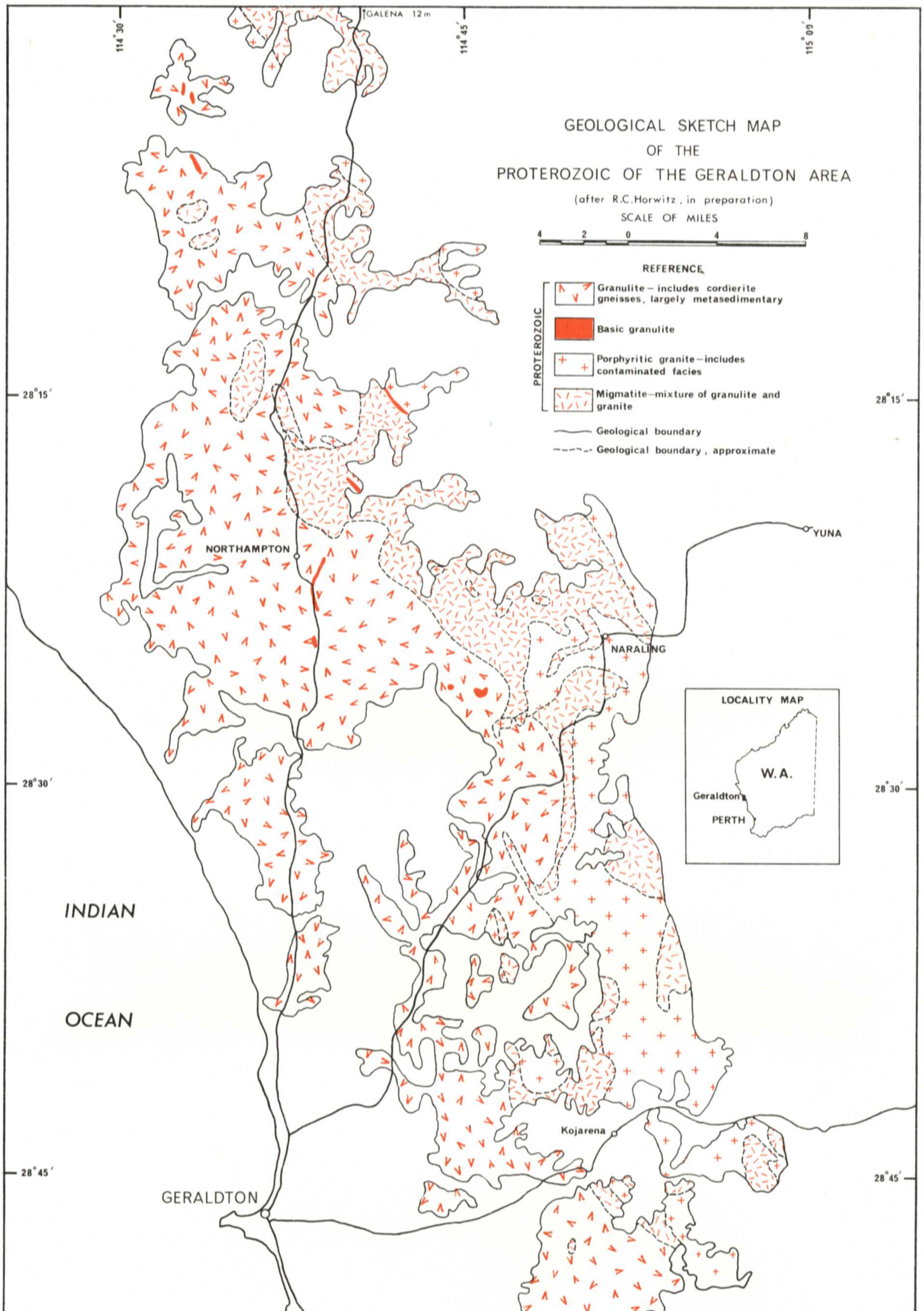
PART OF MINISTERIAL RESERVE 4537H

Geology by J.D. Lewis

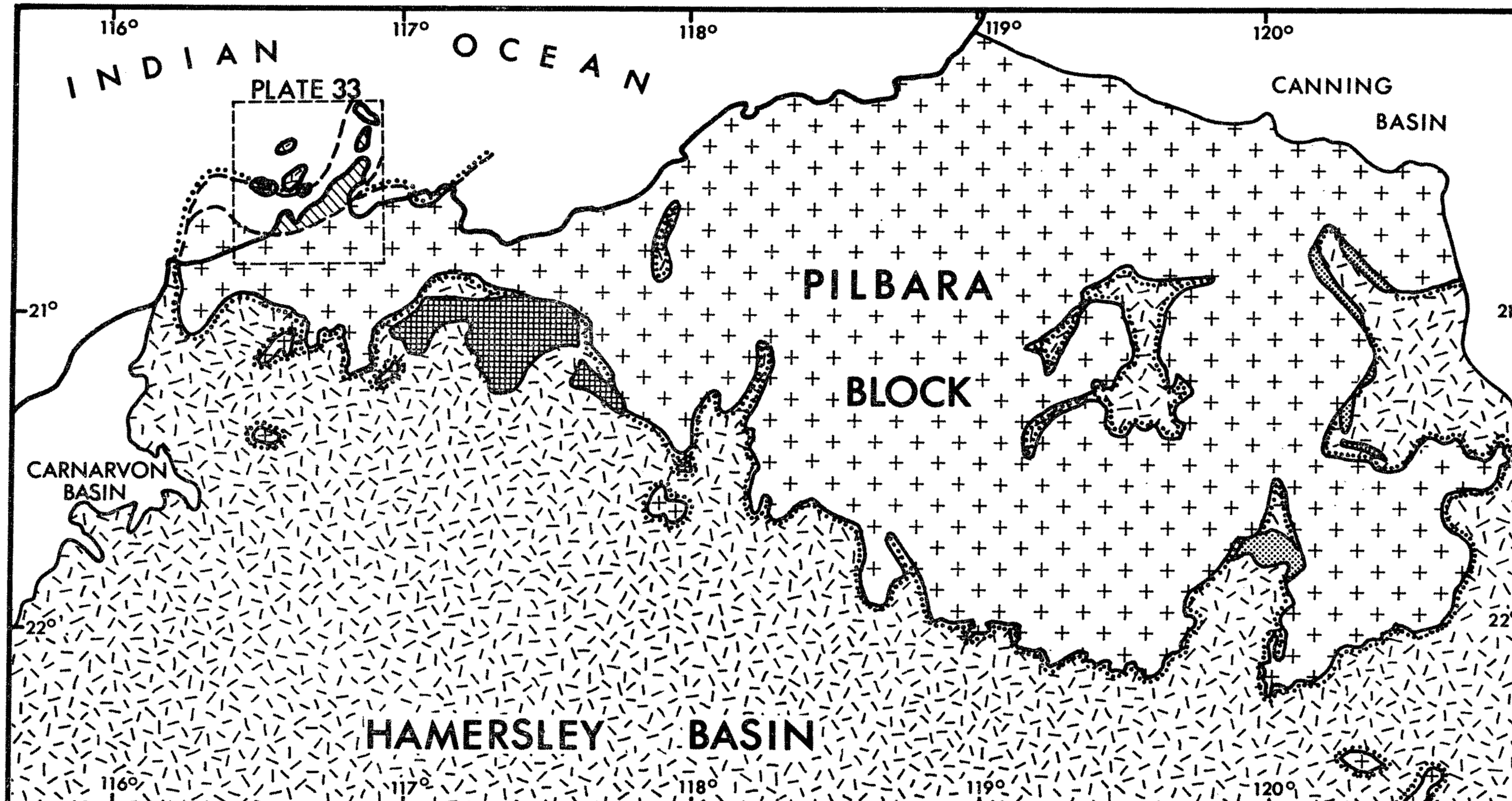
SCALE

0 100 200 FEET

12290



GEOLOGICAL SKETCH MAP
OF THE
PROTEROZOIC OF THE GERALDTON AREA
(after R.C.Horwitz, in preparation)
SCALE OF MILES
4 2 0 4 8
REFERENCE
PROTEROZOIC
Granulite – includes cordierite gneisses, largely metasedimentary
Basic granulite
Porphyritic granite – includes contaminated facies
Migmatite – mixture of granulite and granite
Geological boundary
Geological boundary, approximate
LOCALITY MAP
W.A.
Geraldton
PERTH
GALENA 12 m
114°30′
114°45′
115°00′
28°15′
28°30′
28°45′
NORTHAMPTON
YUNA
NARALING
Kojarena
GERALDTON
INDIAN
OCEAN
DONGARA 20 m



