GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# ANNUAL REPORT

FOR THE YEAR

## 1967

1968

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

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FOR THE YEAR

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EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

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

Under Secretary: I. R. Berry

Director, Geological Survey: J. H. Lord

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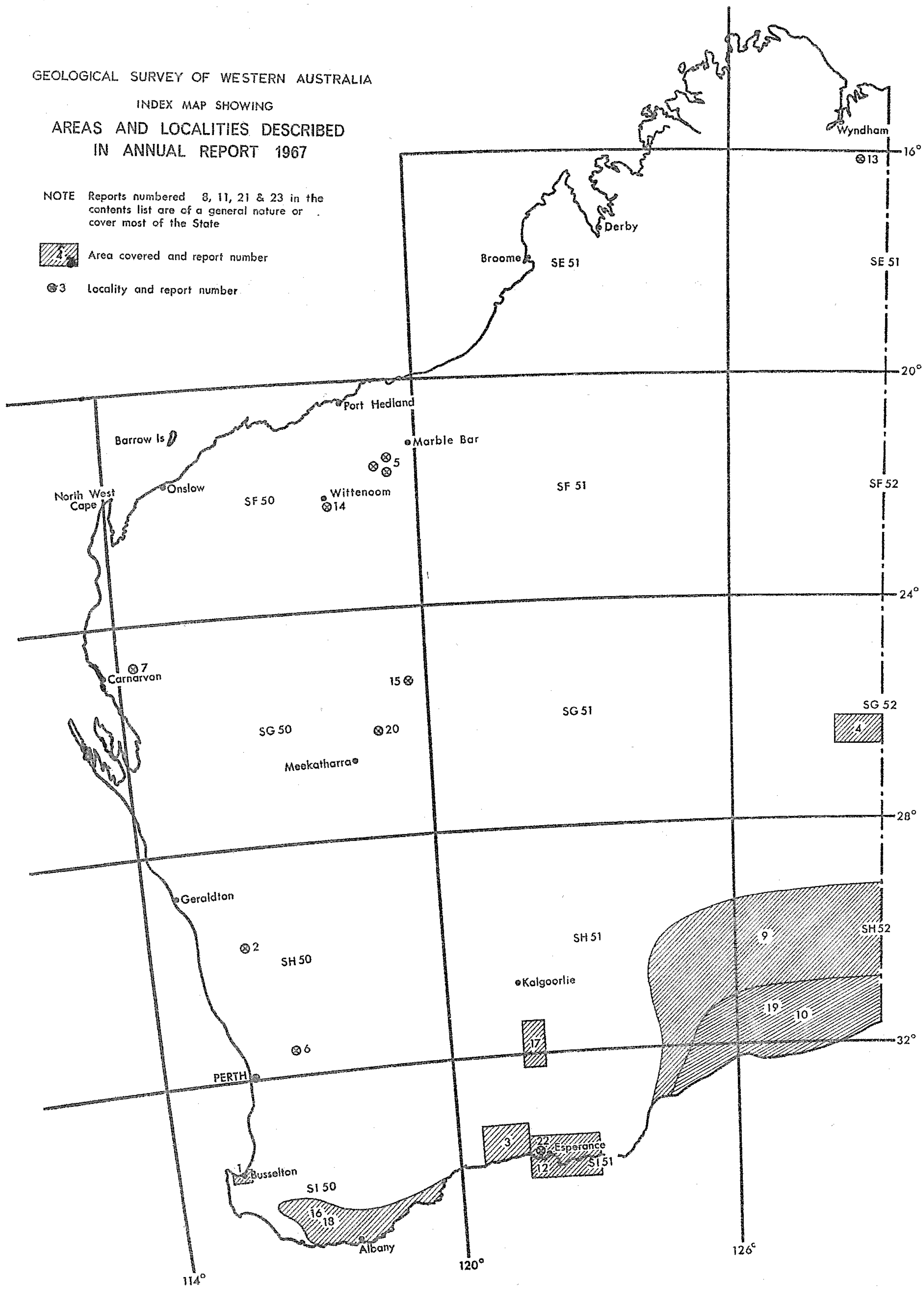
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
INDEX MAP SHOWING
AREAS AND LOCALITIES DESCRIBED
IN ANNUAL REPORT 1967
NOTE Reports numbered 8, 11, 21 & 23 in the contents list are of a general nature or cover most of the State
Area covered and report number
Locality and report number
Wyndham
Derby
Broome
SE 51
SE 51
Port Hedland
Marble Bar
Barrow Is
North West Cape
Onslow
SF 50
Wittenoom
SF 51
SF 52
Carnarvon
SG 50
SG 51
SG 52
Meekatharra
Geraldton
SH 50
SH 51
SH 52
Kalgoorlie
PERTH
Busselton
SI 50
Albany
Esperance
SI 51
16°
20°
24°
28°
32°
114°
120°
126°

**FIGURE 1**

# DIVISION IV

## *Annual Report of the Geological Survey Branch of the Mines Department for the Year 1967*

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# DIVISION IV

## Annual Report of the Geological Survey Branch of the Mines Department for the Year 1967

*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 for the year 1967, together with some of the reports on investigations made for departmental purposes.

### INTRODUCTION

The tempo of exploration in this State, particularly for nickel and base metals, increased again this year. The number of local, interstate, and overseas companies involved far exceeded expectations. No new ore bodies were discovered although many prospects, particularly for nickel, were examined in detail.

This unparalleled activity has created a great demand for the services and assistance of this Branch. Our field geologists, particularly those working on Precambrian areas, frequently assisted company geologists with ideas and discussions on regional geology and stratigraphy of prospect areas. Company operators usually discuss progress and methods of mineral search and rely on this Branch to provide regional geology on which they base more detailed investigations.

The Survey's library, card indexes, and open files have been continually searched and used for and by exploration companies, consultants, research workers, and the general public. Also the specialists with the Survey have been consulted on many aspects of geology affecting exploration.

The hydrogeologists and engineering geologists were used to their full capacity in the search for underground water and in the investigation of dam sites for additional water supplies, which are vital to the rapid mineral, agricultural, and pastoral development occurring within this State at present.

The increasing demand for geological investigations and services shows no sign of slackening and, as it is estimated that the value of the mineral production will rise to at least $A380 million in 1971, this demand must continue to increase rapidly.

It is considered that the specialists' activities of the Branch should expand gradually to carry out more research into problems arising out of this great period of exploration. Very few of the operating companies have the facilities or staff available for research activities. Such activities are considered necessary for developing our mineral resources even further than visualised at present.

### STAFF

Six new professional positions, including a production geologist for the Sedimentary (Oil) Division and a geochemist, were approved during 1967.

As in other geological organizations some staff members have resigned to accept more lucrative positions with companies, and difficulties are being experienced in recruiting new staff. At the end of the year there were nine vacancies, although some appointments were being negotiated.

The establishment of the Geological Survey is now 47 professional, 6 clerical, and 12 general officers.

*PROFESSIONAL*

*Appointments*

| Name | Position | Effective Date |
|---|---|---|
| H. Rutter, B.Sc. (Hons.) | Geophysicist, Grade 2 | 5/1/67 |
| L. J. Peet, B.Sc. | Geologist, Grade 2 | 13/2/67 |
| P. M. Hancock, B.Sc. (Hons.) | Geologist, Grade 2 | 3/7/67 |
| R. Lake, B.Sc. | Geologist, Grade 2 (Temp.) | 30/8/67 |
| A. H. Pippet, B.Sc. (Hons.) | Production Geologist | 23/10/67 |

*Resignations*

| | | |
|---|---|---|
| J. D. Wyatt | Geologist, Grade 1 | 11/10/67 |
| L. J. Peet | Geologist, Grade 2 | 15/12/67 |

*CLERICAL AND GENERAL*

*Appointments*

| | | |
|---|---|---|
| J. G. Neil | Geological Assistant | 5/1/67 |
| K. Gannon | General Assistant | 27/11/67 |
| R. E. Peters | Clerk | 4/12/67 |
| D. Jennings | Clerk | 15/12/67 |

*Resignations*

| | | |
|---|---|---|
| V. D. Thornber | General Assistant | 24/11/67 |

*Transfers*

| | | |
|---|---|---|
| F. Hargrave | Clerk | 11/8/67 |
| G. W. Wiltshire | Clerk | 28/12/67 |

### ACCOMMODATION

It became necessary during 1967 to rent part of yet another separate small building for this Branch. This was to relieve the cramped conditions existing in the library and records section. The Branch is now spread through six buildings. It is hoped that a solution to this unsatisfactory condition will be announced shortly.

Although plans have been prepared for the expansion of the core library at Dianella, building has not yet commenced.

A block of land in the suburb of Morley has been purchased for the establishment of a new store and vehicle park, when the existing area has to be vacated. Building of this new store will be required during the next financial year.

### OPERATIONS

*HYDROLOGY AND ENGINEERING GEOLOGY DIVISION*

E. P. D. O'Driscoll (Chief Hydrogeologist), K. Berliat, F. R. Gordon, T. T. Bestow (Senior Geologists), D. H. Probert, K. H. Morgan, J. R. Passmore, P. Whincup, R. A. Farbridge, C. C. Sanders, J. L. Baxter, L. N. Wall, P. Hancock, A. D. Allen (on leave without pay at London University), and R. S. Chaturvedi (Colombo Plan Fellow).

*Hydrology*

Exploratory drilling in the Arrowsmith River area was completed, and a large supply of groundwater is now being pumped to Morawa township and the district en route.

At Mandurah the last of the fourteen bores is now completed and the project has been suspended.

An east-west line of deep bores was continued in the Quindalup—Busselton region. Drilling will later be extended eastward towards Donnybrook.

At Albany, one exploratory bore for the town water supply scheme was completed near Snake Hill.

The final seven bores forming part of a geophysical investigation at Neridup were drilled.

To try and augment the Northern Comprehensive Water Supply Scheme by using groundwater, exploratory rotary and percussion drilling is now being done on the central Perth Basin westward of Watheroo and Coomberdale, and will continue into 1968. Westward of the same area two successful bores were constructed for the Midlands Light Lands Committee.

For the Metropolitan Water Board several parts of an extensive shallow sand aquifer in the Lake Gnangara area have had groups of bores installed, and these are being test pumped to establish aquifer characteristics.

With the exception of a relatively small inaccessible corner, regional mapping and a bore census have been completed on the Esperance 1:250,000 geological sheet. Part of the Ravensthorpe Sheet has also been mapped, and a bore census is under way. Census work is also being done on the Perth Basin.

To assist an arid zone research project, three groups of test bores were drilled and test pumped in calcreted areas in the Cue district. The hydrology of the Cue 1:250,000 geological sheet is also being studied.

One geologist was seconded to regional mapping of the Talbot, Bentley, and Cooper 1:250,000 geological sheets, part of his duties being a hydrological assessment of the area. Mapping has also been done of a belt of Moora Group cherts along the Darling—Urella fault zone, to examine its groundwater potential.

Field surveys were made for seven government projects and 80 for private landholders. Compilation of bore records throughout the State has continued.

The draft of proposed legislation on underground water is now being prepared.

*Engineering Geology*

A proposed dam site at Rocky Pool on the Gascoyne River was mapped in detail and the foundations have been explored by auger drilling. Site feasibility studies included drilling and setting up piezometer tubes in several flood channels or anabranches which may be zones of reservoir leakage.

In the Kimberleys two proposed dam sites, Moochalabra Creek No. 3 for Wyndham water supply, and Arthur Creek were examined, and also two sites in the Pilbara district. Seven sites for irrigation water storage were mapped on Ferguson Brook and Joshua Brook near Dardanup, and Gemcodril work supervised on three. A new proposed spillway for the Ord River main dam site has been inspected.

A major project was the examination of the foundations of Waroona Dam, and supervision of extensive test drilling to determine leakage paths and to instal remedial works.

Some further mapping has been done on a new spillway area at North Dandalup dam site, and diamond drilling supervised.

SEDIMENTARY (OIL) DIVISION

P. E. Playford (Supervising Geologist), A. H. Pippet (Production Geologist), G. H. Low, D. C. Lowry.

During 1967 an increased part of the Division's time was occupied in the collation of oil exploration and production data, and in reviewing company exploration programmes. The Division was also called on to assist in drafting the new petroleum legislation which was enacted during the year. With the appointment of a Production Geologist, the Geological Survey now has the services of a geologist with specialised knowledge of petroleum production and conservation.

Regional mapping of the Perth Basin was continued on the Moora and Perenjori 1:250,000 Sheets. Exposures in this area consist largely of the Proterozoic Moora Group. Compilation of the Eucla Basin maps and bulletin proceeded during the year, and a brief field trip was made to complete mapping in the Point Dover area.

The Supervising Geologist spent three months in the United States and Canada working on a joint project with the Denver Research Center of the Marathon Oil Company to compare the Devonian reef complexes of the northern Canning Basin with those of western Canada.

REGIONAL GEOLOGY DIVISION

R. C. Horwitz (Supervising Geologist), J. L. Daniels (Senior Geologist), M. J. B. Kriewaldt, I. R. Williams, and J. J. G. Doepel.

*Eastern Goldfields area*

Geological mapping was continued on the Kurnalpi 1:250,000 Sheet and was commenced on the Menzies 1:250,000 Sheet. Both are nearly completed. A persistent stratigraphic succession has been established for the Kurnalpi Sheet, and mapping on the Menzies Sheet has linked the Kalgoorlie general area to a province to the northwest.

Gossans in Archaean sedimentary rocks have been found on both these geological sheets. The geological setting indicates that they are not primarily nickel prospects but that they could represent deposits of other base metals.

*Blackstone—Warburton general area*

Geological mapping was completed on the Cooper and Bentley 1:250,000 Sheets and the Talbot Sheet is well advanced. Chemical results, on samples collected last year, revealed the presence of vanadiferous magnetite on the Scott Sheet; these deposits have been further mapped on the Bentley and the Scott Sheets.

*General*

Mapping of the Precambrian has started on the Geraldton Sheet. Mapping of the Perth Sheet, including a revision of the geology of the Perth metropolitan area, was commenced, and mapping of the Peak Hill Sheet was continued. Liaison was maintained with field parties of the Hydrology Division during the mapping of Precambrian rocks in the southern part of the State and the islands of the Archipelago of the Recherche.

The progress of geological mapping at 1:250,000 scale to the end of 1967 is shown on Figure 2.

MINERAL RESOURCES DIVISION

L. E. de la Hunty (Supervising Geologist), J. Sofoulis (Senior Geologist), J. G. Blockley, P. C. Muhling, and J. L. Baxter.

*Kimberley Division*

The field work for the Kimberley mapping project, conducted jointly with the Bureau of Mineral Resources, was completed during 1967. Areas of Precambrian rocks on the Yampi, Charnley, Lennard River, and Noonkanbah 1:250,000 Sheets were mapped. Deposits of chromite, goethite, and emery were investigated.

An inspection was made of a new silver-lead-gold-copper deposit near Kununurra, in the eastern part of the Kimberley Division.

*North-West Division*

Brief inspections were made of several iron ore deposits in the Hamersley Iron Province, including those at Wittenoom Gorge, Mt. Lockyer, and Dales Gorge.

## GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
### 1:250,000 OR 4 MILE GEOLOGICAL MAPPING
### 1967

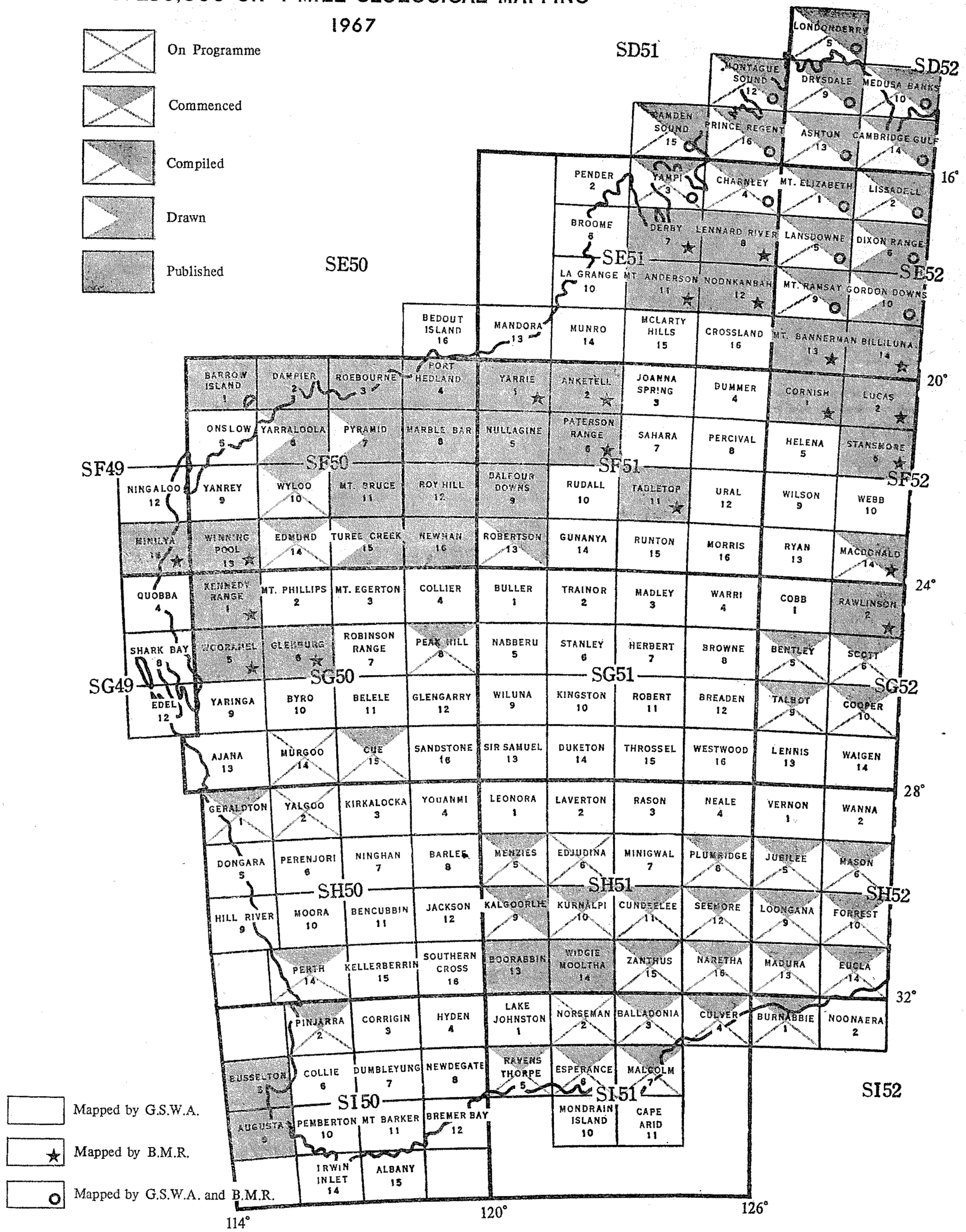



**FIGURE 2**

Some mapping was done on recently abandoned mineral claims for blue asbestos in the Wittenoom Gorge area, and compilation of the bulletin on blue asbestos was continued. A photographic type section of the Dales Gorge Member of the Brockman Iron Formation was prepared.

A subsidised diamond drilling programme was carried out at the Thaduna copper mine, north of Meekatharra.

Field work was continued on the mineral resources, regional geology, and hydrology of the Cue 1:250,000 Sheet.

Miscellaneous inspections were made of deposits of gold, copper, ochre, water, and a reported meteorite occurrence.

*COMMON SERVICES DIVISION*

*Petrology* (A. F. Trendall and R. Peers).

Thirty file reports were written during the year, mainly for the various Divisions of the Geological Survey, but some in response to public enquiries. The majority of these reports were the work of Miss Peers. A total of 1,230 thin-sections and 47 polished sections were prepared by the technical staff; many of these were passed directly to the collecting geologists for examination. Discussion with geologists of problems arising during such examination forms an important part of the Geological Survey petrological work.

It is a policy of the Geological Survey to avoid the divorce of detailed petrological work from the broad environment of the rocks studied; in accordance with this policy Miss Peers visited the Cue Sheet mapping party, and Dr. Trendall made a tour of field parties in the Warburton Range area, the Menzies Sheet and the Kurnalpi Sheet, in addition to spending a month in the Hamersley Range area.

During much of the year Dr. Trendall was engaged jointly with Mr. J. Blockley on the preparation of a final account of a continuing study of iron formations of the Hamersley Range area, with particular attention to the associated crocidolite. This is almost completed.

Mineralogical and chemical work by the Government Chemical Laboratories continued to complement petrological work, and this is gratefully acknowledged.

*Palaeontology* (A. E. Cockbain, B. S. Ingram).

Seventy-three file reports were written in 1967. These reports covered a wide variety of work and included studies of the Cretaceous of the Perth Basin, Tertiary of North West Cape and the Denmark-Esperance area, Cretaceous of the Warburton-Blackstone area, Permian of Kennedy Range dam site, and Precambrian of the Watheroo-Coomberdale area. As in 1966 the main interest of the section has been in the Mezozoic palynology of the Perth Basin and the stratigraphic palaeontology of Foraminifera and Bryozoa from the Eucla Basin. A statistical breakdown of the file reports is given below.

| Reports written for | Field of Palaeontology | | |
|---|---|---|---|
| | Palynology | Micropalaeontology | Macropalaeontology |
| Hydrogeology/Engineering .... | 40 | 10 | 1 |
| Sedimentary (Oil) .... .... .... | 4 | 6 | 4 |
| Regional Mapping/Mineral Resources .... .... .... .... | 1 | .... | 2 |
| Miscellaneous .... .... .... | 1 | 4 | .... |

Once again, we are grateful to Mr. B. E. Balme (University of Western Australia) and Mr. G. W. Kendrick (Western Australian Museum) for their help in examining certain samples.

*Geophysics* (D. L. Rowston and H. Rutter).

Routine well-logging services for the Hydrology Division again dominated geophysical activities. During the year 72 logging operations, involving 42 individual drillholes with a total logged footage of 51,700 feet, were carried out. This was a significant increase over 1966 when 35 runs were made in 26 holes totalling 38,000 feet.

Normal laboratory facilities were maintained and field salinity determinations made on 700 water samples. The estimation of formation water salinities from the long normals resistivity well-logging was re-assessed; salinities in Cretaceous and younger sediments of the Perth Basin can now be determined with a minimum accuracy of ± 15 per cent.

An evaluation of the geophysical results at Esperance (1966) was made on the completion of test drilling early in the year. Notably, all the high yielding bores were in magnetic lows associated with depressions and drainages in the Archaean basement. The resistivity method can also be usefully employed to determine the thickness of sediments.

Minor geophysical investigations were made at Northampton (lead) and Big Bell (gold). An experimental resistivity survey near Cue indicated that interpretations of depth probe curves from this saline, calcrete environment, in terms of geology, can be highly speculative.

*Technical Information Section* (R. R. Connolly, M. E. Redman, and S. M. Fawcett).

The demand for information from companies and individuals has continued to increase. Such requests are for reports, plans, photocopies, samples, bibliographies, displays, rock and mineral identification, etc. Service is often hampered by inadequate storage and operating space.

Library loans to the staff increased to 2,429 and loans to other than staff totalled 490. This is an overall increase of 33 per cent. Requisitions to the Drafting Office for services numbered 734. Eight publications were edited, printed, and distributed, and 23 Records were prepared.

At the core library the storage capacity of the existing building has been reached and the planned extension is required to cope with samples being received.

## 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) Regional geological mapping of the Yampi, Charnley, Lennard River, and Noonkanbah 1:250,000 Sheets in the Kimberley Division, jointly with the Geological Survey of Western Australia.

(2) Continuation of the sampling of Precambrian rocks in the Kimberley area for age determination.

(3) Aeromagnetic survey (DC3 aircraft) of the Sir Samuel and Duketon 1:250,000 Sheets.

## PROGRAMME FOR 1968

*HYDROLOGY AND ENGINEERING DIVISION*

*Hydrology*

1. Continuation of the hydrogeological survey of the Perth Basin including deep drilling.
2. Hydrogeological investigation and exploratory drilling for groundwater in the following areas:
   (a) Watheroo—north to Carnamah and south to Moora.
   (b) Albany.
   (c) Gnangara Lake.
   (d) Mandurah-Pinjarra.
   (e) Mullewa.
   (f) Ravensthorpe.
   (g) Port Gregory.
   (h) Fitzroy Crossing.
   (i) Millstream.
   (j) Horrocks Beach.
   (k) Others may be added.

3. Kimberley—hydrogeological assistance to pastoralists.
   (a) bore site selection as required
   (b) completion of the hydrogeological mapping in conjunction with the Bureau of Mineral Resources.
4. Miscellaneous minor investigations as requested by other departments and the public.

*Engineering*

1. Ord River Dam—northern spillway investigation.
2. Helena River—investigation of possible new dam sites.
3. North and South Dandalup dam site—further investigation.
4. Erosion studies at Bandicoot Bar Dam.
5. Moochalabra Creek—mapping of foundation area.
6. Pilbara—investigation of possible dam site.
7. Other dam site investigations for Public Works Department if staff available.

*SEDIMENTARY (OIL) DIVISION*

1. Maintain an active interest in the progress of oil exploration in Western Australia.
2. Continuation of the mapping programme in the Perth Basin.
3. Completion of the geological survey of the Eucla Basin.
4. Bugle Gap detailed biostratigraphic study in association with the Bureau of Mineral Resources.
5. Miscellaneous investigation as required.

*REGIONAL GEOLOGY DIVISION*

1. Completion of the mapping of the Kurnalpi, Menzies, Balladonia and Malcolm 1:250,000 Sheets in the Eastern Goldfields.
2. Commence the mapping of the Edjudina and Norseman 1:250,000 Sheets in the Eastern Goldfields.
3. Complete the mapping of the Talbot 1:250,000 Sheet in the Eastern Division.
4. Complete the mapping of the Geraldton and Peak Hill 1:250,000 Sheets.

*MINERAL RESOURCES DIVISION*

1. Continuation of the mineral survey of the Yalgoo and Murchison Goldfields.
2. Detailed investigation of the Ministerial Reserve near Rocky Dam, Kurnalpi 1:250,000 Sheet.
3. Preparation of a mineral resources bulletin on the silver-lead-zinc deposits of W.A.
4. Miscellaneous investigations as required.

## PUBLICATIONS AND RECORDS

*Issued during 1967*

Mineral resources of Western Australia.

Bulletin 117, the geology and iron deposits of the Hamersley Range area, Western Australia.

Annual report 1966.

Geological map of Widgiemooltha 1:250,000 Sheet (SH/51-14 International Grid) with explanatory notes.

Bulletin 118, Devonian reef complexes of the Canning Basin, Western Australia.

*In Press*

Geological map of Pyramid 1:250,000 Sheet (SF/50-7 International Grid) with explanatory notes.

Geological map of Busselton and Augusta Sheets (SI/51-5 and SI/51-9 International Grid) with explanatory notes.

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

Geological map of Turee Creek 1:250,000 Sheet (SF/50-15 International Grid) with explanatory notes.

*In Preparation*

Bulletin 119, Iron Formations of the Precambrian Hamersley Group Western Australia with special reference to the associated crocidolite. Geological maps (1:250,000) with explanatory notes, the field work for each having been completed: Robertson, Kalgoorlie, Wyloo, Scott, Edmund, and sheets covering the Western Australian portion of the Eucla Basin, namely Culver, Naretha, Burnabbie, Madura, Loongana, Jubilee, Noonaera, Eucla, and Forrest.

*Records Produced*

1967/1 Water supplies in the East Kimberley region, by J. R. Passmore.
1967/2 Interim report on a vanadium prospect, Jameson Range, Western Australia, by J. L. Daniels.
1967/3 Hydrogeology of the Yule River area, Port Hedland town water supply, by P. Whincup.
1967/4 Explanatory notes on the Robertson 1:250,000 geological sheet, Western Australia, by L. E. de la Hunty.
1967/5 The hydrogeology of the Yampi and Lennard River 1:250,000 geological sheets, by R. A. Farbridge.
1967/6 Esperance geophysical survey, by D. L. Rowston.
1967/7 Explanatory notes on the Turee Creek 1:250,000 geological sheet, Western Australia, by J. L. Daniels.
1967/8 Notes on Ministerial Reserve 3811H near Lake Rebecca, Western Australia, by R. C. Horwitz.
1967/9 Hydrogeological features of the Gascoyne River, west of the Kennedy Range, by J. L .Baxter.
1967/10 Explanatory notes on the Kalgoorlie 1:250,000 geological sheet, Western Australia, by M. J. B. Kriewaldt.
1967/11 Big Bell mine geophysical survey, by D. L. Rowston and H. Rutter.
1967/12 The origin of blow-holes and the development of domes by exsudation in caves of the Nullarbor Plain, by D. C. Lowry.
1967/13 The mineral resources of Western Australia and their potential, by J. H. Lord.
1967/14 Geological investigations at the Kennedy Range dam site, by J. D. Wyatt (*Restricted*).
1967/15 Groundwater in the Busselton area, progress report on exploratory drilling, by D. H. Probert.
1967/16 The general geology of the Rocky Pool dam site, by J. L. Baxter (*Restricted*).
1967/17 Exploratory drilling for a water supply north of Wingellina, by R. A. Farbridge.
1967/18 Geological reconnaissance of a dam site at Bullinnarwa Pool, by F. R. Gordon (*Restricted*).
1967/19 Silver-lead-gold-copper prospect, M.C.38, Kununurra area, Kimberley Goldfield, Western Australia, by J. Sofoulis.
1967/20 Prospective dam sites on the Shaw River, Pilbara Division, by F. R. Gordon.
1967/21 Wells drilled for petroleum exploration in Western Australia, by P. E. Playford.
1967/22 Groundwater investigation in the Werillup area for the Albany town water supply, by D. H. Probert.
1967/23 Petrography and depositional environment of some Precambrian sedimentary rocks from Thaduna, Western Australia, by A. F. Trendall.

*Reports in other Publications*

Cockbain, A. E., 1967, *Asterocyclina* from the Plantagenet Beds near Esperance, W.A.: Australian Jour. Sci. v. 30, p. 68-69.

Horwitz, R. C., 1967, Pangaea and some units in the Precambrian and the Palaeozoic: Tectonophysics v. 4, p. 5-15.

Lord, J. H., 1967, The mineral resources of Western Australia and their potential: Royal Soc. West. Australia Jour. v. 50, p. 33-40.

Lowry, D. C., 1967, List of large collapse dolines in the Western Australian part of the Eucla Basin: Western Caver v. 7, no. 3, p. 1-7.

———1967, The origin of Eastern Cave doline, Western Australia: Australian Geographer v. 10, p. 300-302.

Lowry, D. C., and Lowry, J. W. J., 1967, Discovery of a thylacine, Tasmanian tiger, carcase in a cave near Eucla, Western Australia: Helictite v. 5, no. 2, p. 25-29.

Williams, I. R., and Sofoulis, J., 1967, The geology of the Prince Regent and Camden Sound 1:250,000 Sheet areas SD 51/16-15: Australia Bur. Mineral Resources Rec. 1967/38 (unpublished).

12th February, 1968.

J. H. LORD
Director,
Geological Survey.

# GROUNDWATER IN THE BUSSELTON AREA, PROGRESS REPORT ON EXPLORATORY DRILLING

by D. H. Probert

## INTRODUCTION

Between September 1966 and August 1967 an east-west line of exploratory groundwater bores was drilled in the Busselton area in the southern part of the Perth Basin. The bores were drilled to investigate groundwater occurrence in the rapidly developing coastal areas between Busselton and Dunsborough and also as part of the general investigation of the Perth Basin. Five bores ranging from 1,485 feet to 2,010 feet deep were drilled at locations shown on Plate 1.

The drilling confirmed the presence west of Busselton of major faulting beneath a strong unconformity seperating underlying older sediments of Permian and Lower Jurassic ages from an overlying blanket of South Perth Formation and Quaternary sediments. The faulting divides the western section of the basin into fault blocks of different ages. Groundwaters in the sediments west of Quindalup bore 1 are generally of poor quality and supply, and unsuitable for domestic use or irrigation. In Quindalup bores 1, 4, and 5 promising supplies of low salinity groundwater were encountered in Lower Jurassic to Lower Cretaceous sediments. This water is suitable for domestic use, but because of high bicarbonate content, some may have to be treated before being acceptable for irrigation use on clayey soils.

The bores were drilled using the Mines Department Mayhew 2000 rotary rig, with sludge samples collected every 10 feet and cores taken wherever practicable. Water samples were collected by means of Halliburton and Johnson Formation Testers and samples sent for analysis at the Government Chemical Laboratories. The bores were geophysically logged by the Geological Survey and routine palynology was carried out on selected samples. The results of chemical analyses and palynological determinations are shown in Appendices 2 and 3.

## PHYSIOGRAPHY

The southern part of the Perth Basin has been divided (Lowry, 1965) into four broad physiographic regions.

The *Swan coastal plain* is a flat dune, soil, and alluvium covered plain extending northwards along the coast of Geographe Bay, bounded in the south by the Whicher scarp, and in the east by the Darling fault scarp. The plain has an average width of about 12 miles.

The *Blackwood area* is in the central section of the basin, and has a maximum elevation of about 500 feet, capped by sand and laterite and underlain by Mesozoic sediments.

The *Leeuwin—Naturaliste ridge,* which marks the western margin of the basin, has a maximum elevation of about 700 feet and is a north-south trending ridge of Precambrian crystalline rocks capped by laterite and Coastal Limestone. The ridge is bounded on the east by the Dunsborough fault.

The *Scott coastal plain* is a low lying swampy flat plain marked by scattered dune ridges.

## GENERAL GEOLOGY

The southern part of the Perth Basin consists of a deep trough of sediments flanked on the east and west by Precambrian crystalline rocks of the Western Australian Shield and the Leeuwin-Naturaliste ridge. The trough continues to the north and south beneath the Indian Ocean, forming a graben between the Dunsborough and Darling faults.

Geophysical evidence suggests that a maximum thickness of 15,000 to 20,000 feet of easterly dipping sediments is present in the central and eastern sections of the basin, and that this is intersected by four major, branching, north-south trending, faults having throws of up to 8,000 feet.

Lowry has described in detail the surface geology, which consists of a few scattered outcrops of Mesozoic sediments mainly masked by Quaternary deposits including alluvium, dune sands, and Coastal Limestone in the coastal plains, and sand and laterite in the Blackwood area.

Bores have intersected the sediments underlying the Quaternary sequence but mostly they are shallow and have been confined to the Lower Cretaceous—Upper Jurassic South Perth Formation, which probably blankets older sediments over a large proportion of the basin. However Sue No. 1, Alexandra Bridge No. 1 petroleum exploration wells and several coal bores in the southwest encountered Lower Permian sediments beneath the South Perth Formation, and the Abba River and Western Titanium bores encountered the Upper Jurassic Yarragadee Formation.

### *Quindalup bores 1 to 5*

Drilling in the present part of the programme was confined to the Swan coastal plain. Bores 1 to 3 were located on the fringes of Geographe Bay 2½, 6½ and 10 miles west of Busselton respectively, and bores 4 and 5 at Wonnerup and Ruabon, 8 and 12 miles east of Busselton (Plate 1).

The bores intersected a thin veneer of Quaternary sediments overlying South Perth Formation, which in turn is separated from underlying older sediments by a strong unconformity. These sediments include those of Permian, Lower Jurassic, and Upper Jurassic ages.

The stratigraphic relationship between the bores is shown in Table 1.

### *Quaternary*

The Quaternary sediments vary from 20 to 35 feet in thickness, forming a veneer above the South Perth Formation. In bores 1 to 3 they consist of well-sorted, fine-grained sand, marly clay, and shelly limestone of the Quindalup Dune System. In bores 4 and 5 farther inland, the sediments are poorly sorted, iron-stained sand and shelly limestone which possibly belong to the older Bassendean Dune System.

### *Lower Cretaceous to Upper Jurassic*

Current thought on the South Perth Formation includes sediments described by previous workers as belonging to the Capel River Group and Yarragadee Formation.

In the Quindalup bores the thickness ranges from 270 feet in bore 4 to 1,180 feet in bore 5. The sediments are dominantly of continental type but rare microplankton indicate some marine influence during deposition. They are typically poorly consolidated, finely current-bedded, and lenticular. Correlation between bores is difficult and suspect, but the general dip is very gentle from east to west.

The sequence consists mainly of silt, siltstone, clay, poorly-sorted sand and sandstone containing abundant carbonaceous material, pyrite, and mica, and thin bands of lignite.

The arenaceous sediments are feldspathic, and are more consolidated with depth, making up 60 to 75 per cent of the total section.

The South Perth Formation unconformably overlies older sediments in each of the Quindalup bores.

### *Upper Jurassic*

The Upper Jurassic Yarragadee Formation was encountered in Quindalup bores 4 and 5 and in nearby bores in the Abba River and Capel areas where it underlies the South Perth Formation.

The section is dominantly an arenaceous continental deltaic deposit containing less than 20 per cent. clay and silt. The sandstone and sand differ little from those of the overlying South Perth Formation but are typically garnetiferous and slightly more consolidated. They are generally moderately to poorly sorted, medium to very coarse in grain, and slightly feldspathic. Interbedded siltstone, clay, mudstone, and rare lignite make up the remainder.

*Lower Jurassic*

Lower Jurassic sediments of continental type are present between 630 and 1,930 feet in Quindalup bore 1. They consist of cross-bedded, poorly-sorted, silty to coarse-grained sand and poorly consolidated sandstone interbedded with mottled grey to red claystone, grey to green pyritic shale and siltstone. The claystone shows slickensiding and slumping.

Overlain unconformably by the South Perth Formation, the Lower Jurassic material in Quindalup bore 1 is the first observed occurrence of sediments of this age in the southern part of the Perth Basin, and is equated to the Cockleshell Gully Formation.

*Permian*

Permian sediments, also overlain unconformably by the South Perth Formation, occurred in Quindalup bores 2 and 3, the westernmost bores of the line.

In Quindalup bore 2 they are present between 365 and 1,807 feet, and consist of well consolidated fine to coarse-grained, slightly argillaceous sandstone containing abundant garnet, finely current-bedded, grey siltstone, 17 seams of carbonaceous shale, and poor quality dull coal ranging from 7 to 11 feet in thickness. The sandstone contains rare calcareous material.

In Quindalup bore 3 the sequence is lithologically similar except that only one 8-feet thick dull coal seam was encountered, although carbonaceous material commonly occurred as partings on bedding planes.

The Permian sequences are of different ages, that of Quindalup bore 3 being the younger of the two.

## STRATIGRAPHY AND STRUCTURE

The stratigraphic relationships are shown in Plate 2, and in Table 1.

The Quaternary material forms a thin veneer over the South Perth Formation, and the maximum observed thickness of 35 feet is probably exceeded only in the Wonnerup area where gamma-ray logging of existing bores indicates a thickness of about 50 to 120 feet near the Wonnerup Estuary.

The South Perth Formation is present throughout the drilling area and ranges widely in thickness from 345 to 668 feet west of Busselton, thickening to over 1,000 feet in the Milne Street, Abba River 1, and Quindalup 5 bores. It thins again to 180 to 300 feet in the Wonnerup-Capel area. The cross-section between Abba River 1 bore and Capel (Plate 2) shows this variation, which may either be due to deposition over a deeply dissected Upper Jurassic surface or to post-Yarragadee Formation faulting. There is little concrete evidence to support the latter supposition, but differences in levels of basalt flows encountered in Quindalup bore 5 and Abba River bore 3 may either be due to depositional dip or to minor faulting. If a deep trough of South Perth sediments exists it probably is an old erosional channel which may extend as far east as the Whicher scarp, and possibly be related to basalt occurrences in the area.

The variation in thickness of the South Perth Formation illustrates the strong unconformity which separates these beds from the underlying strata. Below the unconformity three major north-south trending faults with throws of several thousand feet have been proved by the drilling. These include the Wirring and Busselton faults inferred from previous gravity and seismic surveys, and a fault postulated by Lodwick from seismic data. The faults divide the area beneath the unconformity west of Busselton into four blocks containing Upper to Lower Permian, Lower Permian, Lower Jurassic, and Upper Jurassic sediments. The block between the Wirring and Busselton faults is uplifted with respect to the others, which are normal east block down.

The Yarragadee Formation is present east of Busselton in Quindalup bores 4 and 5, Abba River bores 1 and 3, and in bores at the Western Titanium mining pit at Capel. No bores have penetrated the full succession of the Jurassic sediments which reach a maximum observed thickness of 1,615 feet in Quindalup bore 4.

Lower Jurassic sediments in Quindalup bore 1 are of similar lithology and age to the Cockleshell Gully Formation in the Hill River area, but the arenaceous sediments appear to be generally coarser in grain. The Lower Jurassic sediments are restricted in occurrence to the fault block immediately west of Busselton and nothing is yet known of their extension to the south.

Lower Permian coal-bearing sediments in Quindalup bore 2 are probably Upper to Lower Artinskian in age. The lower part of the section contains similar spore assemblages to the lower Artinskian coals of the Collie and Irwin River areas and to those encountered at 8,866 feet in WAPET's Sue No. 1 well. In this part of the basin these sediments are confined to the wedge-shaped block between the Wirring and Busselton faults.

The Permian sediments in Quindalup bore 3 appear younger than those in bore 2 and have been tentatively dated as early Upper Permian to Upper Artinskian. They lie between the Dunsborough and Wirring faults and their southward extent is not known.

## OCCURRENCE OF GROUNDWATER

Groundwater was present in sediments of all ages and was sampled wherever possible by formation testers. The water samples were used by D. L. Rowston as controls for the estimation of salinities from resistivity logging. These results are shown on bore completion reports and on Plate 1.

*Quaternary aquifers*

Small supplies of groundwater are available from the thin veneer of Quaternary sediments. The water varies from stock to domestic quality and

TABLE 1

STRATIGRAPHIC SUCCESSION IN QUINDALUP BORES (EAST TO WEST)

| Age | Formation | Bore 3 (feet) | Bore 2 (feet) | Bore 1 (feet) | Bore 4 (feet) | Bore 5 (feet) |
|---|---|---|---|---|---|---|
| Quaternary .... .... .... | Recent sediments and Quindalup and Bassendean Dune Systems | 0–32 | 0–20 | 0–22 | 0–35 | 0–22 |
| Lower Cretaceous to Upper Jurassic | South Perth Formation .... .... | 32–700 | 20–365 | 22–630 | 35–305 | 22–1180 |
| Upper Jurassic .... .... .... | Yarragadee Formation .... .... | Not present | Not present | Not present | 305–1920 | 1180–2010 |
| Lower Jurassic .... .... .... | Cockleshell Gully Sandstone equivalent | Not present | Not present | 630–1930 | .... | .... |
| Early Upper Permian .... .... | .... .... .... .... .... | 700 to 1485 | Not present | | | |
| Artinskian .... .... .... | .... .... .... .... .... | | 365–1807 | | | |

Correlation based on lithology, palynology, and geophysical data.

usually contains high $H_2S$ and bicarbonate. Bores near the coast and tidal drainage channels are subject to saline intrusion. The sediments form a useful source of domestic and garden water in coastal cottages in and around Busselton.

*South Perth Formation aquifers*

The aquifers of the South Perth Formation are lenticular and contain groundwater of variable quality and supply. Lowry (1965) has summarised bore census data for the Busselton area and gives the following relationship between bore depth and frequency:

Table 2

| Bore depth (feet) (average 60) | No. of bores |
|---|---|
| 31–50 .... .... .... .... .... .... | 123 |
| 51–70 .... .... .... .... .... .... | 123 |
| 71–100 .... .... .... .... .... .... | 66 |
| 101–150 .... .... .... .... .... .... | 37 |
| >150 .... .... .... .... .... .... | 10 |

These sediments are the most important source of groundwater for farmers, particularly the shallow glauconitic sands near Quindalup. Generally bores are sited for convenience, and as the beds are very lenticular the landholder continues drilling until he obtains water. Most supplies are sub-artesian, yielding 200 to 1,000 gallons per hour, and range from good stock to domestic quality, although saline groundwater has been encountered in some areas west of Busselton.

West of Busselton on the fringes of Geographe Bay, groundwater in the South Perth Formation of Quindalup bores 1 to 3 is generally of poor quality. In bore 1 thin layers of stock quality groundwater are intercalated with layers ranging in salinity from 8,000 to 20,000 ppm TDS. In bore 2 the quality is uniformly poor, avering about 14,000 ppm TDS. Farther west the quality improves to 450 to 1,500 ppm TDS.

Between Quindalup bore 1 and Capel, domestic quality groundwater is obtained at depths of 50 to 1,000 feet from the South Perth Formation. A little saline groundwater has been met near the coast at shallow depths but generally the supply and quality improves with depth. Supplies are generally good ranging from 200 gph in shallow bores to over 30,000 gph in bores 500 to 1,000 feet deep. Near the coast the bores flow.

*Yarragadee Formation aquifer*

Sediments of the Yarragadee Formation were encountered 305 and 1,920 feet in Quindalup bore 4, and between 1,180 and 2,010 feet in Quindalup bore 5. They have also been encountered in the Abba River bores 1 and 3 and in the Western Titanium works at Capel. In the Wonnerup area the sequence is dominantly arenaceous and formation testing suggests that large quantities of domestic quality groundwater (200 to 400 ppm TDS) are available. In the Capel area, bores produce 20,000 to 25,000 gallons per hour from similar but more argillaceous beds. In the Abba River area, poor results obtained in drilling the three Abba River bores probably reflect bad drilling techniques.

*Cockleshell Gully Formation (?) aquifers*

The Lower Jurassic sand and sandstone in Quindalup bore 1 contain domestic quality groundwater between 670 and 720 feet and between 952 and 1,520 feet. Between 720 and 950 feet and below 1,520 feet the salinity increases to about 2,000 ppm TDS.

Formation testing of these sands indicates that they contain good supplies which are possibly artesian.

*Permian aquifers*

The well consolidated Upper and Lower Permian sandstones in Quindalup bores 2 and 3 vary greatly in porosity and permeability. They contain groundwater ranging from good to poor stock quality (1,300 to 8,800 ppm TDS) and are probably of poor supply.

## CHEMICAL CHARACTERISTICS OF THE GROUNDWATER

Standard chemical analyses were obtained for most of the deeper bore samples in the Busselton-Capel area, and the results are shown in Appendix 3. Appendix 4 shows calculated sodium adsorption ratios, calcium—magnesium ratios, and residual sodium bicarbonate.

In the Busselton—Capel area most groundwater has a salinity of less than 600 ppm TDS and only west of Busselton, in the South Perth, Lower Jurassic, and Permian formations, do some salinities exceed this figure.

The two main groundwater sources, the South Perth and Yarragadee Formations, contain low salinity water of very similar characteristics. They have a pH ranging from 6.3 to 7.6, contain high concentrations of dissolved iron, and are typically low in calcium, magnesium, and fluoride ions. Variation lies mainly in the bicarbonate—chloride ion content of the South Perth Formation aquifers. These show a decrease in the bicarbonate—chloride ratio from east to west, which appears to be related to the incidence of old calcareous dune systems on the Swan coastal plain. The calcium—magnesium ratio shows little variation although there is a general trend of increase from east to west, indicating westerly groundwater movement.

The Yarragadee Formation aquifers show primary salinity, and both calcium-magnesium and bicarbonate-chloride ratios increase from east to west across the basin, indicating groundwater movement to the west. The bicarbonate ion content also decreases with depth and is possibly related to intake from overlying dune areas. The bicarbonate content is, with one possible exception, marginal to high, and untreated groundwater is generally unsuited for use in the irrigation of clayey soils. The exceptional groundwater, which probably belongs to the Yarragadee aquifer system, was in Yoganup bore 1 in the eastern section of the Swan coastal plain at the base of the Whicher scarp. This water has a low pH and very low bicarbonate content and suggests that groundwaters at the eastern margin of the coastal plain near the Whicher scarp may be more suitable for irrigation use.

## RECHARGE

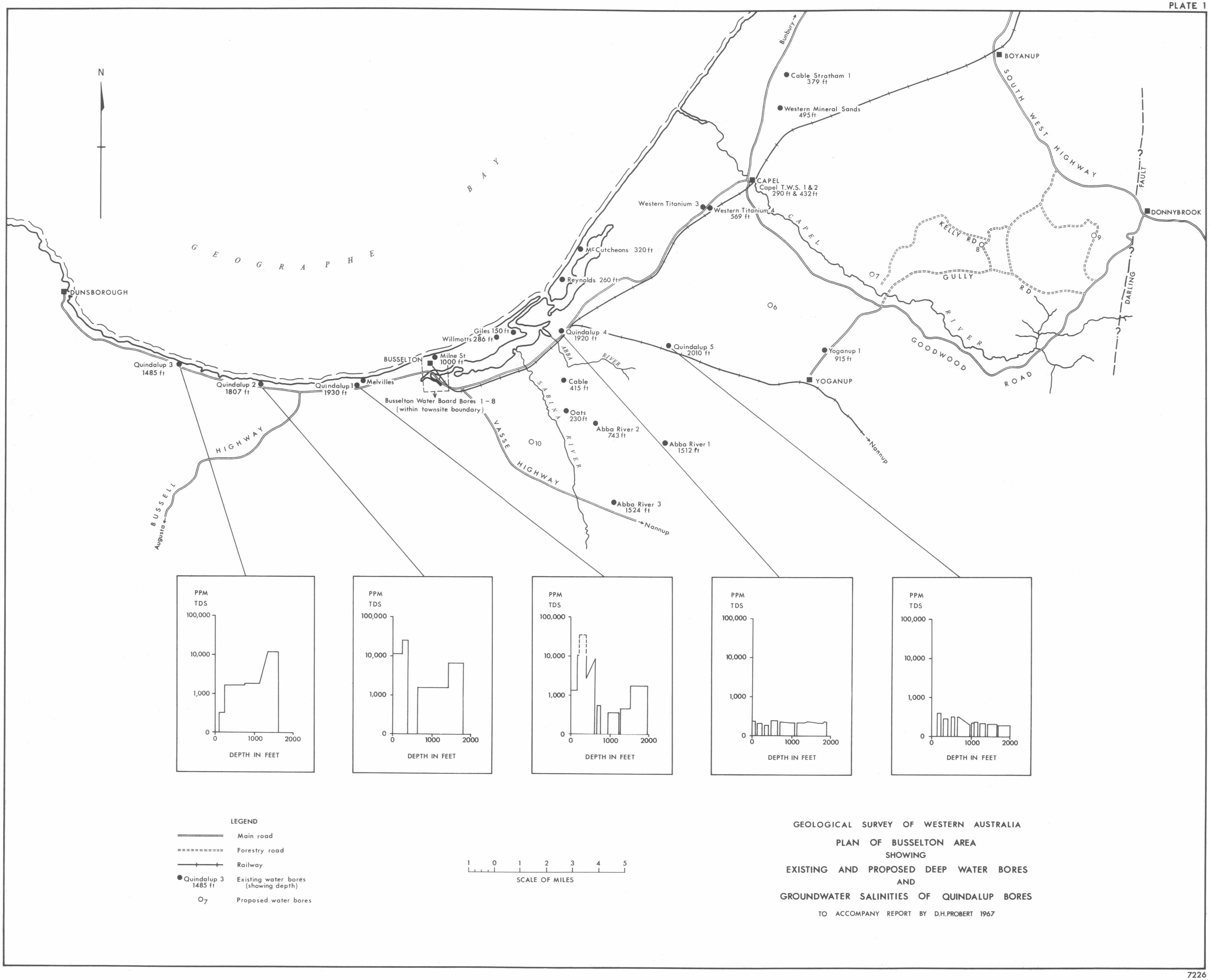
Only limited data are yet available on static water levels. Between Busselton and Yoganup two distinct water levels are present in the Yoganup bores and Quindalup bores 4 and 5, suggesting different potentiometric surfaces for the South Perth and Yarragadee aquifer systems. These have average downward gradients from east to west of 4 and 2½ feet per mile respectively over most of the plain, but rise towards the Whicher scarp.

Data from levels, lithology, and chemical analyses suggest that recharge of the South Perth aquifers is mainly by direct infiltration of rainfall and river water from the Swan coastal plain. The recharge is selectively governed by topography and the lenticular nature of the sediments, particularly in the areas west of Busselton where saline groundwater is present in both the South Perth Formation and Permian strata.

The Yarragadee Formation probably receives groundwater from the elevated areas between the Darling fault and the Swan coastal plain, although some direct recharge may occur if areas of shallow Upper Jurassic sediments are present in the eastern sections of the plain.

## AVAILABILITY AND USE OF GROUNDWATER

At present a maximum of about 10 million gallons per day of groundwater is extracted from the Yarragadee and South Perth aquifer systems for stock, domestic, town supply, and industrial purposes in the Busselton-Capel areas. It is not possible to estimate the total amount of groundwater available in this area but probably 20 million gallons could be extracted safely without depleting supplies.