GEOLOGICAL MAP SHOWING
THE REGIONAL SETTING OF THE GIDLEY GRANOPHYRE
AND SOME RELATED INTRUSIONS

REFERENCE

PHANEROZOIC ROCKS

MOUNT BRUCE SUPERGROUP, WITH THE BASAL UNCONFORMITY OF THE FORTESCUE GROUP (MAPPED OR INFERRED) DOTTED

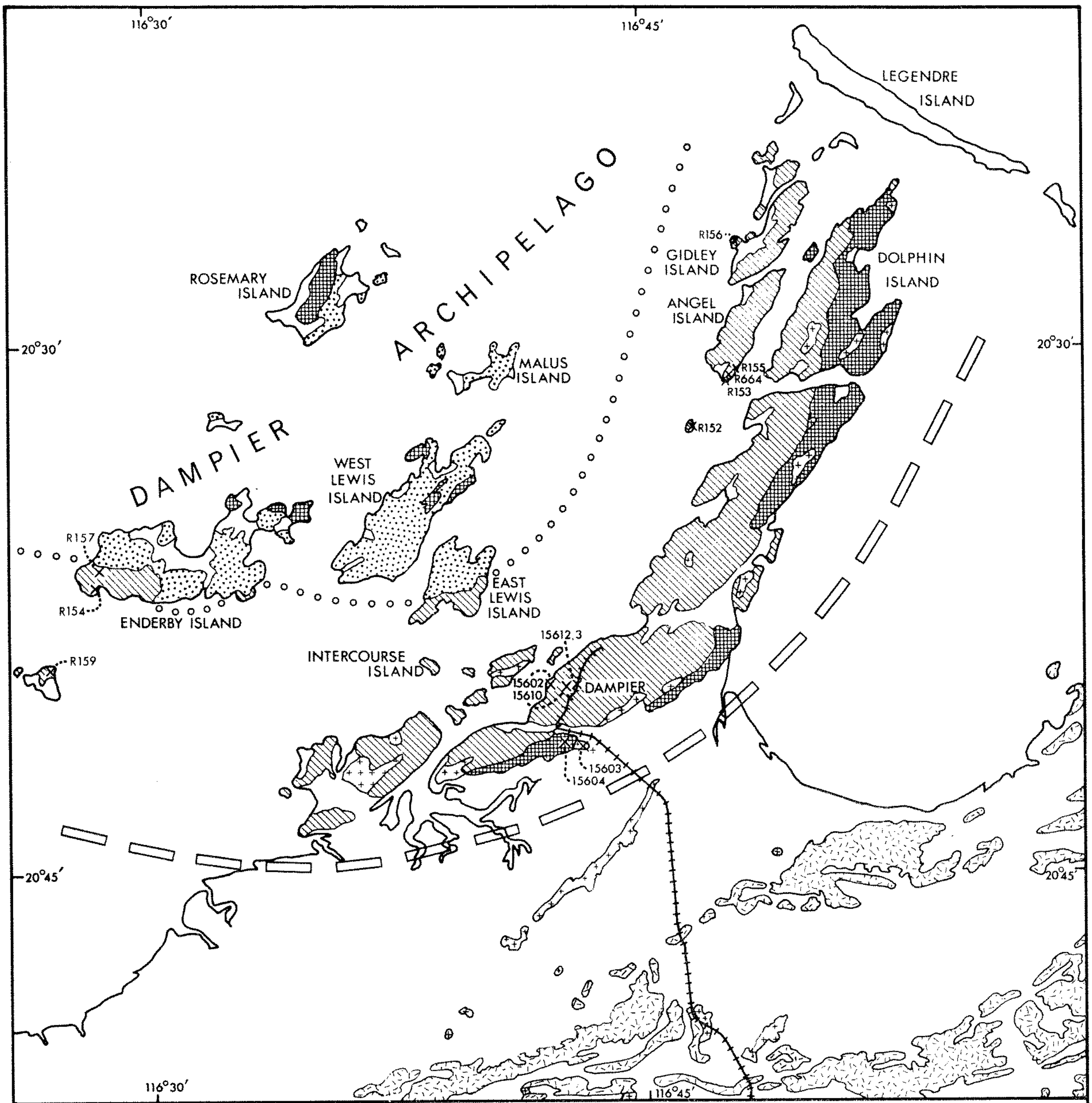
ARCHAEAN ROCKS

GIDLEY GRANOPHYRE

COOYA POOYA DOLERITE

BAMBOO CREEK PORPHYRY

12292



GEOLOGICAL MAP OF THE DAMPIER ARCHIPELAGO
(after Kriewaldt 1964)

SCALE

MILES 0 5 10

KILOMETRES 0 5 10

REFERENCE

TERTIARY AND PLEISTOCENE COVER