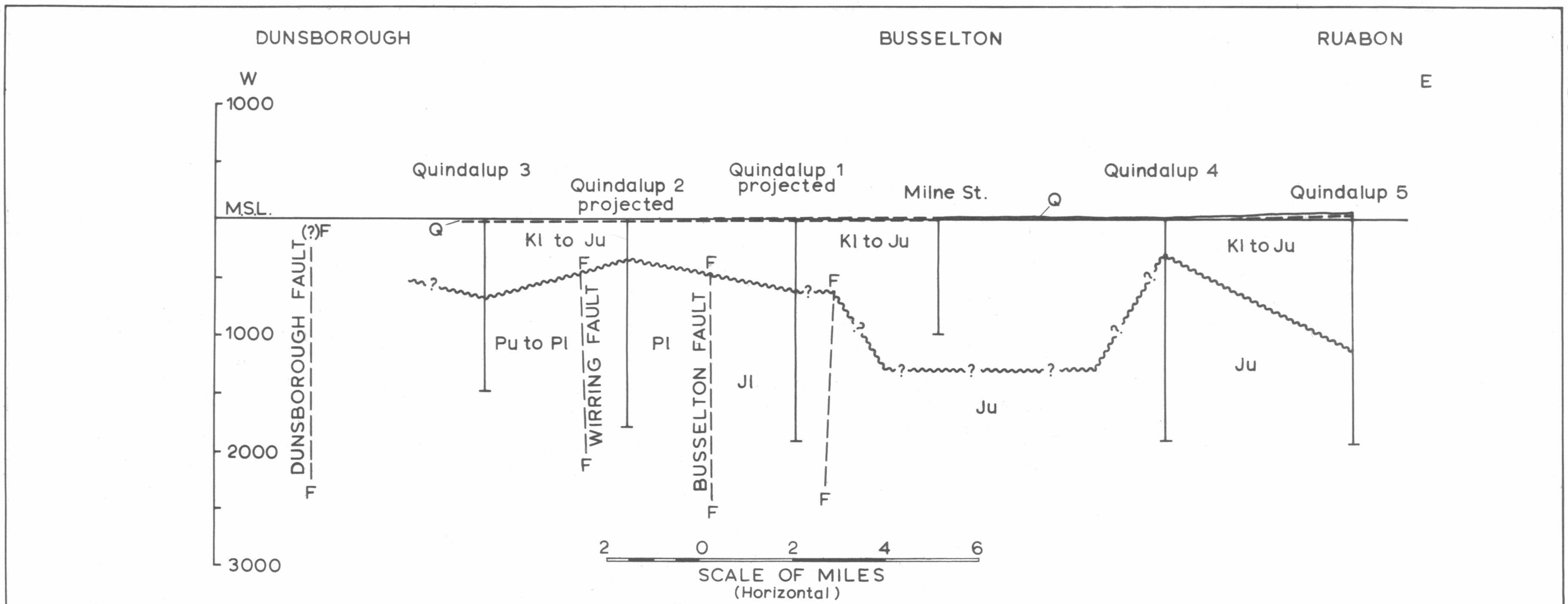

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

PLAN OF BUSSELTON AREA SHOWING EXISTING AND PROPOSED DEEP WATER BORES AND GROUNDWATER SALINITIES OF QUINDALUP BORES

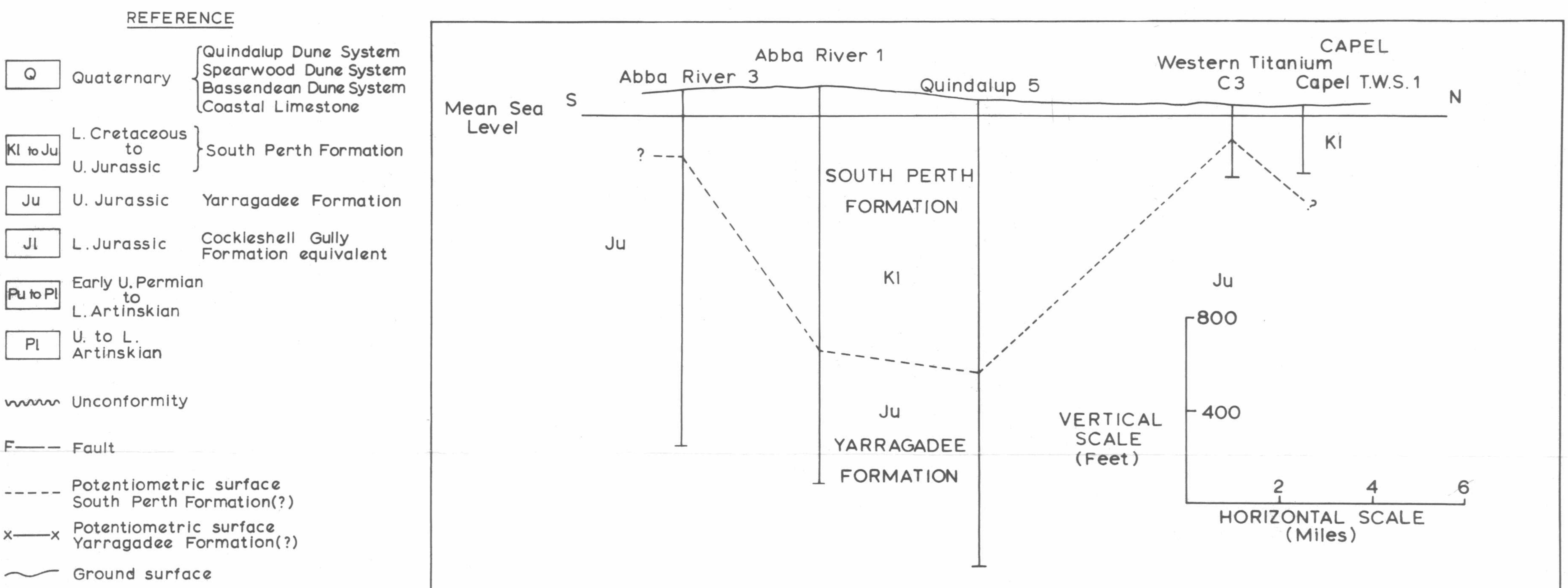
TO ACCOMPANY REPORT BY D.H.PROBERT 1967

7226

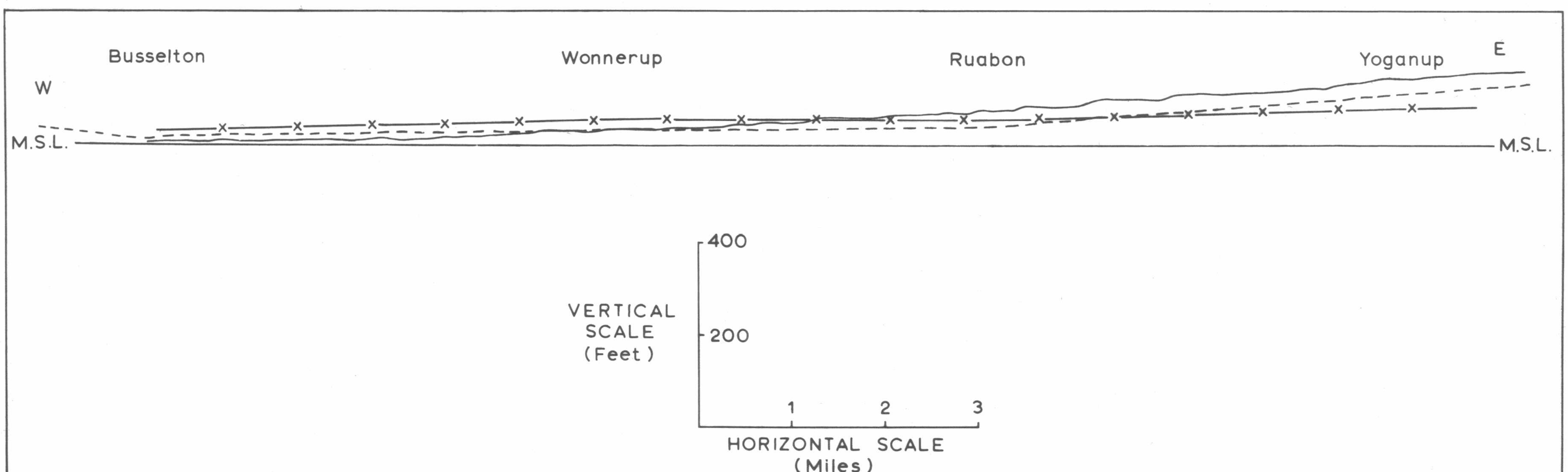
PLATE 2




STRATIGRAPHIC SECTION FROM DUNSBOROUGH TO RUABON




STRATIGRAPHIC SECTION BETWEEN CAPEL AND ABBA RIVER 3 BORE




TENTATIVE POTENTIOMETRIC SURFACE BETWEEN BUSSELTON AND YOGANUP

To accompany Report by D.H.Probert, 1967

7227

All low salinity waters are suitable for domestic use, but the waters of the Jurassic and deeper South Perth aquifers contain moderate concentrations of bicarbonate ions which would make them unsuitable for the irrigation of heavy clay soils and use in some industries without treatment. Appendix 4 shows the relationship of sodium adsorption ratios and residual bicarbonate (Eaton, 1950). Calculations based on Handa (1964) indicate that the groundwater could be made suitable for irrigation by the application of between 0.2 and 0.6 tons of gypsum per acre foot of water used.

## CONCLUSIONS AND RECOMMENDATIONS

The drilling has shown that large supplies of low salinity groundwater are available from Lower Cretaceous and Upper Jurassic sediments east and north of Busselton. This groundwater is suitable for domestic and some industrial use, but as usual in groundwaters from this area, has a high iron content. Some of the groundwaters also contain moderate concentrations of bicarbonate ions which make them unsuitable for use in irrigation without treatment. This should be no great problem.

West of Busselton the groundwater in sediments underlying the near coastal strip is of marginal to very poor quality, and between Busselton and the Busselton fault, moderate to low salinity groundwater suitable for domestic use was encountered only in the Lower Jurassic sediments. Small quantities of domestic to stock quality groundwater are present in shallow Quaternary sands or in low lying areas underlain by Lower Cretaceous sediments east of Geographe Bay. These supplies are too small and irregular to be of great value other than for farming purposes.

Plate 1 shows the location of five drill-holes proposed for the second stage of the programme. Four bores continue in a line between Ruabon and Donnybrook and will investigate the stratigraphy and hydrological potential of the eastern section of the Swan coastal plain and the elevated area of Mesozoic sediments between Yoganup and Donnybrook. A further bore is proposed to investigate the presence of groundwater between the Sabina and Vasse Rivers, 5 miles southeast of Busselton, where poor and conflicting results were obtained during the drilling of the Abba River bores in 1958.

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# Appendix 1

## LIST OF DEEP BORES IN THE BUSSELTON—CAPEL AREA

| Bore | Depth (feet) | Remarks |
|---|---|---|
| G.S.W.A. Quindalup 1 .... | 1930 | 8 in. casing to 504 feet |
| 2 .... | 1807 | Plugged, capped and abandoned |
| 3 .... | 1485 | Plugged, capped and abandoned |
| 4 .... | 1910 | 10 in. standpipe to 80 ft.; bore capped |
| 5 .... | 2010 | Plugged, capped and abandoned |
| G.S.W.A. Abba River 1 .... | 1712 | Abandoned |
| 2 .... | 743 | Abandoned |
| 3 .... | 1524 | Abandoned |
| Busselton Water Board 1 .... | 470 | Drilled 1908, abandoned 1960 |
| 2 .... | 480 | Abandoned 1938 |
| 3 .... | 560(?) | Abandoned |
| 4 .... | 163 | Bore in use |
| 5 .... | 495 | Bore in use |
| 6 .... | 363 | Bore in use |
| 7 .... | 555(?) | Bore in use |
| 8 .... | 490(?) | Bore in use |
| Milne Street .... .... .... | 1000 | Bore in use |
| Western Titanium 1 .... .... | 351 | Bore in use |
| 2 .... .... | 572 | Bore in use |
| 3 .... .... | 632 | Bore in use |
| No bore 4 drilled | | |
| 5 .... .... | 569 | Bore in use |
| Westralian Oil Capel 1 .... | 193 | Bore in use |
| Westralian Oil Yoganup 1 .... | 915 | Bore abandoned |
| 2 .... | 361 | Bore abandoned |
| Western Mineral Sands Capel 1 | 496 | Bore in use |
| 2 | 498 | Bore equipped |
| Capel town water supply 1 .... | 290 | |
| 2 .... | 432 | |
| Oats bore .... .... .... | 320 | Wonnerup-Ruabon area |
| Cable (1956) Ruabon .... .... | 450 | |
| Cable (1956) Stratham .... | 450 | |
| McCutcheon's bore .... .... | 320 | Wonnerup area |
| Vasse coal bore 1 .... .... | 159 | Drilled 1892–1900 |
| 2 .... .... | 143 | Drilled 1892–1900 |
| 3 .... .... | 269 | Drilled 1892–1900 |
| 4 .... .... | 476 | Drilled 1892–1900 |
| 5 .... .... | 656 | Drilled 1892–1900 |
| 6 .... .... | 330 | Drilled 1892–1900 |
| Blums bore .... .... .... | 297 | Bore in use |
| Reynolds bore .... .... .... | 200 | Bore in use |
| Wilmotts bore .... .... .... | 286 | Bore in use |

# Appendix 2

## PALAEONTOLOGICAL DETERMINATIONS IN THE BUSSELTON—CAPEL AREA

*Quindalup Bore 1*

| feet | |
|---|---|
| 22 .... | Quaternary—Recent |
| 110 .... | Lower Cretaceous : South Perth Formation |
| 140 .... | Lower Cretaceous : South Perth Formation (?) |
| 270 .... | Lower Cretaceous—Upper Jurassic : South Perth Formation |
| 507 .... | Barren |
| 620–650 | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 926–934 | Barren |
| 1266 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 1580 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 1680 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 1690 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 1820 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |
| 1900 .... | Lower Jurassic : Cockleshell Gully Formation equivalent (?) |

### *Quindalup Bore 2*

| feet | |
|---|---|
| 110 | |
| 170 | Lower Cretaceous (possibly Uppermost Jurassic ?): South Perth Formation |
| 310 | |
| 380 | |
| 500 | |
| 630 | Lower Permian—Upper Artinskian (?) |
| 820 | |
| 960 | |
| 1190 | |
| 1300 | |
| 1450 | Lower Permian—Lower Artinskian |
| 1730 | |
| 1800 | |

### *Quindalup Bore 3*

| feet | |
|---|---|
| 75 | |
| 315 | Lower Cretaceous (Aptian—Neocomian): South Perth Formation |
| 400 | |
| 505 | |
| 640 | |
| 840 | |
| 1140 | |
| 1165–1170 | Early Upper Permian to Lower Permian (Upper Artinskian ?) |
| 1282 | |
| 1289 | |
| 1484 | |

### *Quindalup Bore 4*

| feet | |
|---|---|
| 60 | Lower Cretaceous—Uppermost Jurassic: South Perth Formation |
| 310–316 | Upper Jurassic: Yarragadee Formation |
| 405 | Barren |
| 1098 | Upper Jurassic: Yarragadee Formation |
| 1240–1250 | Upper Jurassic: Yarragadee Formation |
| 1620–1627 | Barren |

### *Quindalup Bore 5*

| feet | |
|---|---|
| 88 | |
| 90 | Lower Cretaceous: South Perth Formation |
| 202 | |
| 343 | Barren |
| 484 | |
| 556 | Lower Cretaceous: South Perth Formation |
| 585 | |
| 620 | Aptian—marine (?): South Perth Formation |
| 1051 | Lower Cretaceous: South Perth Formation |
| 1055 | Barren |
| Sludge | |
| 1190 | Lower Cretaceous: South Perth Formation |
| 1337 | Upper Jurassic: Yarragadee Formation |
| 1340 | |

### *Western Titanium Capel Bore C3*

| feet | |
|---|---|
| 195 | |
| 210 | |
| 244 | Upper Jurassic: Yarragadee Formation |
| 260 | |
| 309 | |

### *Western Titanium Capel Mining Pit*

| feet | |
|---|---|
| | Sample taken from mining area 30 feet below ground level |
| 30 | Lower Cretaceous—Upper Neocomian to Lower Aptian—marginal marine |

### *Milne Street Bore (Busselton)*

| feet | |
|---|---|
| 150 | |
| 160 | Lower Cretaceous—Neocomian to Aptian |
| 300 | |
| 550 | |
| 690 | |
| 946 | Lower Cretaceous, probably samples poor |
| 970 | |

### *Capel Town Bore 1*

| feet | |
|---|---|
| 30 | Quaternary, probably Pleistocene |
| 70 | Lower Cretaceous—Aptian to Neocomian marine |
| 270 | Lower Cretaceous—Neocomian |

## Appendix 3

### CHEMICAL ANALYSES—BUSSELTON-CAPEL AREA

| Bore | Depth (feet) | pH | ppm TDS | | NaCl | Hardness $CaCO_3$ | Alkalinity | Ca | Mg | Na | K | Fe | $HCO_3$ | $CO_3$ | $SO_4$ | Cl | $NO_3$ | Fl | $SiO_2$ ppm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Evap. | Cond. | | | | | | | | | | | | | | | |
| Melville .... | 15 .... | .... | 1330 | 1440 | 764 | 579 | 403 | 143 | 54 | 248 | 6 | 0·1 | 491 | .... | 88 | 464 | <1 | ND | 6 |
| Quindalup 1 .... | 460–510 | 6·9 | .... | 17,000 | 11,000 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| | 935–1025 | 8·3 | 640 | 730 | 274 | 76 | 225 | 24 | 4 | 202 | 6 | ? | 274 | .... | 61 | 166 | 1 | ND | 5 |
| | 1180–1250 | 7·5 | 1450 | 1700 | 1110 | 176 | 205 | 31 | 24 | 484 | 18 | 0·4 | 250 | .... | 90 | 675 | .... | ND | 8 |
| | 1455–1580 | 8·1 | .... | 19,700 | 18,100 | .... | .... | CONTAMINATED SAMPLE | | | | | | | | | | | |
| | 1680–1770 | 7·3 | 2720 | 3010 | 2160 | 216 | 233 | 39 | 29 | 933 | 24 | <0·1 | 284 | .... | 185 | 1310 | 3 | ND | 6 |
| Quindalup 2 .... | 238–310 | .... | .... | 42,000+ | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| | 834–884 | 12·0 | .... | 3680 | 1710 | | | CONTAMINATED SAMPLE | | | | | | | | | | | |
| | 1670–1700 | 7·3 | .... | 8930 | 7650 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| | 1670–1700 | 7·1 | .... | 8930 | 7650 | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... | .... |
| Quindalup 3 .... | 275–315 | 7·9 | 1270 | 1470 | 941 | 171 | 90 | 60 | 5 | 404 | 18 | <0·1 | 110 | .... | 168 | 571 | 1 | ND | 9 |
| | 1050–1080 | 8·3 | 1280 | 1440 | 913 | 93 | 155 | 34 | 2 | 442 | 10 | <0·1 | 189 | .... | 124 | 554 | ND | ND | 18 |
| | 1390–1485 | 7·5 | 8850 | 8850 | 7840 | 1980 | 65 | 721 | 43 | 2840 | 53 | <0·1 | 79 | .... | 634 | 4760 | <1 | ND | 9 |
| Quindalup 4 .... | 326 .... | 6·3 | 200 | 220 | 120 | 41 | 50 | 5 | 7 | 53 | 11 | <0·1 | 61 | .... | 14 | 73 | 3 | ND | 16 |
| | 530–560 | 7·1 | 330 | 340 | 120 | 66 | 158 | 20 | 4 | 96 | 10 | <0·1 | 192 | .... | 25 | 73 | 1 | ND | 12 |
| | 1370–1400 | 7·6 | 420 | 420 | 166 | 83 | 181 | 20 | 8 | 109 | 20 | <0·1 | 220 | .... | 21 | 101 | <1 | ND | 13 |
| Quindalup 5 .... | 695–763 | 7·3 | 520 | 540 | 194 | 43 | 210 | 11 | 4 | 174 | 12 | <0·1 | 256 | .... | 59 | 118 | 1 | ND | 16 |
| | 1057–1105 | 6·7 | 310 | 340 | 140 | 74 | 122 | 15 | 9 | 75 | 18 | <0·1 | 149 | .... | 18 | 85 | <1 | ND | 16 |
| | 1338–1392 | 6·7 | 330 | 370 | 178 | 87 | 112 | 17 | 11 | 79 | 16 | <0·1 | 137 | .... | 15 | 108 | <1 | ND | 17 |
| | 1926–1955 | 6·5 | 270 | 310 | 152 | 71 | 85 | 12 | 10 | 63 | 17 | <0·1 | 104 | .... | 14 | 92 | <1 | 0·2 | 18 |
| | 1929–2000 | 6·8 | 310 | 350 | 163 | 65 | 105 | 13 | 8 | 84 | 16 | <0·1 | 128 | .... | 23 | 99 | <1 | 0·2 | 18 |
| Busselton Water B.5 | 585 .... | .... | 240 | .... | .... | .... | .... | 12 | 9 | 49 | 14 | 8 | 54 | .... | 10 | 95 | 3 | 0·25 | 18 |
| Milne Street .... | 350–620 | 6·6 | 190 | 218 | .... | .... | .... | 9 | 7 | 39 | 15 | 0·1 | 82 | .... | 11 | 55 | <1 | ND | ND |
| | 750–1000 | 7·6 | 272 | 361 | .... | .... | .... | 44 | 7 | 37 | 14 | 0·1 | 181 | .... | 12 | 54 | 0·2 | ND | 12 |
| Giles (Wonnerup) | 150* .... | 6·5 | 250 | 260 | 148 | 64 | 48 | 14 | 7 | 52 | 9 | 0·1 | 58 | .... | 4 | 90 | <1 | 0·3 | 24 |
| Willmott (Wonnerup) | 286* .... | 6·3 | 380 | 400 | 270 | 77 | 43 | 13 | 11 | 94 | 9 | 0·1 | 52 | .... | 19 | 164 | <1 | 0·4 | 28 |
| Reynolds (Wonnerup) | 200* .... | 6·3 | 200 | 230 | 124 | 49 | 48 | 5 | 9 | 44 | 14 | 0·1 | 58 | .... | 10 | 75 | <1 | 0·4 | 18 |
| McCutcheon (Wonnerup) | 320 .... | 7·3 | 220 | 250 | 124 | 64 | 67 | 6 | 12 | 53 | 6 | 0·1 | 82 | .... | 14 | 75 | <1 | 0·3 | 21 |
| Oats (Ruabon) .... | 320* .... | 5·9 | 530 | 630 | 428 | 103 | 40 | 10 | 19 | 145 | 9 | 0·1 | 49 | .... | 22 | 260 | <1 | 0·4 | 26 |
| Cable(1956)(Ruabon) | 450* .... | 6·2 | 220 | 240 | 135 | 41 | 48 | 5 | 7 | 55 | 12 | 0·1 | 58 | .... | 13 | 82 | <1 | 0·4 | 17 |
| Western Titanium Capel 3 | 622* .... | 6·7 | 220 | 240 | 92 | 56 | 90 | 11 | 7 | 48 | 20 | (13) 0·1 | 110 | .... | 16 | 56 | <1 | 0·3 | 14 |
| Western Titanium Capel 4 | 569* .... | 6·6 | 220 | 240 | 92 | 52 | 90 | 11 | 6 | 49 | 21 | 0·1 | 110 | .... | 16 | 56 | <1 | 0·3 | 13 |
| Capel Town Bore 1 | 289½* .... | 6·1 | 380 | 380 | .... | 83 | 35 | 11 | 13 | 83 | 15 | 16 | 43 | .... | 17 | 166 | ND | ND | 17 |
| Westralian Oil (Capel) | 193* .... | 6·1 | 280 | 340 | 206 | 73 | 48 | 13 | 10 | 67 | 15 | 0·1 | 58 | .... | 14 | 125 | <1 | 0·2 | 14 |
| Western Mineral Sands | 495* .... | 7·2 | 210 | 230 | 101 | 55 | 72 | 9 | 8 | 42 | 19 | 0·1 | 88 | .... | 13 | 61 | <1 | 0·3 | 16 |
| Cable (Stratham) | 379* .... | 7·0 | 230 | 250 | 110 | 54 | 76 | 10 | 7 | 50 | 18 | 1 | 92 | .... | 15 | 67 | <1 | 0·4 | 15 |
| Westralian Oil .... | 915* .... | 4·6 | 420 | 460 | 331 | 64 | 5 | 4 | 13 | 102 | 15 | 0·9 | 6 | .... | 16 | 201 | <1 | 0·1 | 37 |

* Total depth of bore.

## Appendix 4

CHEMICAL CHARACTERISTICS OF GROUNDWATER

| No. | Bore | Depth (feet) | Calcium magnesium ratio rCa/rMg | Sodium adsorption $\frac{Na^+}{\sqrt{\frac{(Ca^{++}+Mg^{++})}{2}}}$ | Residual sodium bicarbonate |
|---|---|---|---|---|---|
| 1 | Melville .... | 10 | 1·6 | 4·5 | .... |
| 2 | Quindalup 1 .... | 935–1025 | 4·0 | 10·1 | 6 |
| 3 | Quindalup 1 .... | 1180–1250 | 0·8 | 16·3 | 1·1 |
| 4 | Quindalup 1 .... | 1680–1770 | 0·4 | 27·5 | 0·6 |
| 5 | Quindalup 3 .... | 275–315 | 7·5 | 13·5 | .... |
| 6 | Quindalup 3 .... | 1050–1080 | 8·0 | 20·0 | 3·0 |
| 7 | Quindalup 3 .... | 1390–1485 | 10 | 27 | .... |
| 8 | Quindalup 4 .... | 326 .... | 0·4 | 3·5 | 0·3 |
| 9 | Quindalup 4 .... | 530–560 | 3·3 | 4·0 | 3·8 |
| 10 | Quindalup 4 .... | 1370–1400 | 1.5 | 5·1 | 3·0 |
| 11 | Quindalup 5 .... | 695–763 | 1·7 | 11·0 | 6·6 |
| 12 | Milne Street .... | 550–620 | 0·8 | 2·4 | .... |
| 13 | Milne Street .... | 750–1000 | 3·8 | 0·8 | 0·4 |
| 14 | Busselton 5 .... | 407–495 | 0·8 | 2·6 | .... |
| 15 | Quindalup 5 .... | 1057–1105 | 0·9 | 2·9 | 0·9 |
| 16 | Quindalup 5 .... | 1926–1955 | 0·7 | 3·2 | 0·6 |
| 17 | Quindalup 5 .... | 1929–2000 | 1·0 | 3·3 | 1·6 |
| 18 | Yoganup 1 .... | 915 .... | 0·2 | 5·6 | .... |
| 19 | McCutcheon's .... | 320 .... | 0·3 | 2·9 | 0·1 |
| 20 | Western Titanium 3 | 622 .... | 1·0 | 2·8 | 1·3 |
| 21 | Western Titanium 4 | 569 .... | 1·1 | 2·9 | 1·5 |
| 22 | Cable Ruabon .... | 415 .... | 0·7 | 2·6 | 0·2 |
| 23 | Oats .... .... | 230 .... | 0·3 | 6·2 | .... |
| 24 | Giles .... .... | 150 .... | 1·2 | 2·8 | .... |
| 25 | Western Mineral Sands, Capel | 495 .... | 0·7 | 2·4 | .... |
| 26 | Willmotts .... | 157–286 | 0·7 | 4·6 | .... |
| 27 | Reynolds .... | 154–174 | 0·3 | 2·7 | 0·1 |
| 28 | Cable Stratham | 379 .... | 0·9 | 8·6 | 0·9 |
| 29 | Westralian Oil Capel | 192 .... | 0·8 | 3·4 | .... |
| 30 | Capel Town water supply 1 | 289 .... | 0·5 | 4·0 | .... |

# PROSPECTS FOR UNDERGROUND WATER SUPPLIES FOR CARNAMAH TOWNSHIP

**by P. Whincup**

ABSTRACT.

In the Carnamah district, groundwater suitable for the town supply is available only from Quaternary sand overlying chert of the Proterozoic Moora Group. Groundwater in the chert is too brackish to be of use.

Exploratory drilling of an area of Quaternary sand adjacent to the present pumping field is recommended.

### INTRODUCTION

Carnamah is a northern wheatbelt town on the Geraldton Highway, 188 miles north of Perth. It has a population of about 370.

Water is supplied to the town from a catchment which yields an average 3 million gallons per annum, and from shallow sands at Winchester, 7 miles south of the town. Overabstraction from these sands has resulted in a marked increase in groundwater salinity and it has become necessary to locate additional supplies. The Moora Group, a sequence composed mainly of chert and orthoquartzite which provides water for several towns about 50 to 75 miles south of Carnamah, crops out near Winchester. Accordingly a hydrogeological investigation has been made of these rocks in the Carnamah area at the request of the Public Works Department, the primary object being to delineate their extent and assess the groundwater potential. Geological mapping with an associated groundwater census was done between 4th and 13th April, 1967.

A more detailed geological investigation of the Moora Group has been completed recently by G. H. Low and L. N. Wall and some of their results are incorporated.

### TOPOGRAPHY

The major control on the topography is geological. The Mt. Scratch Siltstone and the Permian Nangetty Formation form the flat, low-lying saline areas on the west and probably underlie the Yarra Yarra salt lakes. These flats are succeeded to the east by a narrow zone of low, rounded hills and ridges of the Moora Group, succeeded in turn by gently undulating granite hills. In general the natural surface rises from west to east. Intermittent saline creeks drain westerly towards the large Yarra Yarra saline system. The average annual rainfall is about 15 inches, and ranges between 4 inches and 29 inches.

### GEOLOGY

Rocks exposed are of Archaean, Proterozoic, and Permian age with overlying Quaternary alluvium.

*Archaean*

The Archaean is represented by a massive, medium-grained, porphyritic granite often well-jointed and intruded by dolerite dykes. Generally it either crops out or occurs at shallow depth and weathers to a coarse feldspathic sand with the typical kaolinitic weathering profile often being absent.

*Proterozoic*

The *Moora Group* type section near Coomberdale is subdivided by Logan and Chase into four formations. Near Carnamah no subdivision is possible as only the Coomberdale Chert appears to be present. This is a sequence of chert, chert breccia, and orthoquartzite, often well-bedded and dipping at about 30 degrees to the west. Occasional interbedded siltstone appears towards the west.

The chert contains colonial organisms resembling stromatolites (*Collenia*) which reflect the original calcareous nature of the sediments. Several caves have also been preserved, one directly south of points 4 and 5, while there are several sink holes in the yellow sand area which trends eastwards from points 15 and 79. (See Plate 3.)

The contact between the Archaean and the overlying Moora Group is either faulted or, less commonly, unconformable. The Moora Group is intruded by dolerite dykes and its structure is complicated by the north-south faulting shown on Plate 3. Farther south Low and Wall (pers. comm.) have found evidence of northeast-trending shear zones with associated minor multi-directional faults and shear zones. They are postulating similar faulting near Winchester but this has not been shown on either of the accompanying plates.

The chert is white, yellowish and reddish and weathers to yellow clay and sand. Extensive tracts of yellow sand, such as immediately south and east of Winchester, overlie clay and chert. The sand varies in thickness from a few inches to perhaps 20 feet and may have been derived from the chert by illuviation of the clay fraction.

The *Mt. Scratch Siltstone* is a purple-reddish, well-bedded siltstone which dips very steeply to the west. It may be in faulted contact with the Moora Group. Only one very thin dolerite dyke was seen to intrude it.



(2)—41571

*Permian*

The *Nangetty Formation*, exposed only in the extreme northwest of the area, is a white to reddish, fine-grained, very poorly sorted tillite containing occasional boulders of granite and chert. It is flat-lying and unconformably overlies the Mt. Scratch Siltstone.

*Quaternary*

The Quaternary alluvial sediments are mainly sandy and may in many instances be derived from the Moora Group cherts. Near Winchester several south-westerly trending sandy washes mark drainage lines from the Moora Group, while coarse, sandy colluvium is often found near granite outcrops. North of Carnamah at point 84, the origin of a narrow belt of sand parallel to the adjacent salt lake is uncertain.

## HYDROLOGY

Groundwater characteristics are closely related to the geology and will be discussed accordingly. Reference should be made to the points marked on Plate 3.

*Archaean*

Water in the granite and weathered granite is in most instances too saline for domestic use. Domestic quality water occurs only in the coarse sandy colluvium near granite hills, usually in poor supply and at shallow depth. Thus No. 18 is an 18-foot well which produces 600 gallons of 500 ppm water per day. Several bores have been drilled to intersect joints in the unweathered rock; for example, No. 72 was drilled 90 feet into granite and yielded 1,500 gpd of 3,255 ppm water.

Water from the granite is in poor supply and too saline for domestic use.

*Proterozoic*

The *Moora Group*, between Moora and Watheroo, occasionally yields large supplies of fresh water from fractures in the chert. Near Carnamah however it yields only brackish water and where recharge is very slight, as near points 103 and 104, the salinity may be as high as 11,000 ppm. Recharge is either by runoff from the granite or by infiltration of water from the overlying yellow sand. Bores 39 and 40 which are both located on a creek draining nearby granite, yield 4,000 to 5,000 gpd of 2,200 to 2,500 ppm water from the chert. An adjacent abandoned bore No. 38 does not benefit from this recharge and produced water too saline even for stock use.

In the yellow sand areas, the fresh water often found at shallow depths may extend into the upper weathered chert profile. However the quality deteriorates rapidly with depth as illustrated by the following salinity data obtained from a Public Works Department bore in the present pumping field.

| Depth (feet) | Salinity (ppm) |
|---|---|
| 25 | 350 |
| 35 | 1,650 |
| 45 | 2,100 |
| 60 | 5,700 |

Moora Group rock, weathered in situ, was encountered at about 25 feet in this bore.

Yields from the chert may be quite high. The Main Roads Department pump 30,000 gallons per day from a water-filled cave in the chert, on high ground about half a mile south of points 4 and 5, the water salinity being 4,300 ppm. In no instance was domestic quality water noted in the Moora Group and therefore its development for a town water supply cannot be recommended.

The reason for the higher groundwater salinity at Carnamah than at Moora is not readily apparent in a restricted investigation such as this. It could be a result of lower rainfall and topography and hence poorer recharge conditions at Carnamah.

The *Mt. Scratch Siltstone* yields only very saline water.

Groundwater in the Permian Nangetty Formation is similar to that in the Mt. Scratch Siltstone. Well No. 109 situated on a slope above the salt lakes became too saline and was abandoned.

*Quaternary*

Domestic quality water is generally evailable from shallow soaks and wells in the yellow sand areas south and east of Winchester. Several examples are cited below:

| No. | Depth (feet) | Water level (feet) | Salinity (ppm TDS) |
|---|---|---|---|
| 4 .... .... .... | 9 | 6 | 550 |
| 5 .... .... .... | ?4 | ?2 | 980 |
| 13 .... .... .... | 10 | 4 | 900 |
| 15 .... .... .... | 8 | 4 | 200 |
| 50 .... .... .... | 3 | surface | 210 |
| 51 .... .... .... | 2 | surface | 500 |
| 78 .... .... .... | 6 | 3 | 140 |

No. 79 which is closer to the salt lakes, and at 17 feet is slightly deeper, has a salinity of 6,000 ppm. On Plate 4 it is apparent that there are several larger soaks and lakes in the sands but as they are subject to considerable evaporation during the summer months they are usually saline. Alongside the lakes however the groundwater is again of good quality. The lake shown on Plate 4 directly south of the sand ridge has a salinity of 12,800 ppm whereas the water in a soak excavated by the Main Roads Department about 20 yards north of the lake has a salinity of only 1,340 ppm.

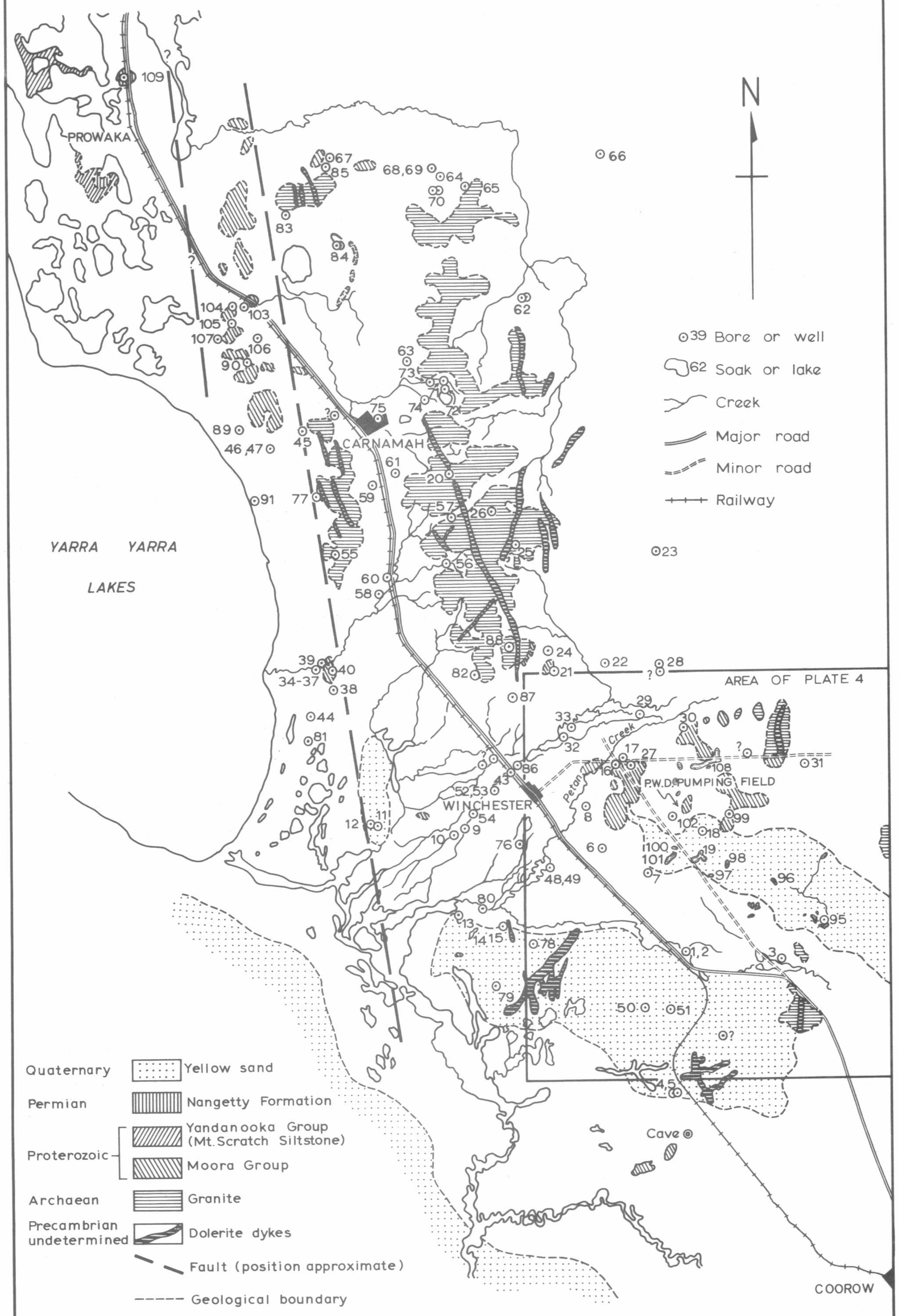
Small supplies of fresh water are also obtained from the stringers of sand which mark drainage lines from the Moora Group rocks near Winchester. Nos. 9, 10, 43, 52, 53, 54, and 86 all have salinities less than 750 ppm.

Two bores north of Carnamah, indicated by No. 84, yield small supplies of fresh water at a depth of 15 feet in the narrow strip of sand parallel to the lake.

The *Public Works Department pumping field* shown on Plate 4 is located in a yellow sand filled depression about 7 miles south of Carnamah and 2 miles east of Winchester. The yellow sand overlies Moora Group chert. The chert crops out to the east and west and a sand ridge cuts off the depression to the south. Several small salt lakes mark the main northerly-trending drainage line.

About 100 shallow auger holes have been drilled in the vicinity of the pumping field, permitting the Public Works Department to draw approximate surface and water table contours. Present production is from five or six spear points, of average depth 20 to 25 feet, centred near the bore with salinity 2,280 ppm. The depth to the water table in the centre of the depression is about 5 to 10 feet, and yields from individual spear points vary from 100 to 200 gph. The direction of groundwater movement is apparently to the north and northwest towards the large southwesterly-draining Petan Creek. Water is actually pumped towards Petan Creek from spear points in the northerly salt lakes in order to prevent the encroachment of salt water into the pumping field. Near the southern end of the depression the groundwater is moving slowly towards the sand ridge. The estimated rate of movement, from hydraulic gradients and an assumed hydraulic conductivity of 100 feet per day, is about 0.05 feet per day.

During the drilling programme in early 1961 it was noted that after 4.18 inches of rain had fallen in one week, water levels generally rose by about one foot nine inches. This indicates that after heavy showers, all the rainfall and much of the runoff from the flanks of the depression find their way to the water table. Unfortunately rainfall is usually light and well dispersed and may vary annually from 4 to 29 inches. Working on the average annual rainfall of 15 inches, Public Works Department engineers have calculated that recharge to the yellow sand is of the order of 5 million gallons per annum. Vollprecht (1962) estimated that in the 130 acres of the pumping field only 2 inches of the average annual rainfall




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# GEOLOGY OF CARNAMAH AREA

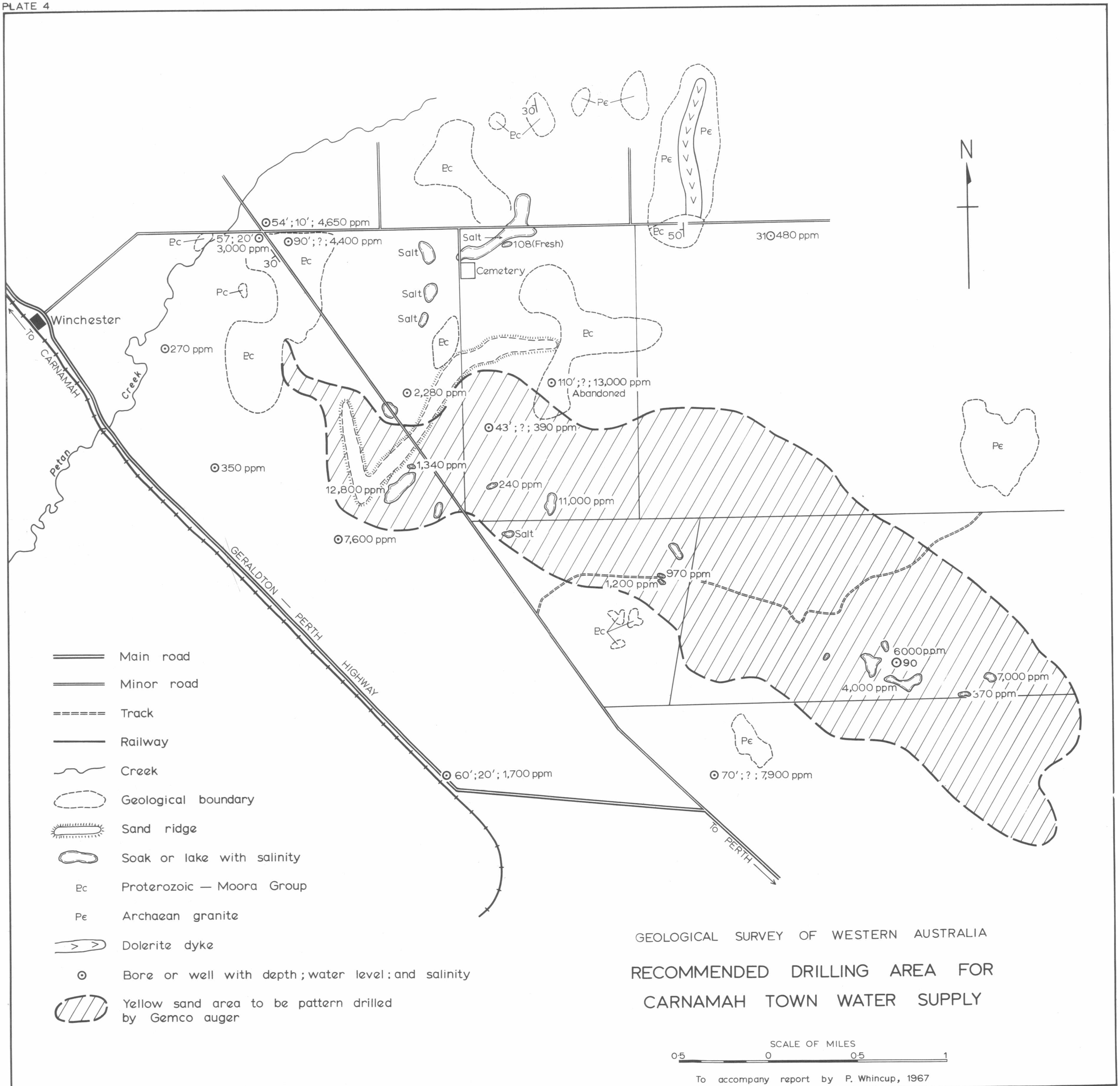
SCALE

Miles 2 0 2 4 Miles

To accompany report by P. Whincup, 1967

7087

PLATE 4




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

## RECOMMENDED DRILLING AREA FOR CARNAMAH TOWN WATER SUPPLY

To accompany report by P. Whincup, 1967

9781

reached the water table. This is an annual recharge of 5.5 million gallons and is roughly equivalent to the Public Works Department estimate.

Subsequent abstraction has gradually risen to the present figure of approximately 6.5 million gallons per annum, an annual overdraw of more than one million gallons. This has resulted in a lowering of water levels and a drastic twofold increase in salinity between March 1966 and 1967 to a value of 1,800 ppm. It is therefore a matter of some urgency that additional groundwater supplies be located.

*Additional groundwater supplies*

The Moora Group cherts are not a prospective source of domestic water. The only possibility is to locate additional yellow sand areas similar to that already being used, and it will be noted on Plate 4 that such an area occurs south and east of the present pumping field. There are numerous soaks and small lakes in the sands, which although they are saline, indicate the presence of a fairly extensive, shallow, water table aquifer. It is suggested that the sands be pattern-drilled with a Gemco auger drill to test their thickness and the groundwater quality. The best results will undoubtedly be obtained in the lower lying areas where the accumulations of yellow sand are greatest; on the higher ground many of the Gemco holes may be dry, as the water table there is deeper and chert may be encountered at shallow depths.

Two additional spear points have already been equipped.

However the sands are not a reliable groundwater source as their recharge is completely dependent on the annual rainfall and their safe yield in times of drought will fall appreciably. Alternative more distant supplies may eventually have to be sought.

## CONCLUSIONS AND RECOMMENDATIONS

The Moora Group cherts near Carnamah yield only brackish water and are unsuitable for development as a town water supply. Domestic quality groundwater is available only from shallow yellow sand overlying the chert, and is already utilised east of Winchester. It is recommended that a similar yellow sand area, adjacent to and southeast of the pumping field, be test drilled for additional groundwater supplies. The high salinities of soaks and lakes in the sands are a result of direct surface evaporation and do not reflect the general groundwater quality. However the salinity does increase quite markedly with depth and drilling should be stopped when saline water is encountered. Recharge to the sands is by direct infiltration of rain and hence is very variable.

Thus, as a short term prospect, the additional shallow sand area is probably adequate, but eventually the location of a more reliable water supply for the town will become necessary.

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# HYDROGEOLOGY OF THE EASTERN PART OF THE RAVENSTHORPE 1:250,000 GEOLOGICAL SHEET

by C. C. Sanders

## ABSTRACT

A hydrogeological assessment of the eastern part of the Ravensthorpe 1:250,000 geological sheet area was made during regional mapping. There is groundwater of stock and occasionally of domestic quality near the coast, and also where Quaternary soils overlie Tertiary sediments in the southeastern part of the sheet. Elsewhere the groundwater is generally saline.

## INTRODUCTION

Geological mapping and an associated groundwater census was carried out on the Ravensthorpe Sheet area during 1967 as a continuation of the hydrogeological assessment of the Esperance Sandplain. This area is undergoing very rapid farm development from virgin land, and as farms are new, there is a paucity of groundwater information. The bores so far constructed are mainly concentrated on well developed properties in the southeastern corner adjoining the Esperance 1:250,000 geological sheet area. Usable groundwater mainly comes from Eocene siltstone and spongolite which are thinly draped over Precambrian granitic gneiss in the southern third of the sheet.

## TOPOGRAPHY AND RAINFALL

The major topographic control is geological. Sofoulis (1958) divided the Ravensthorpe area into three distinct divisions on physiographic grounds.

The *Hinterland Division* (Salinaland of Jutson, 1934) has internal drainage, the foci being the salinas and dry lakes in the northernmost part of the sheet and on the adjoining Lake Johnston Sheet area. The rainfall is generally less than 14 inches per annum.

The northern boundary of the *Intermediate Division* is determined by the limits of the river systems which drain into the Southern Ocean. The southern boundary is a low escarpment which leads down to a narrow coastal plain.

A mantle of white to grey sand and sometimes red loamy soils supports low scrub and mallee, typical of the Esperance Sandplain. The area is deeply dissected in the vicinity of the pronounced drainage system, the rivers assuming youthful characteristics in their lower reaches where they cut Eocene rocks. Steep-sided, gorge-like valleys 100 to 150 feet deep and capped with breakaways 10 to 30 feet high are common, especially on the Oldfield River.

Rainfall over the division declines from about 22 inches per annum near the coast to 14 inches per annum at the northern limit. It is only after heavy and lengthy downpours that river flow occurs. Throughout most of the year rivers are dry except for disconnected pools. These are generally saline or brackish, though some pools are known to remain fairly fresh through the summer drought period.

The *Coastal Division* is a narrow plain covered by vegetated sand dunes and long limestone ridges. Rainfall ranges from 22 to 25 inches per annum.

## GEOLOGY

Morgan (pers. comm.) believes that the Esperance Sandplain is a fossil archipelago which existed in Eocene times when the sea level was nearly 1,000 feet higher than at present. The plain is now a dissected plateau covered by Quaternary soils.

The underlying basement of granitic gneiss is exposed as "islands" through the soil cover and in the dissected river valleys (Plate 5). Associated with the gneiss are dyke rocks, which have undergone high-grade metamorphism and are now represented by hornblende granulite (amphibolite). These rocks are severely deformed and crossfolded but show a general south-westerly foliation trend.

North of the Esperance-Ravensthorpe road the basement rocks lie about 15 feet beneath the Quaternary soil mantle. South of the road thin Tertiary sediments no greater than 150 feet thick, unconformably overlie the gneiss.

During Eocene times the sea covered most of the present south coast region, and in the Esperance-Ravensthorpe area siltstone and spongolite were deposited in a marine archipelago similar to the Archipelago of the Recherche. High gneissic islands were only thinly covered by sediment and, with erosion since Eocene times, are seen today as inliers protruding through the Tertiary and Quaternary cover. The spongolite is richly fossiliferous, but most carbonate parts are now replaced by opaline silica. Solution cavities and sink holes are common.

The Quaternary soils are divisible into two distinct units which are developed over the Precambrian and Tertiary rocks: red sandy loam over limestone, and sand over pisolites and yellow clay.

The *red sandy* loam forms a plain over gneiss in the northern part of the Sheet. It is an ancient soil horizon which continues inland from the sand and pisolite soils. In places the loam is stripped away by wind action exposing a cemented limestone and sometimes a silcrete sub-horizon.

The *sand horizon* covers most of the area and consists of white to grey siliceous soil over pisolite and yellow clay, the sand ranging in thickness from a few inches to a few feet. Pisolite has formed near the base of the sand and in areas of strong wind erosion it has been exposed to form patches of usable gravel. The yellow clay sub-horizon underlies the pisolite zone and results from weathering of the upper surface of the Eocene sediments; it is present therefore only in the southern part of the Sheet.

## HYDROLOGY

Groundwater characteristics are closely related to the geology.

*Gneiss* is the predominant rock type, and the ground water overying it is very saline, because of the low permability of the rock itself, and availability of soluble salts resulting from the decomposition of basic minerals. However, stock quality water occasionally occurs within coarse, sandy colluvium found in shallow depressions and drainage lines, and in zones of deeply weathered gneiss. These occurrences are rare.

Rainwater runoff from the basement rocks tends to become quickly saline. A field salinity test 30 miles inland on the Lort River immediately after heavy rain, registered a salt content of 18,000 ppm TDS. Salinity measurements on water in the lower reaches of the river made some days later after widespread rains gave similar values.

Farmers working properties on the banks of the Young River report that the river is normally saline except after flash floods. When these floods occur, the rivers rise and fall very quickly and fresh water is occasionally trapped in semi-permanent rock pools. This water slowly becomes saline due to evaporation and salt uptake from the confining rocks, but it generally remains of stock quality until late summer.

The denudation of large tracts of land in the area for pasture improvement, especially where the sandplain overlies gneiss, is likely to lead to a severe salt problem in the future. The natural vegetation is probably highly salt tolerant, and the deep root system of some shrubs would tend to prevent the upward movement of saline water resting on the gneiss. The planting of extensive areas with shallow rooted pastures such as most clovers, is liable to lead to salting due to a rise of the salt water table. The root system may also not be deep enough to prevent wind erosion, particularly in late summer, when pasture is in a poor condition. A suggested remedial measure would be the reafforestation of paddock boundaries and road verges, using deep-rooting, salt tolerant trees. In areas still to be developed farmers should clear selectively, leaving untouched as much natural vegetation as possible. The planting of pasture around numerous clumps of trees is advisable.

*Eocene sediments,* which unconformably overlie the Precambrian bedrock, are the most important aquifers in the south coast region. The northern limit of their extent on the Ravensthorpe Sheet area is about the Esperance-Ravensthorpe road, except in the area adjacent to the Esperance Sheet. Even there, the sediments have been eroded out a few miles north of the road. They occur in well drained, elevated, and high rainfall ports of the sheet.

The Tertiary rocks are of variable thickness, but sufficient information is not yet available to accurately predict depth to bedrock at any particular locality. Islands of granitic gneiss commonly protrude through the sediment mantle and these further complicate any estimate of thickness. The functioning bores in the area generally tap water from zones between 30 and 80 feet below ground level. This interval can probably be regarded as the target zone for groundwater.

Water of variable quality occurs sporadically throughout the Eocene sediments, generally resting on the regionally saline groundwater body. These accumulations normally occur under sandy depressions, at the base of drainage channels, and as a result of rainfall runoff from hills of bedrock entering permeable sections of Eocene sediments. The latter intake environment is the most important in the Neridup area, east of Esperance, where granitic hills shed less saline water than the gneissic hills on the Ravensthorpe Sheet.

Sandy sink holes are the best surface indication of permeable strata within the Eocene sediments. Subsidence results from leaching of the carbonate fraction from the underlying rocks by percolating rainwater.

Intake occurs over the whole area of Tertiary rocks through sink holes and drainage channels. Depressions which hold water throughout the year are common but are considered poor sites for usable groundwater, as they indicate perching of the surface water on bedrock or impermeable saline clay.