FORTESCUE GROUP – BASIC AND INTERMEDIATE LAVAS WITH SOME SEDIMENTARY ROCKS

MIXED METASEDIMENTARY AND METAVOLCANIC ROCKS OF ARCHAEAN AGE

ARCHAEAN GRANITIC ROCKS

POST-ARCHAEAN INTRUSIVE GRANOPHYRE

POST-ARCHAEAN INTRUSIVE GABBRO AND DOLERITE

(ALL PART OF THE GIDLEY GRANOPHYRE EXCEPT POSSIBLY SOME DOLERITE SILLS WITHIN THE FORTESCUE GROUP)

STANDARD GAUGE RAILWAY (DAMPIER TO TOM PRICE)

ASSUMED APPROXIMATE MARGINS OF THE GIDLEY GRANOPHYRE

UPPER

LOWER

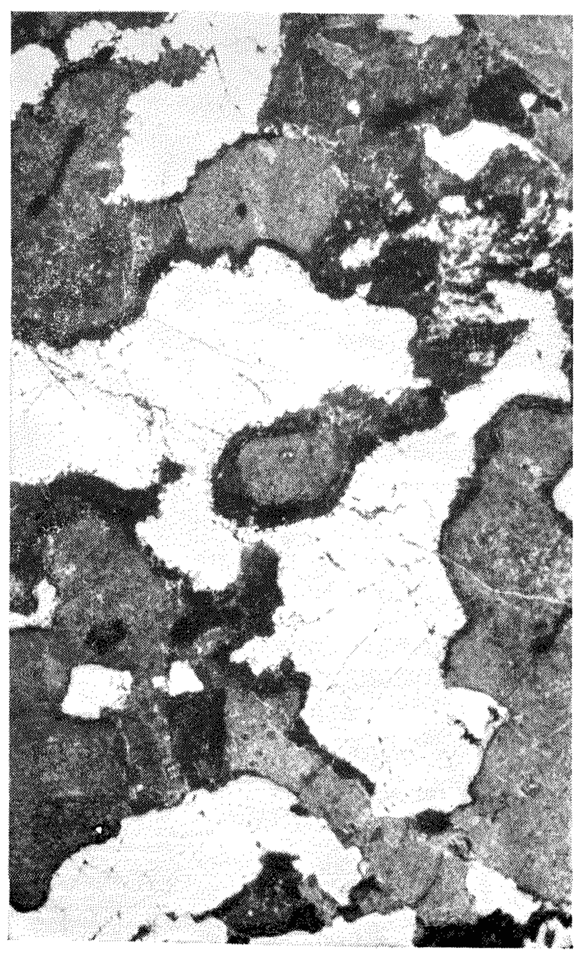
12293

PLATE 34

A 1MM

B 1MM

C 2MM



D 2MM