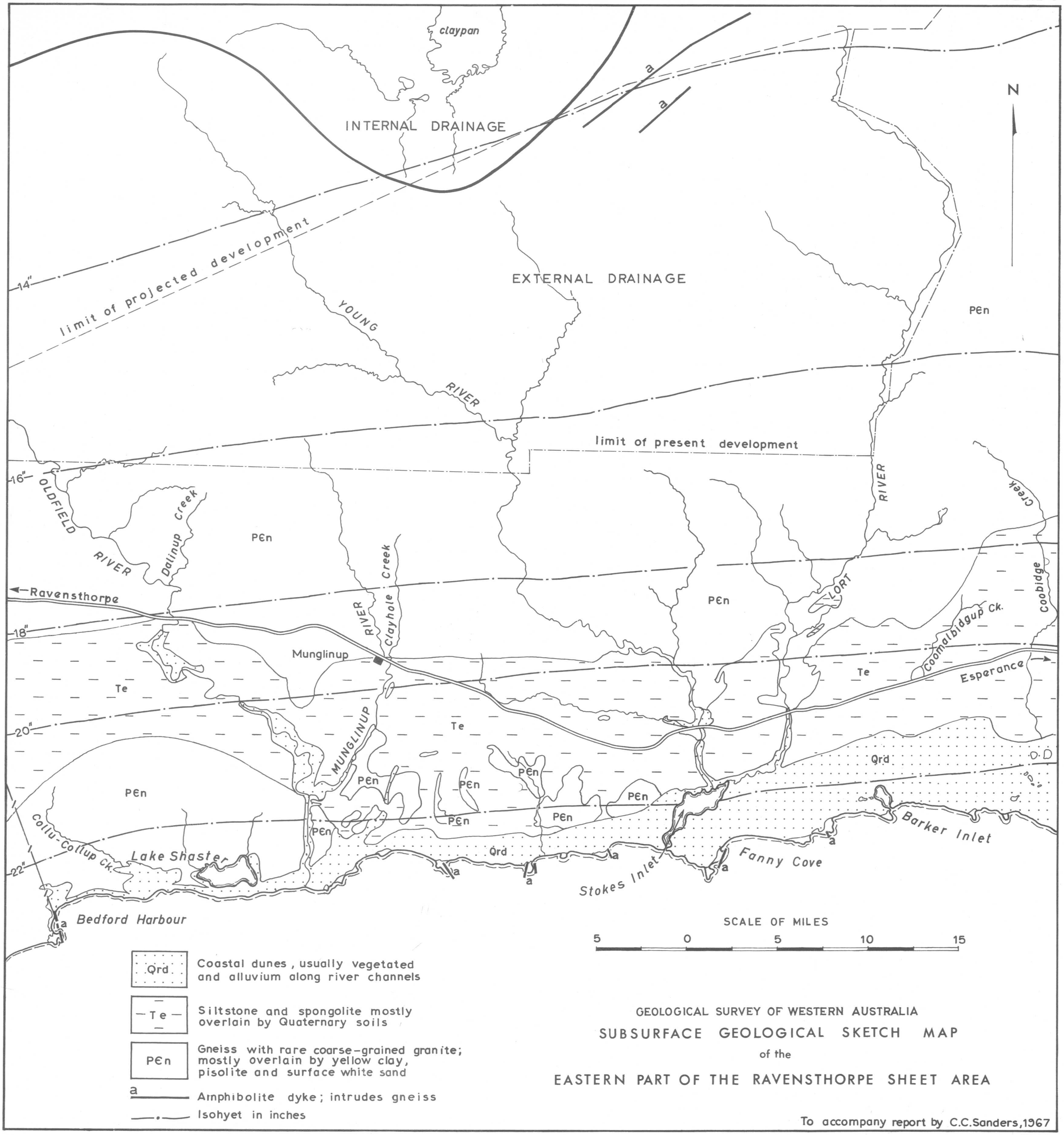
Bores sunk into the Eocene rocks often silt up after some years, due to an influx of fine-grained sediment. This may be overcome by inserting a fine gravel packing around the bore screen or spear.

*Alluvial flats and benches* on the Young and Oldfield Rivers are a possible source of good quality groundwater. They are fairly common in the lower reaches of the rivers, but as yet have not been tested. Intake to these alluvial zones would be from rainfall and occasional flash floods.

The *coastal dune system* is a potential source of potable groundwater. The system occupies the narrow coastal plain adjoining the inland Precambrian plateau. The dunes are vegetated and often attain a height of 300 feet, although over a large area the interdune flats are at an elevation of 50 feet or less above sea level. Rainfall runoff from the dunes can be expected to collect in the interdune flats and soak downwards into the underlying sand and limestone. The effect is more pronounced where the dunes have been cemented to ridges of hard limestone.

The coastal area of the Ravensthorpe Sheet is mainly gazetted as faunal reserve, but even so, watering points could be established in this area for use by farmers during summer or in times of drought.

PLATE 5




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SUBSURFACE GEOLOGICAL SKETCH MAP of the EASTERN PART OF THE RAVENSTHORPE SHEET AREA

To accompany report by C.C.Sanders, 1967

7214

CONCLUSIONS AND RECOMMENDATIONS

The gneissic basement rocks of the Ravensthorpe Sheet generally yield saline water, although brackish water may occur in deeply weathered zones and in sandy colluvium. Supplies from these accumulations are small.

Domestic and stock quality groundwater is available from Eocene siltstone and spongolite which are thinly draped over gneiss in the southernmost part of the Sheet. Bore sites should be selected in sandy depressions and drainage channels where recharge is greatest. The groundwater is usually encountered at depths between 30 and 80 feet below ground level.

Alluvial flats and benches on the Young and Oldfield Rivers should yield usable groundwater. Also, semi-permanent rock holes in the rivers occasionally hold water of stock quality until late summer.

The coastal dune system which lies mainly within Crown Land is a suitable environment for the accumulation of potable groundwater. As yet, this source has not been tapped. Farmers in the area should be advised on the necessity to conserve natural vegetation as a means of controlling a rise in the salt water table, which is expected to occur on the Sandplain with continual clearing. Planting of salt tolerant trees on paddock boundaries and road verges is a remedial measure suggested for those areas already cleared.

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# DRILLING FOR WATER IN COBB DEPRESSION, NORTH OF WINGELLINA

by R. A. Farbridge

ABSTRACT

The results of drilling suggest that there is a potentially important groundwater source in Phanerozoic sedimentary rocks in the Scott 1:250,000 Sheet, about 55 miles north of Wingellina.

Yields of 10,000 to 13,500 gph of water with salinity of 1,000 to 2,000 ppm have been obtained, although samples analysed have salt contents above those acceptable for human consumption.

Further testing will be necessary to evaluate aquifer potential and the suitability of the water for industrial and domestic purposes.

INTRODUCTION

There is current mineral exploration in the Warburton-Blackstone region for vanadium, nickel, and copper. The region is arid, the surface waters are ephemeral, and little is known of the groundwater potential.

Any mineral exploitation would require large water supplies close to the ore bodies.

LOCATION

This remote area, approximately 1,100 road miles from Perth, is near to the junction of the boundaries of Western Australia, South Australia, and the Northern Territory.

Formed tracks link the mining camps with Giles meteorological station and with Warburton mission.

The tested area is about 55 miles north of Wingellina on the Giles road, where the latter crosses an extensive dune field.

GEOLOGY

Phanerozoic sediments are found in a shallow east-west trough which rests upon the Precambrian rocks of the Musgrave block (Horwitz and others, 1967).

Flat-lying porcelanous siltstone, kaolinitic sandstone, and conglomerate crop out as low rubbly breakaways or mesas. Superficially the sediments may be silicified and lateritised.

Well-rounded polished pebbles have been found on ironstone gravel surfaces, which are thought to overlie Phanerozoic sediments. The limits of the Phanerozoic rocks, based on surface evidence, are shown in Plate 6.

A reconnaissance gravity survey (Lonsdale and Flavelle, 1962) established an extensive gravity low termed the Cobb gravity depression, which can be traced into the south Canning Basin.

The position of the -95 mg gravity anomaly coincides roughly with the presumed centre of the sedimentary trough, as deduced from surface evidence by the Geological Survey of Western Australia in 1966. Subsequently, Southwestern Mining which was advised to test these sediments for water supplies, sited and drilled three bores.

BORE DATA

Bores drilled by: Southwestern Mining.

Date: 12th April 1967 to 15th April 1967.

Plant: Drillmaster.

Method of Testing: Drum measurement of water expelled by compressed air during drilling.

Logged by: H. R. Butler.

| Bore No. | Depth (ft.) | Present S.W.L. (ft.) | Water cut (ft.) | Salinity (ppm) | Supply (gph) | Aquifer(s) |
|---|---|---|---|---|---|---|
| D57 .... | 350 | 73·5 | 90 | 1,075 | 10,000 at 350′ | Phanerozoic sandstones |
| D58 .... | 93 | 55·5 | 83 | Not analysed | Soak | Weathered acid gneiss |
| D59 .... | 400 | 127·5 | 80 | 2,013 | 13,500 at 400′ | Phanerozoic sandstones |

DRILLING RESULTS

Bores D57 and D59 were both successful, D57 being drilled on the centre of the Bouguer anomaly. D58 encountered chlorite schist and acid gneiss at shallow depth.

Bore D57, drilled to 350 feet, cut a section of interbedded ferruginous clayey sandstone, white medium to coarse sandstone, and minor ferruginous sandy clay. The groundwater was confined, possibly by a ferruginous clay seal. Bore D59 penetrated 400 feet of light-grey or ferruginous partly conglomeratic sandstone with clayey sand and clays; the groundwater was apparently unconfined.

The drill cuttings from Bore D59 showed that much of the clastic material was derived from igneous — metamorphic terrains. (Australian Mineral Development Laboratories Rept. MP 2976/67 *in* West. Australia Geol. Survey file 121/1967, p. 42).

A palaeontological examination of drill cuttings failed to find any evidence of their age (Cockbain, 1967).

### WATER ANALYSES

(Analyses by N.T. Administration Animal Industry Branch)

| | D57 | D59 |
|---|---|---|
| *Hardness:* | | |
| Total | 318 ppm | 824 ppm |
| Carbonate | 173 | 189 |
| Non-carbonate | 145 | 635 |
| *Analyses:* | | |
| Chloride | 275 | 695 |
| Sulphate | 178 | 431 |
| Bicarbonate | 211 | 230 |
| Nitrate | 65 | 43 |
| Fluoride | 1·4 | 1·5 |
| Carbonate | Nil | Nil |
| Sodium | 205 | 320 |
| Potassium | 36 | 47 |
| Calcium | 39 | 112 |
| Magnesium | 65 | 133 |
| pH | 7·8 | 7·9 |
| Total dissolved salts | 1,075 | 2,013 |
| *Remarks:* | Chemically suitable for adult consumption. Unsuitable for children under 1 year due to high nitrate. | Chemically unsuitable for human consumption due to high $Mg^{++}$, $Ca^{++}$, $SO_4^{--}$ |

### CONCLUSIONS

The drilling suggests that large supplies of underground water may exist in an extensive sedimentary trough.

The bores were drilled with an air percussion rig, and hence the quoted supplies represent water which was forced to the surface by a compressor unit. They cannot be regarded as having been effectively tested.

There are no data on water salinity changes with depth, and salinities quoted may be of water derived from several aquifers in the same bore.

Because the water salinity from Bore D59 is high (2,013 ppm) and the water is unsuitable for human consumption, salinities in any further bores must be tested during drilling.

Successful development of these water-bearing beds may assist the exploitation of the known nickel prospects of Wingellina and the vanadium prospects of the Jameson Range.

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# PROSPECTIVE DAM SITES ON THE SHAW RIVER, PILBARA DIVISION


**by F. R. Gordon**


### INTRODUCTION

In 1966 the Public Works Department requested a geological reconnaissance of eight prospective dam sites in the Pilbara area for possible use by heavy industry such as an iron ore pelletizing plant at Port Hedland or Roebourne.

Three of the sites, North Pole, North Shaw, and Hillside, were situated on the Shaw River. Site examination of North Pole occupied a day, in the company of Messrs. K. C. Webster and C. Ion of the P. D. & I. Branch of the Public Works Department. North Shaw and Hillside were examined in a day for each.

A light aircraft flight, chartered by P. W. D., provided a quick perspective of all the locations.

### GENERAL PHYSIOGRAPHY

The Shaw River in its upper course traverses the Nullagine Plateau in a young valley with deep gorges and ravines. On leaving Nullagine rocks, it flows across wide plains largely composed of granite, and therefore has the appearance of an old river. On the plains there are long and narrow ridges of hard rocks such as dolerite, in which water gaps have been cut, as at the Hillside site. The middle reaches of the Shaw are in rugged country consisting of sandstone, conglomerate, and jaspilite. Both North Shaw and North Pole sites are located at river constrictions in this area.

### NORTH POLE DAM SITE

The North Pole site (Plate 7) is located on the Marble Bar 1:250,000 Sheet (SF/50-8) at latitude 21° 05′ S and longitude 119° 17′ E, and is approximately 4 miles northwest of the battery at the North Pole mining centre. Access is gained from the Port Hedland-Marble Bar road at a point 68 miles from Port Hedland, thence by bush track 30 miles to near the North Pole centre, followed by a 3-mile walk down creek and river bed to the site.

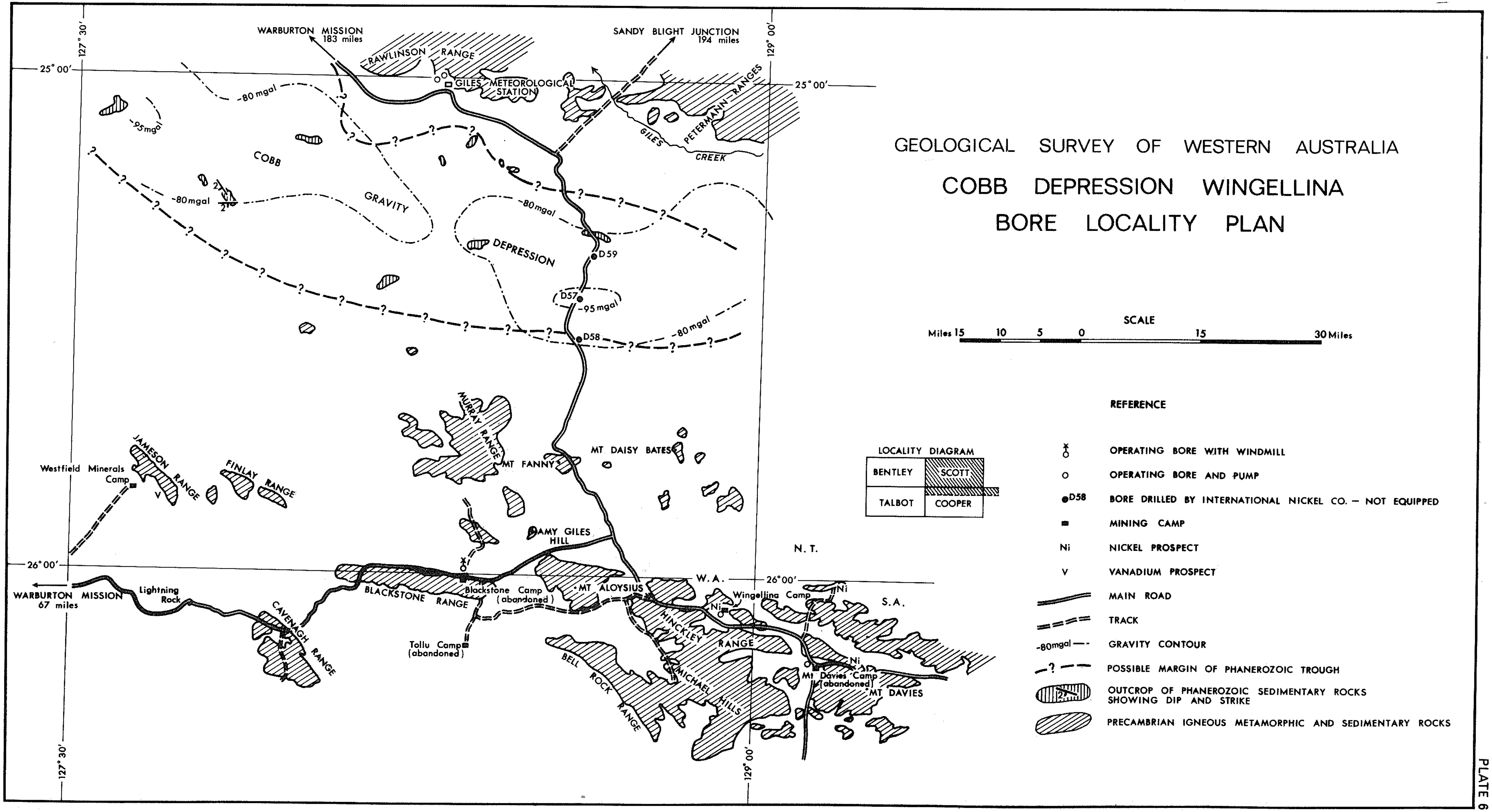
The site is topographically favourable as there is a reasonably wide storage basin immediately upstream of the river constriction. There is a deeply incised creek on the upstream edge of each abutment, and valley depth and straightness suggest the presence of a fault or major unconformity striking at right angles to the river direction. The course of the Shaw River is also at right angles to the general strike of the quartzite and sandstone beds that occur as strike ridges, and thus form valley constrictions. Local deformation resulted in a folded structure with joints nearly at right angles to the river bed on the right hand bank. The rock is a well-bedded quartz sandstone, and the joints dip to the north at angles between 25° and 45°. A minor joint set at right angles to the main folding is parallel to the river, but no leakage is expected (Plate 10A).

On the left hand bank the beds strike nearly parellel to the river and have a steep to vertical dip. The bedding planes are about 6 inches apart in a coarse, metamorphosed sandstone. The visible joints are an easterly striking set with vertical dip, and flat joints that dip at 30° to the north or downstream. The rock on this abutment is mainly a siliceous pebble conglomerate with inclusions of banded iron formation and a grey to ferruginous red weathered matrix. There is a thin mantle of scree on the abutment where thin-bedded rocks have weathered, and massive boulder conglomerate beds are exposed at the foot of the abutment.

The effective height of the dam is governed by a small saddle on the ridge forming the left abutment, about 330 feet above river bed. While the strike of the bedding on this abutment favours the passage of water, the joints are reasonably well closed, and flat sheet jointing is probably of equal significance. The valley slopes on both abutments are quite steep.

### NORTH SHAW DAM SITE

The North Shaw site is in the gorge of the Shaw River, 5 miles northwest of the North Shaw mining centre, on the Marble Bar 1:250,000 Sheet


GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
COBB DEPRESSION WINGELLINA
BORE LOCALITY PLAN
SCALE
Miles 15 10 5 0 15 30 Miles
REFERENCE
OPERATING BORE WITH WINDMILL
OPERATING BORE AND PUMP
D58 BORE DRILLED BY INTERNATIONAL NICKEL CO. – NOT EQUIPPED
MINING CAMP
Ni NICKEL PROSPECT
V VANADIUM PROSPECT
MAIN ROAD
TRACK
-80mgal GRAVITY CONTOUR
POSSIBLE MARGIN OF PHANEROZOIC TROUGH
OUTCROP OF PHANEROZOIC SEDIMENTARY ROCKS SHOWING DIP AND STRIKE
PRECAMBRIAN IGNEOUS METAMORPHIC AND SEDIMENTARY ROCKS
LOCALITY DIAGRAM
BENTLEY
SCOTT
TALBOT
COOPER
WARBURTON MISSION 183 miles
SANDY BLIGHT JUNCTION 194 miles
RAWLINSON RANGE
GILES METEOROLOGICAL STATION
PETERMANN RANGES
GILES CREEK
COBB GRAVITY DEPRESSION
-80 mgal
-95 mgal
D59
D57
D58
MURRAY RANGE
MT FANNY
MT DAISY BATES
JAMESON RANGE
FINLAY RANGE
Westfield Minerals Camp
AMY GILES HILL
N. T.
W. A.
S. A.
WARBURTON MISSION 67 miles
Lightning Rock
CAVENAGH RANGE
BLACKSTONE RANGE
Blackstone Camp (abandoned)
MT ALOYSIUS
Wingellina Camp
HINCKLEY RANGE
Tollu Camp (abandoned)
BELL ROCK RANGE
MICHAEL HILLS
Mt Davies Camp (abandoned)
MT DAVIES
25° 00'
26° 00'
127° 30'
129° 00'

6966

PLATE 6


REFERENCE
(PRECAMBRIAN)
LOWER PROTEROZOIC
Nullagine Series (Fortescue Group)
Sediments
Lava flows
Barren quartz reefs
Basic dyke swarms
ARCHAEAN
Granite complex
Granite and granite gneiss
Warrawoona Series
Banded iron formations
Pillow lavas, dolomites
GEOLOGICAL BOUNDARIES
Approximate
STRIKE OF GEOLOGICAL STRUCTURES N40E
BEDDING
Strike and dip
Vertical
Strike and dip with plunge of slickensides
JOINTS
Strike and dip
Vertical
Horizontal
FOLIATION
Strike and dip
Vertical
Strike and dip with plunge of lineation
CLEAVAGE
Strike and dip
Vertical
Horizontal
DRAGFOLD
Strike and dip
FAULT
MINING CENTRE
TRACKS
60 0 60 120 180
SCALE IN CHAINS
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REGIONAL GEOLOGY
NORTH POLE DAM SITE
PILBARA GOLDFIELD
Geology after Noldart and Wyatt, 1962
SHAW RIVER
MIRALGA CREEK
DAM TRIAL LINE
Warrawoona lava rubble
Sheared dolomites at mine
Lalla Rookh Mine
Normay G.M.
Granite rubble and Granite flats
Warrawoona lavas and schists with Tertiary capping and soil cover
Highly sheared schists and lavas
Siliceous conglomerate with b.i.f. inclusions, shales and grits
Thin capping coarsely amygdaloidal Nullagine acid lavas
occasional Nullagine lava capping

PLATE 8

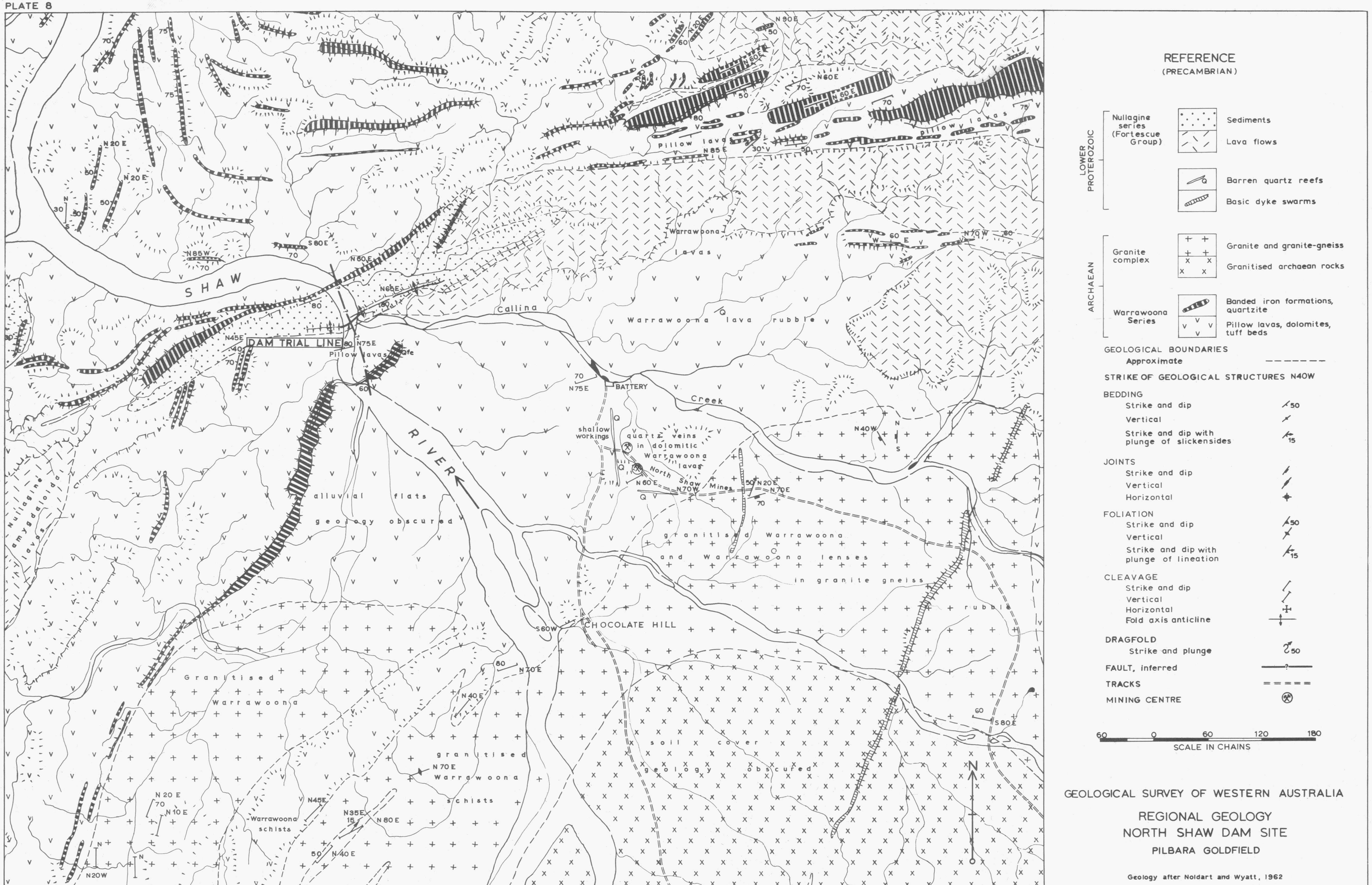
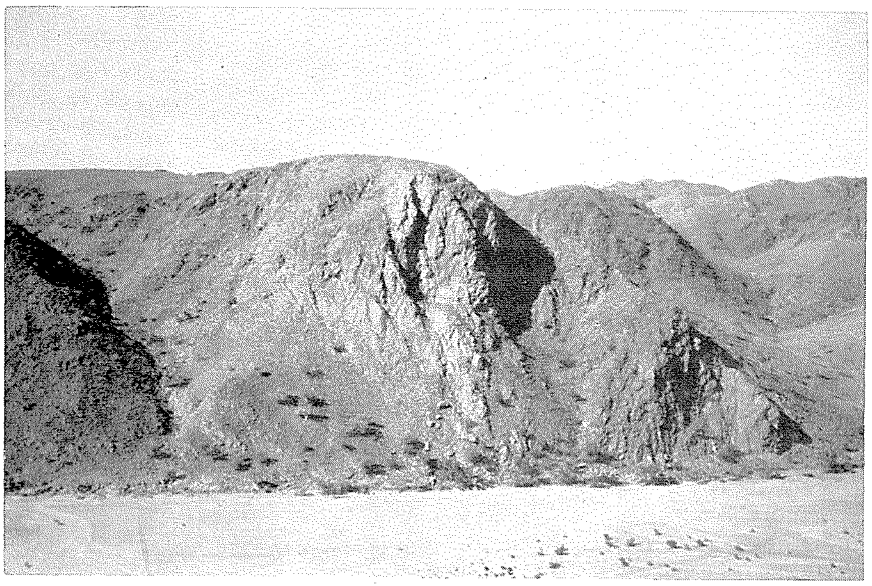

REFERENCE
(PRECAMBRIAN)
LOWER PROTEROZOIC
Nullagine series (Fortescue Group)
Sediments
Lava flows
Barren quartz reefs
Basic dyke swarms
ARCHAEAN
Granite complex
Granite and granite-gneiss
Granitised archaean rocks
Warrawoona Series
Banded iron formations, quartzite
Pillow lavas, dolomites, tuff beds
GEOLOGICAL BOUNDARIES
Approximate
STRIKE OF GEOLOGICAL STRUCTURES N40W
BEDDING
Strike and dip
Vertical
Strike and dip with plunge of slickensides
JOINTS
Strike and dip
Vertical
Horizontal
FOLIATION
Strike and dip
Vertical
Strike and dip with plunge of lineation
CLEAVAGE
Strike and dip
Vertical
Horizontal
Fold axis anticline
DRAGFOLD
Strike and plunge
FAULT, inferred
TRACKS
MINING CENTRE
60 0 60 120 180
SCALE IN CHAINS
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REGIONAL GEOLOGY
NORTH SHAW DAM SITE
PILBARA GOLDFIELD
Geology after Noldart and Wyatt, 1962
SHAW
RIVER
DAM TRIAL LINE
Pillow lavas
Warrawoona lavas
Warrawoona lava rubble
Callina
Creek
BATTERY
shallow workings
quartz veins in dolomitic Warrawoona lavas
North Shaw Mines
alluvial flats
geology obscured
granitised Warrawoona and Warrawoona lenses in granite gneiss
rubble
CHOCOLATE HILL
Granitised Warrawoona
granitised Warrawoona schists
Warrawoona schists
soil cover
geology obscured
Nullagine amygdaloidal lavas
pillow lavas

PLATE 9

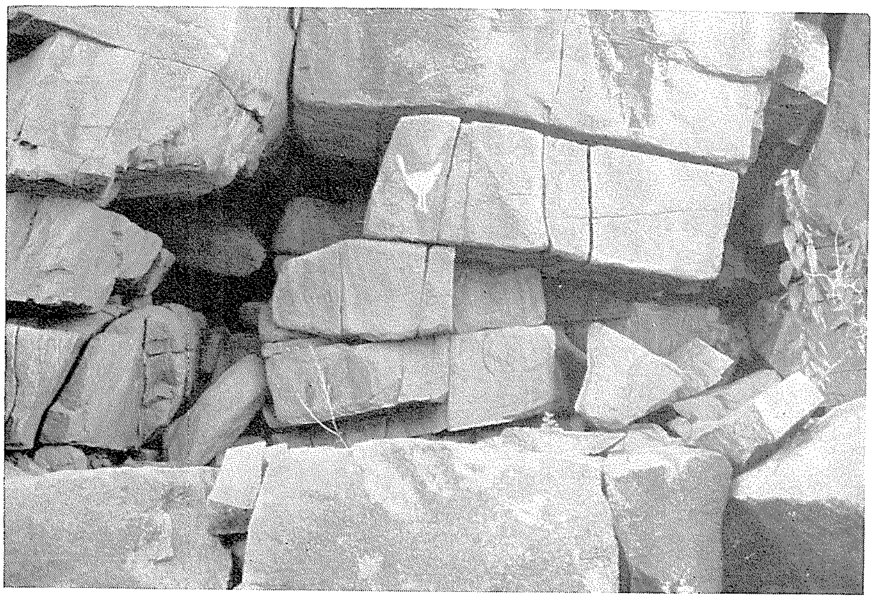

REFERENCE
(PRECAMBRIAN)
PROTEROZOIC
Barren quartz reefs
Basic dyke swarms
ARCHAEAN
Granite complex
Granite and granite gneiss
Granitised archaean rocks
Warrawoona Series
Pillow lava, dolomites, tuff bed, etc
GEOLOGICAL BOUNDARIES
Approximate
STRIKE OF GEOLOGICAL STRUCTURES N40E
BEDDING
Strike and dip
Vertical
Strike and dip with plunge of slickensides
JOINTS
Strike and dip
Vertical
Horizontal
FOLIATION
Strike
Vertical
Strike and dip with plunge of lineation
CLEAVAGE
Strike and dip
Vertical
Horizontal
DRAGFOLD
Strike and plunge
FAULT
TRACKS
MINING CENTRE
60 0 60 120 180
SCALE IN CHAINS
SHAW RIVER
BLACK RANGE
LONG TIN CREEK
HILLSIDE HSD
DAM TRIAL LINE
soil cover with granitic rubble
very rough granite hills
sand plain with occasional granite outcrops
sand plain with occasional granite knobs
Fol. Gr. Gn.
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
REGIONAL GEOLOGY
HILLSIDE DAM SITE
PILBARA GOLDFIELD
Geology after Noldart and Wyatt, 1962

9870



A. North Pole Dam Site, right abutment viewed from left abutment; F1190.

B. North Shaw Dam Site, the anticlinal folding forming the left abutment, and the faulting and large joint openings are shown; F1191.



C. Hillside Dam Site, large joint openings in the dolerite; F1192.

(SF/50-8) at latitude 21° 18′ S, longitude 119° 20′ E. Access is gained from Pilga homestead, 35 miles from Marble Bar on the Hillside road, thence by bush track 13 miles north, followed by a 3-mile walk downstream.

The site is in a band of sedimentary rocks of the Proterozoic Nullagine Series flanked by quartzite and banded iron formation (Plate 8).

The first constriction of the Shaw River at the commencement of the gorge is superficially attractive, but the banded iron formation of the right abutment is folded and large gapes have developed, which would certainly allow heavy leakage through the thin ridge (Plate 10B). Furthermore, Callina Creek breaches the reservoir rim a mile east of the site, and this gap is almost as wide as the main river valley.

The second constriction which constitutes the proposed dam site, is formed by the breaching of an anticlinal ridge of boulder and pebble conglomerate. There appears to be a slight displacement of about 200 yards of the right abutment in a downstream direction with respect to the left abutment. Air-photo interpretation indicates that the anticlinal ridge forming the right hand abutment and reservoir rim has been displaced by a north-northeasterly striking fault at a position 1½ miles east of the site. The movement has been west block (abutment) to the north. The hinge line is in the present position of the river. A zone of breakage or of minor faulting may be expected in the river bed, transecting the foundation area of the dam.

The right abutment rises steeply from the sandy river channel to 212 feet above it, then rises gently. The rock, a boulder and pebble conglomerate, is extremely competent and is sheeted on bedding planes which are from 1 to 10 feet apart, and there is often a gap of from 1 to 6 inches between the beds and occasionally an overhang. The fold axis strikes at 085° and plunges at 20° to the west. From the crest of the ridge a breccia-filled fault zone about 6 inches wide follows the direction of the fold axis down to river level. Two joint sets, in addition to bedding set, are present; one strikes 065° and dips south at 75° to 90°. These joints are open to 1 inch and are about 20 feet apart. The other joint set strikes 175° and dips at 65° to 75° to the west.

The left abutment is likewise dominated by widely separated, open-bedding joints that have an anticlinical form (Plate 10B). Some of the gapes are up to 12 inches wide, and the fold axis appears to be horizontal and strikes 110°. The abutment is further broken by three faults that are parallel to the ridge, and are vertical or steeply dipping. The result is that the left abutment is composed of a number of huge blocks of conglomerate, averaging about 15 feet in thickness and of great structural integrity within each block.

It is apparent that leakage would take place through the left abutment and immediate reservoir rim, but to a lesser extent through the right abutment. The problem of rendering the gaping conglomerate beds watertight is relatively simple because of the separation and size of the openings.

There is probably some faultng of the rock in the river bed, and this will probably be a path of leakage.

## HILLSIDE DAM SITE

Hillside dam site is on the Shaw River, ½ mile southeast of Hillside homestead, on the Marble Bar 1:250,000 Sheet (SF/50-8, sheet 108) at latitude 21° 43′ S, longitude 119° 24′ E. Access is from the Marble Bar—Hillside road, ¼ mile distant from which a new road runs through the dam site to J. A. Johnstone's tin workings immediately upstream, and to the mining village 4 miles to the north.

The site is one of the few constrictions of the middle reaches of the Shaw River and is formed by the breaching of a long narrow ridge of dolerite, known as Black Range. This dyke has an exposed length of approximately 50 miles and is almost continuous, with minor breaks and displacements. It is prominent topographically and rises to about 200 feet above the granite plain. The dyke trends north-northeast and the Shaw River flows north-westerly through the water gap.

In the vicinity of the right abutment the Black Range ridge is composed of three dolerite dyke bodies, separated by granite, and has a total width of about 1,500 feet. At the actual water gap there is only one dyke and the ridge has a width of about 350 feet (Plate 9). The water gap is about 700 feet across, and there are occasional dolerite outcrops showing through alluvium. A bore 22 feet deep has been sunk on the proposed centre line, yielding a good supply of water for a tin treatment plant, immediately upstream (Whincup, 1966). From the river bed the right abutment rises steeply for 120 feet to the crest of the range, which then rises gently to the north-northeast.

The coarse-grained quartz dolerite is highly jointed. The major division is from flatly dipping joints (horizontal to a 10° dip southwesterly) that have an average incidence of 1 every 6 feet, and are open from 1 to 12 inches. There are two other sets; (1) 038° strike, dip 70° northwest with an incidence of 1 every 10 feet, and (2) strike 125°, vertical dip, incidence 1 in 10 feet (Plate 10C). It is impossible to tell if the blocks visible in the abutment are in situ or not, but it is highly likely that the joint openings were all filled with calcite, and thus any exposure showing open joints has settled and the blocks have rotated to some extent. It is likely that all openings above ground water level are open, or partly so.

The left abutment consists of two dolerite dykes enclosing a horse of granite, but in every other respect it is similar to the right abutment.

Although there are zones of intense jointing alternating with zones of comparatively little mechanical division, the expectation is that the right abutment will transmit large quantities of water.

## COMPARISONS AND CONCLUSIONS

It is assumed that all sites are topographically satisfactory and that the reservoir rim is complete in each case. Table 1 shows a comparison of the three.

Table 1

COMPARISON OF SHAW RIVER DAM SITES

| | North Pole | North Shaw | Hillside |
|---|---|---|---|
| 1. Foundations | Sandstone and conglomerate beds | Conglomerate beds | Quartz dolerite |
| 2. Effective height | 300 feet | 200 feet | 120 feet |
| 3. Structure .... | Deflected strike ridge | Anticlinal ridge | Dyke |
| 4. Leakage .... | Little expected | Large on left abutment | Large on right abutment |
| 5. Adverse faulting | .... | Probably in river bed | .... |
| 6. Other defects | Poor access | .... | Floods tin mine |
| 7. Advantages | .... | .... | .... |
| 8. Storage .... | Valley flat and valley | Wide valley flats | Flat plain |
| 9. Distance to Port Hedland | 72 miles | 85 miles | 110 miles |

On the evidence available, the North Pole dam site is the only site on the Shaw River worth further consideration.

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# RAILWAY CUTTINGS IN ROCK

by F. R. Gordon

## INTRODUCTION

Although the basic methods used to determine the stability of slopes are the same for open pits and for railway cuttings, the approach to safety is fundamentally different. In an open pit operation certain risks are justified with the expectation that slope failure will possibly only involve further excavation. Also many pit operations are of limited duration with constantly changing wall positions. A railway cutting has a normal engineering life expectancy of 100 years, during which time the batters are not altered, and should remain stable.

Even a minor slope failure on a rail cutting could be catastrophic because of the fixed line; whereas a road allows for manoeuverability of vehicles which usually carry fewer passengers. A blocked road usually causes less delay because of alternate routes or by-passes.

Railway construction for development was common at the turn of the century, and the present building of iron ore railways has coincided with the development of rock mechanics, the new phase of engineering and geology. The necessity for flat grades for modern trains has meant that deep cuttings are imperative, while improved methods of stripping, drilling, blasting, and haulage have lowered the cost of rock excavation and made the construction of deep cuttings feasible. It is against the background of the construction of a standard gauge railway which will carry iron ore in Western Australia that aspects of rock cuttings are viewed.

The railway is under construction between Kalgoorlie, through the iron ore deposits of Koolyanobbing, to Fremantle and Kwinana on the coast, a distance of about 390 miles. Most of the cuttings evaluated are situated in the Avon Valley Deviation which follows a natural transportation route along the valley of the Swan-Avon River, through dissected topography of the Darling Range between Northam and Upper Swan (Plate 11).

## GEOLOGICAL SETTING

*Rock Types*

The two main elements of the geology are the Precambrian basement complex of the Darling Range and fault scarp, and the Tertiary and Recent superficial deposits mantling both the sedimentary sequences of the Perth coastal plain and the weathered Precambrian rocks of the Darling Range and scarp.

The main rock types of the Precambrian are: a granite-gneiss-amphibolite suite; a banded granite gneiss suite hybridized in part; intruding batholithic granite; pegmatites and quartz veins; quartz dolerite intrusions; metasedimentary quartzite and schist of the Jimpeding Series (Prider, 1944) in the vicinity of Toodyay.

*Geomorphology*

The mature valley of the Swan-Avon River system has a fall of 450 feet in 60 miles, and follows foliation or bedding structure except in a few gorge areas where control is from shears or big joints. Generally the valley is asymmetric in cross section, with physical weathering of sheet jointed structures dominant on the northern side and chemical decay of rock dominant on the southern side. Down-cutting by the river has resulted in some exposure of rock in the valley bottom, partly mantled by alluvium. A typical cross section is shown in Figure 3.

*Jointing*

The dominant joint sets are sheet joints conforming to the topography, and joints following the bedding or foliation.

Sheet joints not only dominate the mechanical division of the rocks, but often have a profound effect on chemical weathering by channelling the movement of groundwater, and rock decay often results in the production of thick bands of clay between layers of fresh granite. Sheet joints may also limit water movement by an impervious lower joint surface, resulting in complex layering, with clay passing abruptly to fresh granite (Figure 4), rather than the transitional sequence resulting from prolonged chemical weathering (Table 1 and Figure 5).

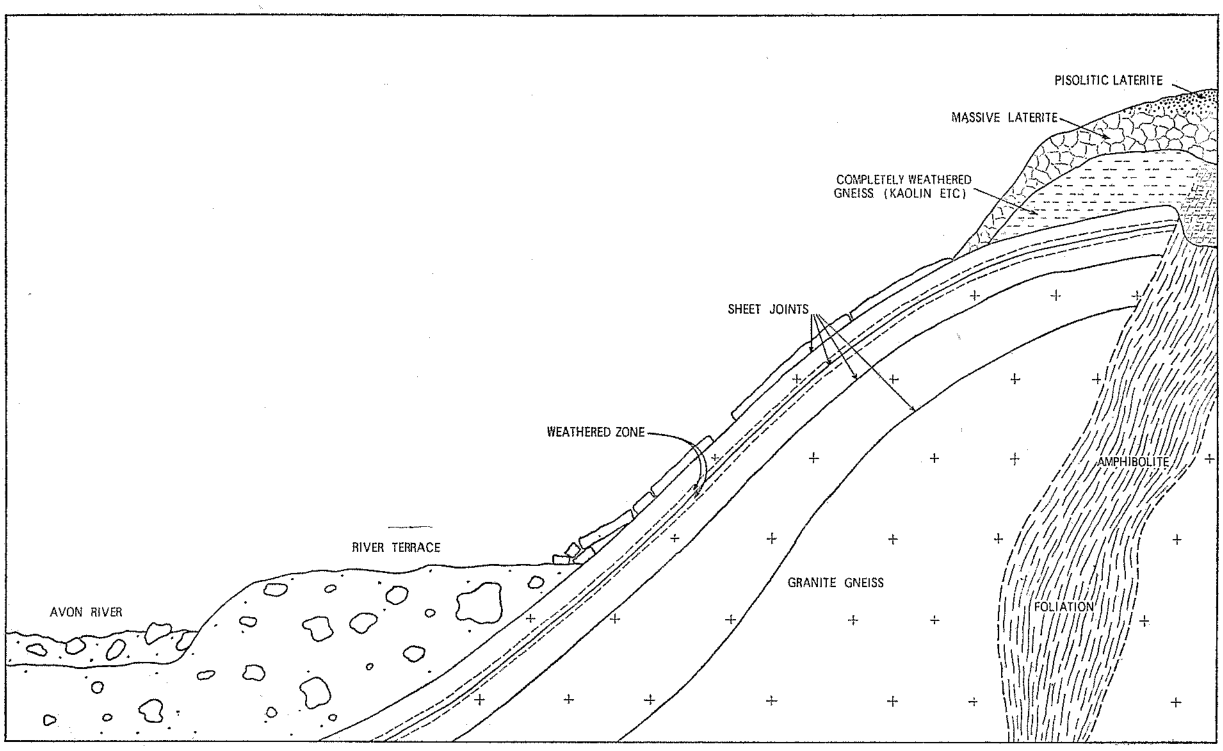


Figure 3—Typical diagrammatic section of south bank of Avon Valley, standard gauge rail project.

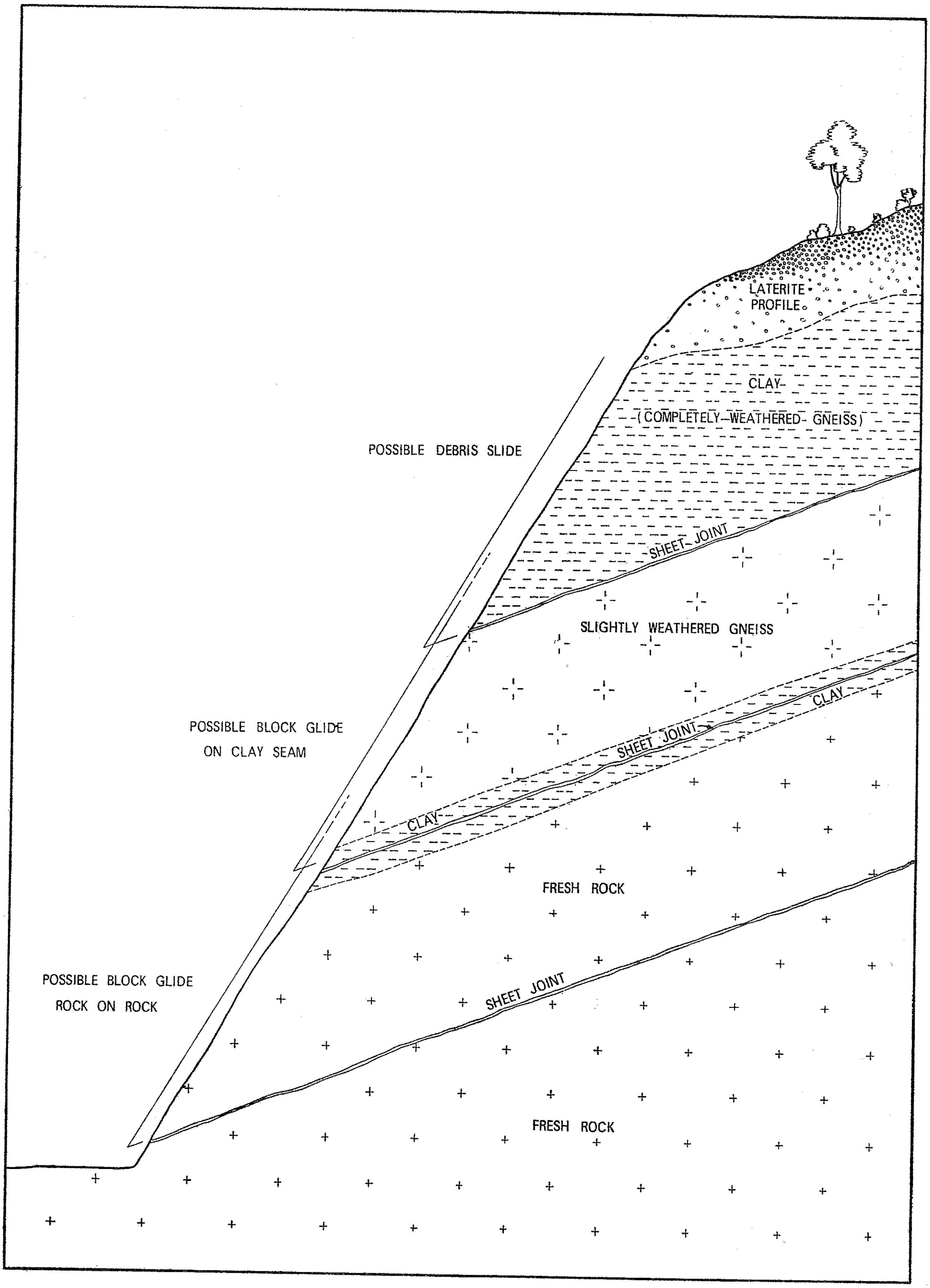


Figure 4—Diagrammatic section showing conditions of instability in cuttings resulting from sheet joints, standard gauge rail project.

## SLOPE STABILITY

### *Rock and soil mechanics*

There has been some discussion as to the precise point in a weathered sequence when soil mechanics methods are not valid and where rock mechanics techniques should be employed.

In the cuttings of the Avon Valley Deviation it was found that no guide lines could be fixed, that the stability of some sequences of highly weathered rocks of the kaolin phase (Gordon, 1964) were dominated by relict geological structures, and that the stability of some blocks of fresh rock was governed by the soil properties of joint-filling material. The interface between the two disciplines was often found to extend from ground level to Formation Level, a depth of as much as 120 feet, and even in isolated places where a clear-cut division was apparent, variations of rock type and depth of weathering allowed little lateral extension. Most of the stability problems were encountered in this interface zone.

### *Type of slope failure*

The various types of slope failure encountered are classified according to the inherent geological defect, rather than to the physical form of the failure. The effects of construction methods on stability have been discussed elsewhere (Gordon, 1966) and this aspect is noted only incidentally. Many of the types of slope failure have developed after excavation, that is, long after a decision has been made on the overall angle of the batter. Each of these problems is an individual one, and in most instances the underlying geological cause was not discerned during the initial site examination. To this extent the unstable areas represent partial failures of the investigation and design methods employed, as failure in a railway cutting must be classified as the failure even for one individual block. It is conceded that the calculation or pronouncement of a stable slope angle is an overall approximation, although it is possibly the most essential part of exploration and design phases. Experience to date indicates that the most comprehensive site examination possible under any economic limits would not discern all the possible types of failure.

### *Sheet joints*

One of the most serious difficulties in the investigation stage concerned the presence and influence of folded geological structures or of large, curved, and spoon-shaped joint surfaces. The latter are of common occurrence as sheet joints in the granite terrain, and the non-planar structures often contain clay partings. Mathematical expression of such features in rock mechanics calculations is difficult, moreover empirical judgments are apt to err, as the general attitude of the sheet joints was connected with topography at the time of formation, which is not necessarily the same as the present scene.

The rock type, attitude of geological structures, and the amount and nature of other types of jointing all have a bearing on the configuration and prominence of sheet joints. A dominant joint pattern usually means that the sheet joints, which are formed later than joints of tectonic character, are absent or are not prominently developed. Where the continuity of the granite gneiss is interrupted by dolerite dykes, which are usually well jointed, the sheet joints continue, displaced along one of the flat pre-existing cooling joints. Sheet joints are not well developed in areas where the older amphibolite-gneiss suite has been folded, with the protection of joints in the more brittle gneiss. The sheet joints dipping into the cut were invariably on the uphill or highest side.

The following types of slope instability are a direct result of the presence of sheet joints:

(1) debris falls of completely weathered rock above a joint plane,

(2) block glide of rock on clay as a sheet joint replacement,

(3) block glide of rock on rock on an over-step **joint plane.**

These three cases are illustrated in a section (Figure 4).

If the joint plane is dipping steeply enough, then unstable conditions exist in all three cases. The presence of clay as a joint filling or as a seam adjacent to the sheet joint, means that the critical angle for sliding is much less than if the joint opening were clear and the sliding mass was rock over rock. Terzaghi, (Muller, 1959) assumes a frictional angle of 15° for rock layers with clay partings, and of 25° if there are no clayey flakes. This sliding angle is independent of the angle of the batter.

In essence, the stability of the blocks lying on the sheet joint planes depends on their dip into the cut, which is broadly related to the topography of the hill or spur being cut. The most steeply dipping, and thus the most potentially dangerous joints, are usually found on the flanks of the hill rather than in the centre, unless the cross section profile has a considerable cross fall. Although this happens occasionally, most of the hillslopes involved in cutting slope at 10° to 25° across the direction of the cutting. The critical issue then is the presence or absence of clay in the joint opening, and this varies in individual joints, making it almost impossible to assess the conditions of stability by conventional site exploration.

Once the cutting had been opened up, the exposure of the seams of clay dipping into the cutting and overlain by large masses of fresh rock meant that an assessment of stability had to be made, and remedial measures instituted if there were danger of rock slides. Remedial works were usually restricted to pinning or anchoring, as large-scale removal was not practicable because of topography and a need to retain berms.

### *Cross joints*

Strongly developed open joints that intersect the walls of a cutting in plan between 45° and 90° may be a cause of weakness, as the explosive force from blasting may be channelled along the joint openings giving considerable overbreak. Well developed cross joint sets that are not parallel may also channel the explosive effect, leaving a toe.

Intersection of two cross joints is a situation often allowing block gliding. The usual condition is that the joints dip in opposite directions, with the intersection open to the top. Bedding planes dipping at 55° and striking across a cutting and intersected by occasional major points dipping at 60° in the opposite direction, frequently allowed large blocks to slide in the Windmill Hill Cutting.

### *Folding*

Folding of granite gneiss has usually caused local breakage and deformation, and this condition allows rock falls from the batter. In areas of metasediments, where schists are often enclosed in quartzites, there has been destructive bedding slip on deformation, allowing the development of drag folds and fracture cleavage in the less competent schists.

In the Windmill Hill cutting, folding of Precambrian metasediments has produced a structural terrace of tremolite-biotite schist enclosed in quartzite. Two series of rock slides occurred during construction, the first as a consequence of the geological structure, the second as a result of the construction methods used in remedial works.

The sequence of events of the first series of rock slides is shown in Plate 12. The presence of a band of tremolite-biotite schist enclosed in quartzite had been inferred during preliminary route reconnaisance because of the lack of outcrop or scatter. The structural terrace was exposed during excavation of the bottom lift, where the folding had induced intense fracture cleavages in the tremolite-biotite schist. This had resulted in the production of lens shaped pieces of schist separated by mica flakes. The exposure of this material containing moisture, and the development of groundwater head were facts which caused alarm when noticed during a geological inspection, and

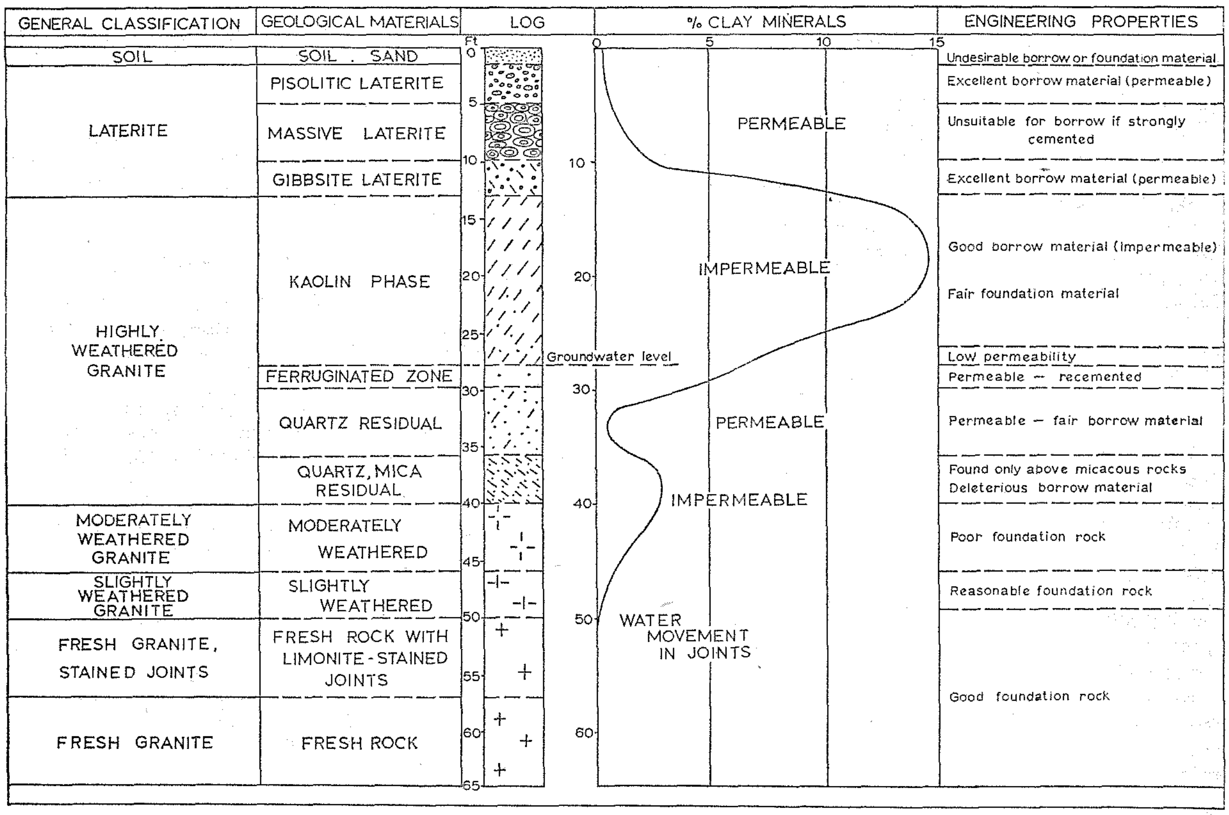


Figure 5—Weathering profile of granitic rocks.

the cutting was cleared of men and machine immediately. Two hours later phase 2 of the sliding occurred, followed by the others in order of undermining, and the whole fallen mass moved as a debris slide following heavy rains, one month later.

It was apparent that if the structural terrace were of significant extent, then a major problem of stability of quartzite sliding on crushed decomposed mica, was involved. The structure was determined by diamond and air track drilling before the excavation of the lowest lift was authorized. The rockslide area in the schist was to be battered back at 35°, and the three top lifts were successfully shapped by dozer when the contractors decided to remove the lower slice by drilling and blasting. The 35°-55°-90° template used to set the angle of the air track drills was wrongly marked with the result that the holes were drilled at 55° to 60°, and on blasting, the slope failed again, proving that the first collapse was not unique. The slide was cleared and the slopes were cut down by a small dozer at 30° for the bottom batter and 35° for the remainder.

*Fault zones*

The nature and size of a fault or shear zone and the rock type involved is important in determining any deleterious effect on the stability of a cutting. The direction and attitude that a fault makes with the length of a cutting is however of critical importance. The most dangerous situation is found when thin clay filled crush zones strike along the cutting and dip into it at flatter angles than the batter. It would be fortuitous if such a structure were detected under the conditions of a thick weathered mantle. As the strike of the fault makes greater angles with the cutting, the problems lessen, and only the stability of the crush zone itself becomes of concern. If the crush zone is wide and ravels, remedial work is necessary. Faults striking across the cutting may be important, however, if they are intersected by other faults or prominent joints in a conjunction that would aid block gliding or rockfall (Plate 13A).

*Rock weathering*

The soils resulting from the in situ decomposition of granitic rocks vary widely in properties according to the depth of weathering, and to the nature of the original rock. At the ground surface a fairly uniform laterite residual reveals few characteristics of the underlying rocks and the differences due to changes in rock types only become more apparent under the laterite mantle. The weathering profile is shown in detail in Table 1, and it is apparent that the more or less horizontal stratification resulting from weathering does not persist as the mineral character of the granite gneiss complex changes laterally. In extreme cases in banded granite gneiss with vertical foliation, outcrops or quartzose granite or massive amphibolite are found immediately adjacent to 60 to 80 feet of completely weathered rock (Gordon, 1963). Deep downcutting of the Avon-Swan River through the weathering profile and the presence of sheet joints are important modifiers.

The weathering of dolerite dykes is found to be a function of the strike. There are two dominant strikes for the dykes, easterly and north-northeasterly. The more northerly trending dykes appear to be the more resistant to weathering and often form the spine of a ridge, while the easterly dykes are often weathered to depths of 20 to 30 feet.

Figure 5 is a geological diagram of one of the cuttings illustrating the variety of rock types, and the complexity of the profile of chemical weathering developed on them. These elements and the mechanical division of the rock by joints make it almost impossible to get an accurate geomechanical picture of the site before construction commences.

The variable depth and nature of weathering mean that overshooting will occur unless the blasting pattern is altered (Plate 13B). It also means that the initial site exploration would need to be exhaustive, in order to effectively assess the optimum slope angle for the batters.

## INFLUENCE OF BEDDING AND FOLIATION PLANES

When stratified or foliated rock is inclined towards a free face, especially at a flatter angle than the face, the decreased shear strength of the rock is liable to result in sliding. Such gross structures can be recognised in the reconnaissance stage and the batter angles can be adjusted to contain them.

In some of the minor cuttings near Northam, close to the Avon River, moderately weathered granite gneiss with steeply inclined foliation planes was exposed at ground level. The foliation joint planes in the upper 10 feet or so were filled with debris and this area was impermeable. Excavation of the cuttings intersected open water-bearing planes, and saturation of sub-base filling, mud boils, and settlement occurred. Deep interceptor ditches on the uphill side of the cutting and use of coarse rock fill instead of weathered rock sub-base were methods used to overcome these problems. A similar seepage problem occurred at 49 miles 25 chains where ground water was confined in flatly dipping foliation planes of amphibolite schist. Vertical, well-jointed quartz reefs acted as natural channels, and springs developed in the cutting floor after excavation (Gordon, 1966).

## MAINTENANCE

Chemical and mechanical weathering of rocks exposed in a cutting are often sufficiently rapid to allow debris and rock falls in the first year of maintenance. Post-excavation relaxation or rebound is thought to occur in the deeper rock cuts and this appears to be conditioned by the method of blasting (Gordon, 1966). In Cut No. 2 well-jointed amphibolite and gneiss that are moderately weathered have deteriorated notably in a period of two years, and debris falls are frequent.

Pyrite mineralisation is a notable feature at the base of Horseshoe Hill cutting below the former ground water level. Where abundant pyrite crystals are disseminated in the altered amphibolite matrix, there has been wholesale deterioration of the rock by chemical oxidation, and subsequent debris falls.

The rock cuttings were designed with a 10-foot wide berm sloping into the hill at 1 in 12, placed every 30 or 40 feet vertical height of the cutting. The benches were meant to be continuous to allow access for clearing of accumulated debris. The shaping of the benches proved most difficult, and the outer angle was often lost due to shattering from 2, 3, or 4 adjacent blasts (Gordon, 1967). The corner between the toe of a slope and the bench, also proved difficult to shape correctly, either from under or overshooting. If the toe is undershot the efficacy of the bench is impaired, and remedial work which can only consist of trimming, usually oversteepens the lower part of the slope above, and weakens it at its weakest point.

## DRAINAGE AND WATER PROBLEMS

Many of the cuttings had distinctive and often troublesome seepage patterns, and before remedial works were commenced, the various types of geological conduits were classified. These were: (1) sheet joints, (2) foliation joints, (3) bedding joints, (4) quartz veins, (5) variations in rock type (Gordon, 1966). The seepage trouble resulted in debris falls from cutting walls, and springs in the floors, saturation of the sub-base and the formation of mud boils.

Most of the cuttings were situated about half way up the gently sloping left bank of the Avon River. A small range of hills of bare granite gneiss forms the crest of the valley wall, and erosion in the valley has meant that the normal weathering sequence is truncated. The cuttings were deep enough to expose slightly weathered rock below the impervious weathered zone, and below the zone where joint openings were filled with weathering products.

A serious stability problem at Windmill Hill was partially caused by the development of a high piezometric head during construction, where a band of relatively impervious weathered schist was enclosed in open jointed quartzite. As the cutting advanced towards the schist which acted as a water barrier, the groundwater level in the excavated quartzite adjusted to formation level. At the time of collapse there was a differential head of 30 feet between the quartzites on either side of the schist, which caused it to collapse into the cutting, commencing in an area of fracture cleavage (Plate 12).

Fortunately in the two deepest cuttings near the Darling scarp, the ground water level was in gneiss with open limonite-stained joints, below the zone of deleterious weathering.

## METHODS OF SITE EXPLORATION

With the benefit of hindsight, it is profitable to review methods of site exploration, and to suggest possible improvements to fit the cases developed in this paper.

At the completion of the reconnaissance survey, the depth and length of cutting are usually known, and these constants can be related to three initially important variables in the determination of safe batter slopes, which are (1) the mechanical condition of the rock, (2) the amount of chemical weathering, (3) spatial relationship of geological weaknesses to the cutting. The first step in the design stage should be precise geological mapping of the cutting area, followed by a rock mechanics joint survey. These studies should be supplemented by the drilling of exploratory holes with an air-track type drill, at a spacing of not more than 5 chains, the hole to be taken down to formation level, and the cuttings to be examined on the site by a geologist. Any anomalies should be diamond drilled.

The batter slopes may then be assessed and the cutting laid out on the assumption that the worst conditions apply from top to bottom unless other information is available. The initial cut in overburden is thus of maximum width. As the top lift is removed, the joint pattern should be reassessed as greater amounts of less weathered rock is revealed. The batter slopes for the remaining lifts are then determined, and if this is steeper than the initial figure, the width of the top bench is made correspondingly greater.

This however may involve a difficult contractural point, where the contractor could claim for compensation for less work and loss of profit. If there are indications of deleterious geological structures or of weathered rock at depth, more detailed investigation is needed including diamond drilling. One of the most necessary measurements is to determine the cross section profile of the rock spur or hillside as well as its shape as intersected by the length of the cutting. This is to give an idea of the possible dip angles of the sheet joints, if developed in the area.

Finally the geomechanical properties of the various rock types and their distribution must be considered in the light of the excavation method proposed, of which the blasting pattern in probably the most important factor.

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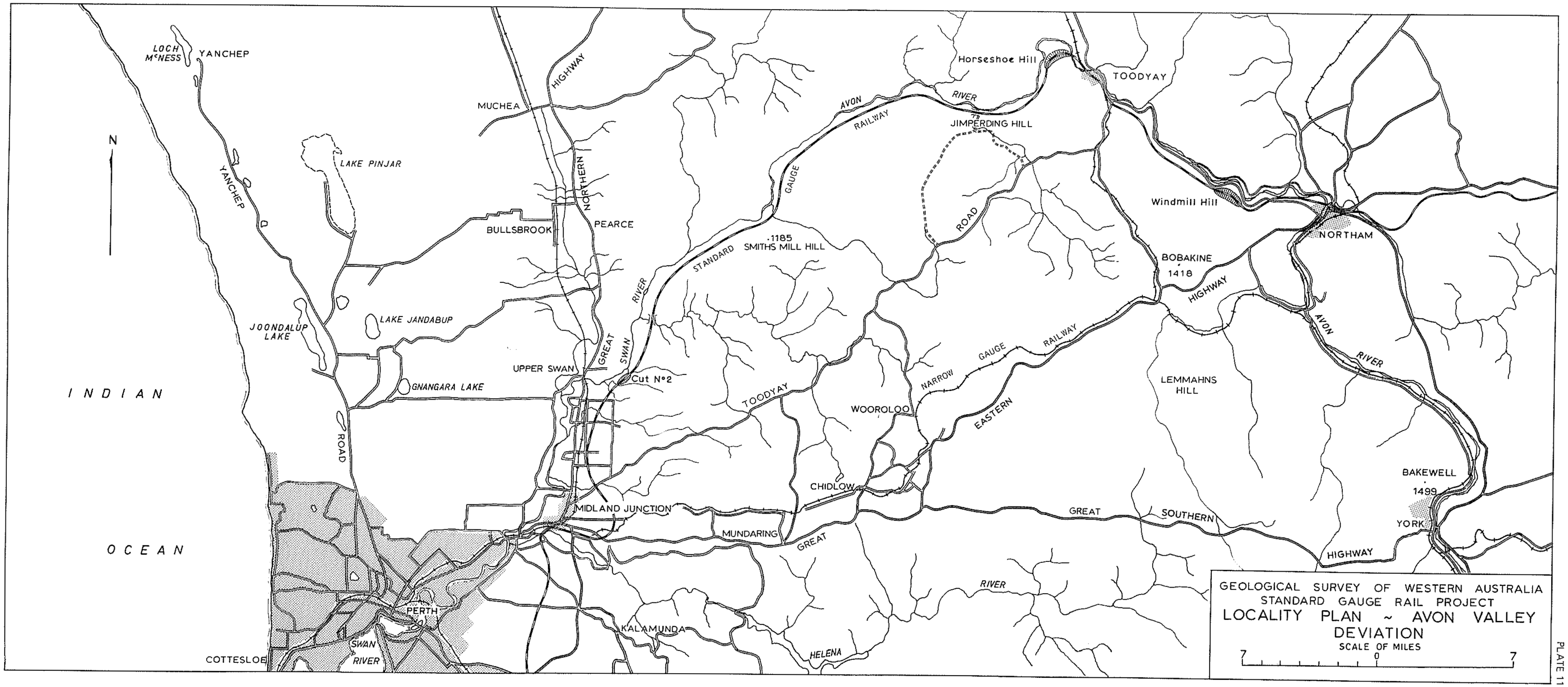
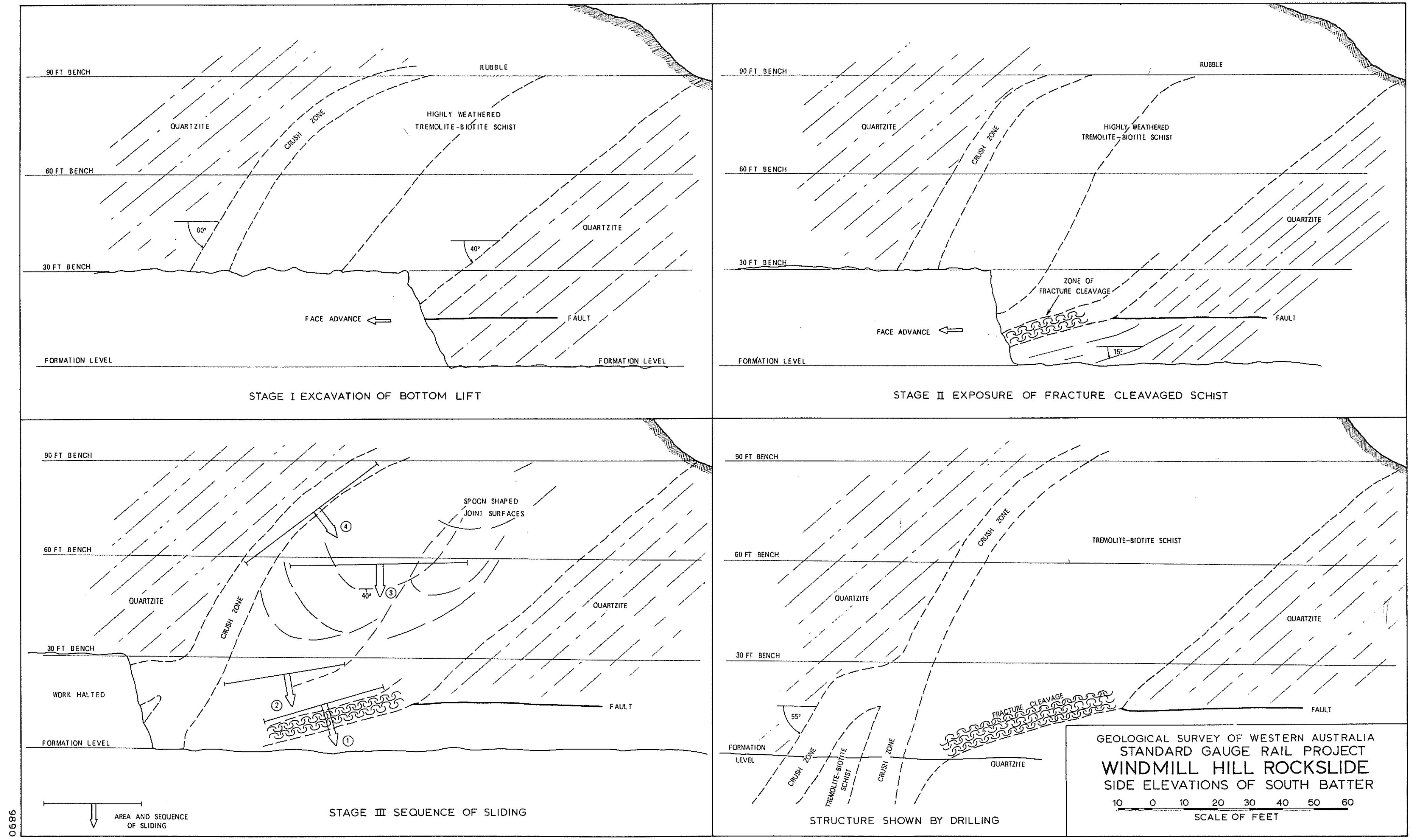


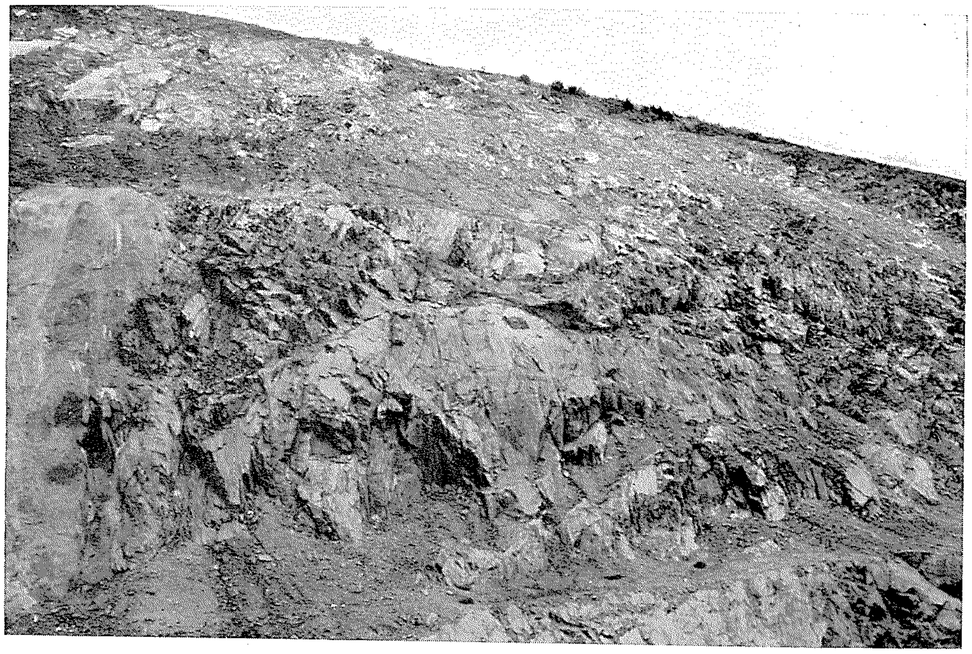

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
STANDARD GAUGE RAIL PROJECT
LOCALITY PLAN ~ AVON VALLEY DEVIATION
SCALE OF MILES 7 0 7

1689

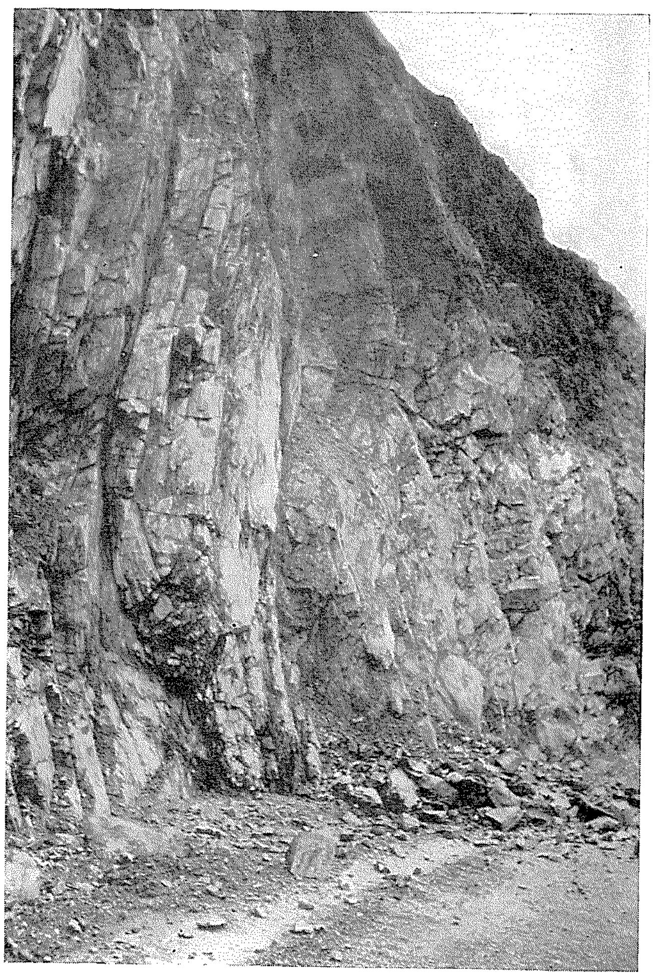
PLATE 11

PLATE 12


90 FT BENCH
60 FT BENCH
30 FT BENCH
FORMATION LEVEL
RUBBLE
QUARTZITE
CRUSH ZONE
HIGHLY WEATHERED TREMOLITE-BIOTITE SCHIST
60°
40°
FACE ADVANCE
FAULT
STAGE I EXCAVATION OF BOTTOM LIFT
ZONE OF FRACTURE CLEAVAGE
15°
STAGE II EXPOSURE OF FRACTURE CLEAVAGED SCHIST
SPOON SHAPED JOINT SURFACES
WORK HALTED
AREA AND SEQUENCE OF SLIDING
STAGE III SEQUENCE OF SLIDING
TREMOLITE-BIOTITE SCHIST
55°
FRACTURE CLEAVAGE
STRUCTURE SHOWN BY DRILLING
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
STANDARD GAUGE RAIL PROJECT
WINDMILL HILL ROCKSLIDE
SIDE ELEVATIONS OF SOUTH BATTER
10 0 10 20 30 40 50 60
SCALE OF FEET
0686



A. No. 2 rock cut showing conjunction of fault and sheet joint to give unstable conditions; F 1193.



B. Overshooting the toe of batter, No. 2 rock cut; F 1194.

# GENERAL GEOLOGY OF THE ROCKY POOL DAM SITE

by J. L. Baxter

## INTRODUCTION

Rocky Pool dam site, 37 miles upstream from the mouth of the Gascoyne River, was investigated during 1967 by geological mapping and auger drilling.

The river has incised its own flood plain to a depth of between 20 and 30 feet, exposing cliffs of sedimentary formations which form the abutments.

During peak flows, the floodwaters are not confined to the main channel, but spill into distributaries to the north and south of Rocky Pool. Two distributaries to the south, which become one channel away from the river, and a distributary to the north will have to be sealed, depending on the position of the wall. These are lower than the full storage level of the dam, understood to be R.L. 160 feet.

Regional and plane table mapping, and the supervision of a preliminary Gemco auger drilling programme at the dam site were conducted during 1967 by J. D. Wyatt, J. L. Baxter, and P. Hancock. R. Passmore inspected the hydrology of the river channel, and its distributaries downstream of the dam site in 1967, siting preliminary bores for the establishment of piezometers.

Mapping was completed by Baxter at a scale of 20 chains to an inch on air photos, taken as part of an erosion study of the Gascoyne River. The two river banks over a distance of 7,200 feet and a width of 4,000 feet were plane tabled by Wyatt and Baxter at a scale of 100 feet to an inch.

## GEOLOGY

Geological mapping of the dam site and surrounding area has been completed at scales of 100 feet to an inch and 20 chains to an inch. The former is presented at 400 feet to an inch as Plate 14 showing also survey lines A, B, D, and F. A contour map at a scale of 1:12,000 and vertical interval 5 feet was supplied by the Department of Lands and Surveys (Rocky Pool Project G87).

Table 1.

STRATIGRAPHIC COLUMN

| Age | Thickness (ft.) | Geological formation | Map unit | Description |
|---|---|---|---|---|
| QUATERNARY | 0–25 | River sand | Qra | Sand and silt, unconsolidated |
| | 0–20 | Superficial deposits | Qrr | Silt, sand, gravel unconsolidated |
| | 2–6 | Boulder scree | Qrt | Pebbles and boulders |
| | 0–6 | Eluvium | Qrs | Indurated sand and clay partly derived from in situ weathering |
| UNCONFORMITY | | | | |
| QUATERNARY or Tertiary | 0–200 | Sandstone | Tqe | Well bedded sandstone with minor conglomerate |
| UNCONFORMITY | | | | |
| TERTIARY | 5–20 | Red siltstone | Tk | Ferruginous siltstone |
| | 10–80 | White siltstone | Ts | White silty sandstone |
| CRETACEOUS | 13–50 | Green clay | Kut | Green calcilutite |
| | ?150 | Blue clay | N.M. | Blue calcilutite |

NOTE—N.M. means not mapped.

### *QUATERNARY*

#### *River sand*

Sand is deposited in the larger tributaries, and in the main channel of the Gascoyne River. It is red-brown to white, fine to coarse-grained, unconsolidated sand up to 25 feet thick. On the banks of the river there is deposited a thin veneer of silty sand which is only a few inches thick.

#### *Superficial deposits*

Superficial eolian and fluvial deposits of silt and sand have been formed on the banks of the river. These deposits are in the form of dunes and levee material, not more than 20 feet thick. Thin bands of coarser pebbly wash are deposited through the sands.

#### *Boulder scree*

Boulder scree slopes on the banks of the Gascoyne River, particularly in the vicinity of the "B" line, are composed of conglomerate.

#### *Eluvium*

Red-brown, silty sand, partly derived from induration of soils and partly from weathering of the underlying rock unit, has formed eluvial deposits. These deposits occur as a thin cover over weathered outcrop.

A sandy bed with some silt and clay is found overlying the green clay in the vicinity of survey station 181. The unit may be a localised sandy lens which has been leached, or a weathering product of the green clay; however in this mapping it has been included with eluvium.

### *TERTIARY OR QUATERNARY*

#### *Sandstone*

Extensive areas of sandstone crop out upstream of the "D" line, and downstream from the "A" line. The unit is a brown silty sandstone containing beds of grit and conglomerate. It is underlain disconformably by a red siltstone. A prominent, near horizontal, parting with a frequency range of 1 per 3 to 12 inches is common. The sandstone contains numerous irregular circular patches of limonitic pisolites in a sandy matrix. The maximum measured section, measured upstream of the "D" line, is 200 feet.

The sandstone in the banks of the river near line "A" has few bands of conglomerate. It is principally a sandstone with minor gritty bands. In the vicinity of Bore 45 the sandstone is thin and overlies red siltstone; here distinction in mapping is difficult.

In the vicinity of the "D" line the sandstone contains numerous pebbly bands. The sandstone overlies a silicified, lateritised siltstone in this area indicating an appreciable time break between the deposition of the two units.

The sandstone is poorly consolidated, and is not suitable for rock fill, or rip-rap. It may be useful as unselected fill.

### *TERTIARY*

#### *Red siltstone*

The red siltstone is best exposed on the right bank at the Rocky Pool constriction, where it ranges in thickness from 10 to 20 feet.

Jointing is irregular, although perfectly formed polygonal shrinkage cracks are common. Exfoliation partings, or sheet joints, parallel to the ground surface, have resulted in the formation of slabs of rock a few inches thick and up to 2 feet in diameter. On the right bank of the river, in the vicinity of station 109, the surface is covered with large masses of rock up to 6 x 6 x 8 feet.

The contact between the red siltstone and the underlying white siltstone shows many variations. In places, particularly at the pool, the contact is gradational, with nodules of red siltstone in the underlying white siltstone, and vice versa. The accessory minerals tourmaline and zircon are common to both the red and white siltstone. In other places the contact between the two siltstones is sharp.

*White siltstone*

The white siltstone varies in thickness from 10 feet to more than 80 feet. The thickest section of the siltstone occurs south of Rocky Pool in Bore 2.

There are sandy and clayey bands within the siltstone unit, and some of the sandy beds have purple staining due to the presence of ferruginous minerals.

The contact between the white siltstone and the green clay is either conformable, or disconformable. This is best observed at a small plunge pool in the vicinity of station 251.

The white stiltstone is a relatively soft plastic rock. Measurement of dip and strike is difficult because the rock becomes desiccated on exposure to the atmosphere, forming a poorly consolidated fragmental material broken by many small, open, irregular cracks.

The white siltstone is poorly to well consolidated and is not suitable as rock fill, and its use as a core material will be limited by the shrinkage properties.

*Green and blue clay*

The green clay crops out in the core of an anticline at the dam site, and the blue clay is observed only in drillholes.

The best exposure is in the banks of the river in the vicinity of the "B" line, where cliffs capped by conglomerate have green clay exposed in the scree slopes.

The rocks are foraminiferal calcilutites correlated biostratigraphically with the Cretaceous Toolonga Calcilutite within the Carnarvon Basin.

The green clay is highly plastic, frequently gypsiferous, and desiccates on exposure to air. It is considered unfavourable as an impermeable core material as it will tend to slip under pressure, but no other suitable material is known to occur in the vicinity of the dam site.

## STRUCTURE

The geological structure of the Rocky Pool area is that of a northward plunging asymmetric anticline with its axis striking approximately 020°, the flanks dipping to the east at 8° to 17°, and to the west at 2° to 5°. Green clay is exposed in the core of the anticline, and siltstone, sandstone, grit and conglomerate on the flanks (Plate 15).

A lineament on the photos bearing approximately 017° cuts the sequence at the "D" line. This lineament is not well defined by outcrop, but Bores 29 and 33 show different sections, and therefore the feature is probably a fault. There are air photo indications of a second fault downstream from this, bearing aproximately 030° and cutting the axis of the anticline beneath the river.

Both northwest and southwest from Rocky Pool deep flood channels leave the river course. These channels have in them between 1 and 40 feet of wash deposited over rock. The channel to the south will have to be sealed if a dam is built on the river, however the northern channel will not affect a dam site east of the "B" line.

## HYDROLOGY

The Gascoyne River is a sand-filled channel, the sand being of variable thickness. Islands in the channel are up to 25 feet high. Rocky Pool, located at a constriction in the river, is a semi-permanent pool, which remained full throughout 1967, after cyclonic rain in January and small winter rains.

The detailed hydrology of the river and the anabranches and distributaries downstream from Rocky Pool has been generally studied by Baxter and will be investigated further with water level recorders established in 1967.

## SITE APPRAISAL

The preliminary investigation programme is now completed. The work done so far indicates that Rocky Pool dam site would be a difficult one on which to build and operate a dam. The basin formed by the dam would be large and shallow, which is a disadvantage in an area where evaporation is approximately 8 feet per year and considerable increase in salinity could be expected as a result. Leakage though the sands on the flanks of the reservoir would occur. The proposed wall is appoximately 3,500 feet long, and would have its foundation on plastic green clay. The overlying white siltstone is an unsuitable foundation as it contains beds of unconsolidated permeable sands. The impermeable green clay would be slippery, and the dam would have to be keyed into the formation. The structure would have to withstand the large peak flows of flash floods, common with cyclonic rains.

Material for construction of a dam would be difficult to obtain, and it is suggested that experiments with the available material, and with mixing of the material, be planned. Filter zone material could be obtained from the river bed sands. The green clay or the white siltstone may be suitable as core material; however three is a possibility that core will have to be mixed from these two units. Unselected fill could be obtained from a white siltstone and a sandstone. Rip-rap is the least likely material to be found in the area, and though the red siltstone may be of some use, it would possibly break up with persistent wave action. Concrete aggregate may be obtained by sieving and washing the sands in the river bed.

Two types of river flow are common, flash floods, which have a high flow rate, and low flow, which can be only a trickle. Scouring by the high flows may cause erosion problems at the wall, and siltation from flows will need constant attention.

The left bank of the river is a wide flood plain flanked by low sand dunes. A prominent depression, south of the main channel, has 40 feet of sand deposited in it, and will require sealing if the reservoir is to be watertight. In the vicinity of the "A" line the green clay is approximately 60 feet below the surface, and is overlain by white siltstone. This site is considered unsuitable as the white siltstone contains a bed of unconsolidated sand 10 to 15 feet thick through which water flows under hydrostatic pressure. This bed would be difficult to seal. In the vicinity of the "B" line, the contact between the green clay and the overlying white siltstone slopes away from the river, and will have to be tested for outflow.

The river sands in the existing channel are of variable thickness, and a noticeable feature is the variation in salinity of the water in the sands, suggesting lenticular aquifers. This may mean that the surface of the green clay in the river is irregular, or that the sand deposits in the channel are divided by deposits of impermeable silt. This should be investigated more fully by auger drilling in the river, and possibly a seismic traverse along the trial centre line of the dam.

The plain on the right bank of the river also has a depression which will only act as an offtake channel if the dam is built in the vicinity of the "A" line. The right bank has extensive flats of conglomerate and sandstone, which will have to be stripped before building a dam. The green clay is generally closer to the surface than on the left bank.

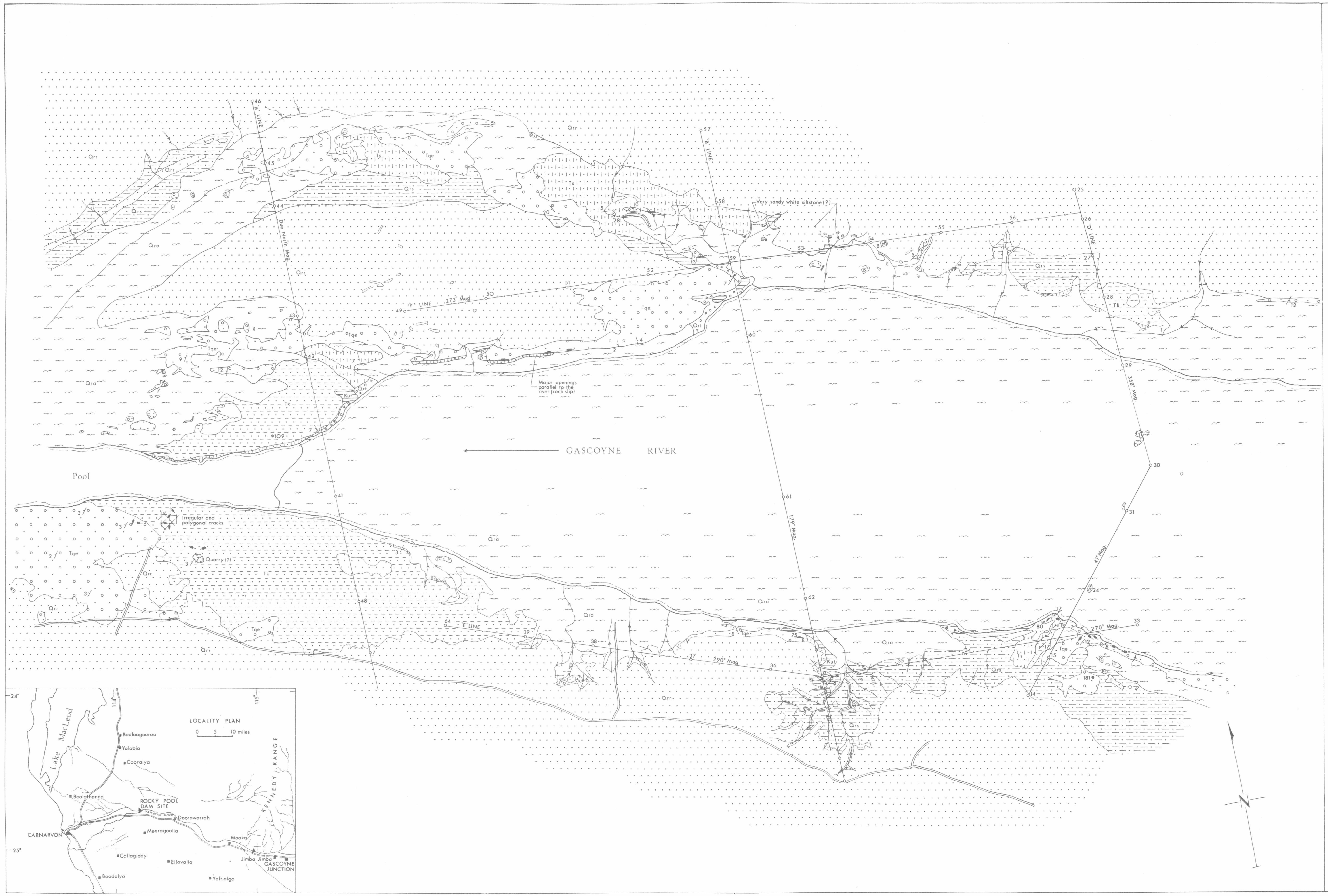
## RECOMMENDATIONS

Seismic traversing across the dam site in the vicinity of the "B" line would give an estimate of the depth to green clay. The survey should include a traverse upstream of the "D" line to attempt to determine the exact position and attitude of the fault.

A trial centre line should be drilled to determine the depth and quality of the foundation material. Drilling of the fault in the vicinity of the "D" line may reveal its characteristics.

Laboratory tests are needed to determine if suitable construction material can be obtained from siltstone, sandstone, and clay, or whether some of these materials will require mixing.

Concrete aggregate may be obtainable from the sand in the river by screening and washing.




**REFERENCE**

QUATERNARY
- Qra — Alluvium : coarse to medium grained quartz sand
- Qrr — Superficial deposits : silts, sands, gravel, unconsolidated
- Qrt — Boulder scree
- Qrs — Eluvium : indurated sand and clay partly derived from in situ weathering

Unconformity

TERTIARY OR QUATERNARY
- Tqe — Sandstone : well bedded sandstone with minor conglomerate

Unconformity

TERTIARY
- Tk — Red siltstone : lateritised siltstone
- Ts — White siltstone : white silty sandstone

Disconformity or Unconformity

CRETACEOUS
- Kut — Green clay : green calcilutite

- Bedding — strike and dip
- Jointing — strike and dip
- Outcrop boundary
- G.S.W.A. survey station
- P.W.D. Gemco auger drillhole
- Tracks
- Depression showing depth
- Zone of earth slide

SCALE OF FEET

0 200 400 600 800 1000 1200 feet

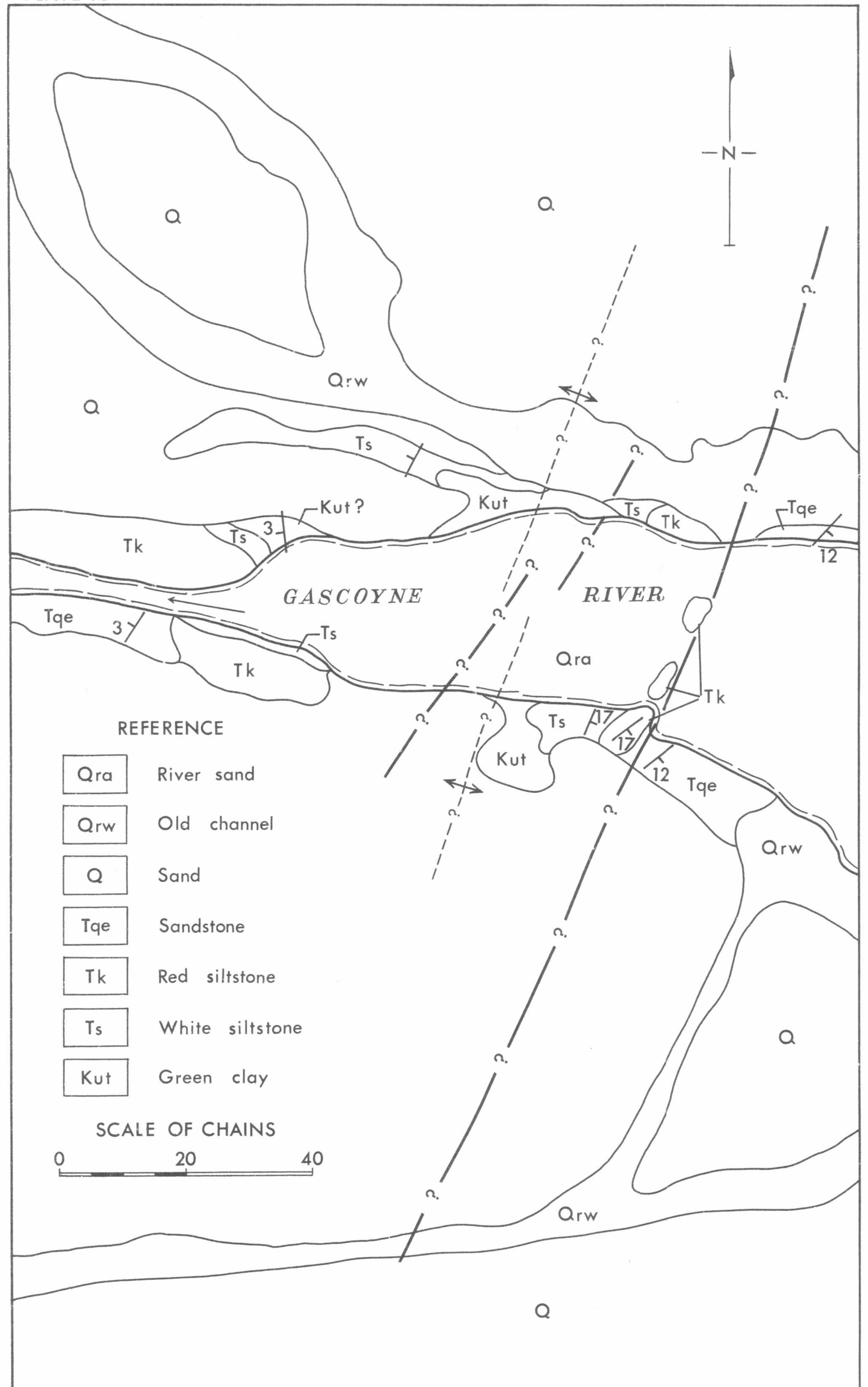
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# GEOLOGICAL PLAN
# ROCKY POOL DAM SITE
# SHOWING GEMCO AUGER DRILL HOLES

Geology by J.D.Wyatt & J.L.Baxter 1967

To accompany Report by J.L.Baxter

PLATE 15




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# ROCKY POOL DAM SITE
# SIMPLIFIED STRUCTURAL PLAN

To accompany Report by J.L. Baxter

9966

# THE SEARCH FOR OIL IN WESTERN AUSTRALIA IN 1967

by P. E. Playford and G. H. Low

## INTRODUCTION

The principal event during the year was the commencement of commercial production from the Barrow Island oilfield. The first oil shipment was loaded on the tanker *P. J. Adams* on April 23, thus marking the successful culmination of more than 16 years of activity by West Australian Petroleum Pty. Ltd. in this State.

The amount of exploratory drilling declined during 1967 as compared with the previous year. A total of 17 test wells and 11 stratigraphic wells were completed, and 1 test well and 2 stratigraphic wells were drilling on December 31. The total footage amounted to 115,970 feet. This compares with 25 test wells and 9 stratigraphic and structure wells completed in 1966 for a total of 180,850 feet of drilling. In 1967 163 development wells (totalling 403,205 feet) were completed on Barrow Island, compared with 5 (totalling 11,503 feet) the previous year.

A new oilfield was discovered at Pasco Island during 1967, and two wells were completed there as potential producers. Another gas well was completed at Dongara; the other wells were abandoned as dry holes. The previous year 11 wells had been completed in the State as potential producers.

Geophysical activity during the year was at a slightly higher level than in 1966. Seismic operations amounted to 53.4 party months (land) and 15.0 party months (marine) in 1967, compared with 51.35 party months (land) and 20.18 party months (marine) in 1966. During the year 14.25 party months of gravity and 6,478 line miles of aeromagnetic surveys were conducted, compared with 5.5 months of gravity and 2,700 line miles of aeromagnetic surveys in 1966. Field geological work increased from 9 geologist-months in 1966 to 22.5 in 1967.

## OIL HOLDINGS

The positions of permits to explore and licenses to prospect in Western Australia at the end of 1967 are shown in Plate 16. Details of these concessions are as follows:

*Permits to Explore*

| No. | Area (Square Miles) | Expiry Date of Current Term | Holders |
|---|---|---|---|
| 27H | 31,650 | 31/12/67 (renewal applied for) | West Australian Petroleum Pty. Limited |
| 28H | 26,040 | 31/12/67 (renewal applied for) | do. do. do. |
| 30H | 123,020 | 31/12/67 (renewal applied for) | do. do. do. |
| 106H | 11,800 | 28/9/68 | Westralian Oil Limited |
| 127H | 13,450 | 28/3/68 | Alliance Oil Development Australia N.L. |
| 151H | 14,200 | 7/2/68 | Beach-General Exploration Pty. Ltd. |
| 152H | 11,650 | 7/2/68 | do. do. do. |
| 153H | 13,050 | 7/2/68 | do. do. do. |
| 172H | 6,150 | 30/3/68 | Alliance Petroleum Australia N.L. |
| 173H | 12,250 | 30/3/68 | do. do. do. |
| 174H | 6,100 | 30/3/68 | do. do. do. |
| 175H | 6,050 | 30/3/68 | do. do. do. |
| 177H | 6,050 | 30/3/68 | do. do. do. |
| 193H | 2,750 | 5/2/68 | Hawkstone Oil Co. Ltd., BP Petroleum Development Australia Pty. Ltd. |
| 205H | 16,700 | 17/9/68 | Alliance Petroleum Australia N.L. |
| 213H | 104,000 | 20/6/68 | Woodside (Lakes Entrance) Oil Co. N.L. B.O.C. of Aust. Ltd., Shell Development (Aust.) Pty. Ltd. |
| 217H | 17,600 | 30/5/68 | West Australian Petroleum Pty. Limited |
| 221H | 44,800 | 28/7/68 | Australian Aquitaine Petroleum Pty. Limited, Arco Ltd. |
| 225H | 8,000 | 20/7/68 | West Australian Petroleum Pty. Limited |
| 226H | 34,700 | 6/4/68 | do. do. do. |
| 227H | 11,400 | 6/4/68 | do. do. do. |
| 228H | 2,900 | 13/5/68 | do. do. do. |
| 232H | 3,000 | 20/6/68 | B.O.C. of Australia Ltd., Shell Development (Aust.) Pty. Ltd., Woodside (Lakes Entrance) Oil Co. N.L. |
| 233H | 6,800 | 10/2/68 | West Australian Petroleum Pty. Limited |
| 235H | 19,400 | 21/1/68 | Canadian Superior Oil (Aust.) Pty. Ltd. |
| 236H | 2,600 | 3/2/68 | Abrolhos Oil No Liability, BP Petroleum Development Australia Pty. Ltd. |
| 238H | 1,190 | 9/1/68 (renewal applied for) | B.O.C. of Australia Ltd., Shell Development (Aust.) Pty. Ltd., Woodside (Lakes Entrance) Oil Co. N.L. |
| 240H | 11,850 | 14/6/68 | Coastal Petroleum N.L. |
| 241H | 11,850 | 14/6/68 | do. do. |
| 242H | 11,850 | 14/6/68 | do. do. |
| 243H | 11,850 | 14/6/68 | do. do. |
| 251H | 4,228 | 29/6/68 | West Australian Petroleum Pty. Limited |
| 253H | 5,200 | 28/12/68 | Westralian Oil Limited |
| 254H | 12,100 | 14/2/69 | Tenneco Australia Inc. |
| 259H | 12,930 | 1/2/69 | West Australian Petroleum Pty. Limited |
| 260H | 5,860 | 19/4/69 | do. do. do. |
| 261H | 3,000 | 19/4/69 | do. do. do. |

*Licenses to Prospect*

| No. | Area (Square Miles) | Expiry Date of Current Term | Holders |
|---|---|---|---|
| 102H | 195·551 | 13/1/68 | West Australian Petroleum Pty. Limited |
| 103H | 200·00 | 20/5/68 | do. do. do. |
| 104H | 197·867 | 6/6/68 | do. do. do. |
| 105H | 196·032 | 14/8/68 | do. do. do. |
| 106H | 195·779 | 11/9/68 | do. do. do. |
| 107H | 200·00 | 25/2/68 | do. do. do. |
| 108H | 200·00 | 22/1/68 | do. do. do. |
| 109H | 200·00 | 22/2/68 | do. do. do. |
| 111H | 150·00 | 4/6/68 | do. do. do. |
| 114H | 67·00 | 27/10/68 | Alliance Oil Development Aust. N.L. |
| 115H | 200·00 | 5/11/68 | West Australian Petroleum Pty. Limited |
| 117H | 200·00 | 10/9/68 | do. do. do. |
| 118H | 117·687 | 29/9/68 | do. do. do. |
| 119H | 109·032 | 12/1/69 | do. do. do. |
| 120H | 195·984 | 30/11/67 | Westralian Oil Limited |
| 121H | 120·00 | 11/7/68 | West Australian Petroleum Pty. Limited |
| 122H | 113·418 | 11/7/68 | do. do. do. |
| 123H | 113·232 | 11/7/68 | do. do. do. |
| 124H | 112·528 | 20/4/68 | do. do. do. |
| 125H | 112·477 | 20/4/68 | do. do. do. |
| 126H | 200·00 | 8/2/68 | do. do. do. |
| 127H | 200·00 | 18/1/68 | do. do. do. |
| 128H | 182·00 | 8/3/68 | do. do. do. |
| 129H | 200·00 | 8/3/68 | do. do. do. |
| 130H | 189·929 | 28/3/68 | do. do. do. |
| 132H | 200·001 | 13/5/68 | do. do. do. |
| 133H | 200·001 | 13/5/68 | do. do. do. |
| 135H | 106·197 | 17/5/68 | do. do. do. |
| 136H | 190·765 | 17/5/68 | do. do. do. |
| 137H | 8·830 | 17/5/68 | do. do. do. |
| 138H | 89·037 | 17/5/68 | do. do. do. |
| 140H | 198·750 | 17/5/68 | do. do. do. |
| 141H | 188·941 | 17/5/68 | do. do. do. |
| 142H | 193·350 | 17/5/68 | do. do. do. |
| 143H | 198·133 | 17/5/68 | do. do. do. |
| 144H | 193·104 | 17/5/68 | do. do. do. |
| 145H | 187·411 | 17/5/68 | do. do. do. |
| 146H | 187.032 | 17/5/68 | do. do. do. |
| 147H | 188·953 | 17/5/68 | do. do. do. |
| 148H | 200·00 | 9/6/68 | do. do. do. |
| 149H | 200·00 | 14/7/68 | do. do. do. |
| 150H | 200·00 | 18/10/68 | do. do. do. |
| 151H | 194·367 | 5/7/68 | do. do. do. |
| 153H | 196·00 | 18/10/68 | do. do. do. |
| 154H | 160·20 | Renewal applied for | Beach-General Exploration |
| 155H | 193·75 | 18/10/68 | West Australian Petroleum Pty. Limited |
| 156H | 189·269 | Application pending | do. do. do. |
| 157H | 188·973 | 15/2/68 | do. do. do. |
| 158H | 196·00 | 20/3/68 | do. do. do. |
| 159H | 196·00 | 20/3/68 | do. do. do. |
| 160H | 195·871 | 20/3/68 | do. do. do. |
| 161H | 196·129 | 20/3/68 | do. do. do. |
| 162H | 196·00 | 20.3/68 | do. do. do. |
| 163H | 200·00 | 20/3/68 | do. do. do. |
| 164H | 199·997 | 20/3/68 | do. do. do. |
| 165H | 200·00 | 20/3/68 | do. do. do. |
| 166H | 133·841 | 13/3/68 | do. do. do. |
| 167H | 160·520 | 13/3/68 | do. do. do. |
| 168H | 186·473 | 13/3/68 | do. do. do. |
| 169H | 200·00 | 20/3/68 | do. do. do. |
| 171H | 190·00 (provisional) | 13/4/68 | do. do. do. |
| 172H | 199·697 | 21/6/68 | do. do. do. |
| 173H | 190·00 (provisional) | 9/8/68 | do. do. do. |
| 174H | 190·00 (provisional) | 28/7/68 | do. do. do. |
| 175H | 200·00 | 10/8/68 | do. do. do. |
| 176H | 188·968 | 27/9/68 | do. do. do. |
| 177H | 200·00 (provisional) | 20/12/68 | do. do. do. |
| 179H | 197·00 (provisional) | 21/3/69 | do. do. do. |
| 180H | 195·00 (provisional) | 21/3/69 | do. do. do. |
| 181H | 200·00 | 9/2/69 | do. do. do. |
| 182H | 200·00 | 6/2/69 | do. do. do. |
| 183H | 74·455 | 30/3/69 | do. do. do. |
| 184H | 200·00 | 4/4/69 | do. do. do. |
| 185H | 199·672 | 26/7/69 | do. do. do. |
| 186H | 200·00 | 14/8/69 | do. do. do. |
| 187H | 200·00 | 13/8/69 | do. do. do. |
| 188H | 111·117 | 27/7/69 | do. do. do. |
| 189H | 200·00 | 13/8/69 | do. do. do. |
| 190H | 100·00 | 2/10/69 | do. do. do. |
| 191H | 200·00 | 16/10/69 | do. do. do. |
| 192H | 130·00 | Application pending | do. do. do. |
| 193H | 190·458 | Application deferred | do. do. do. |
| 194H | 193·620 | Application deferred | do. do. do. |
| 195H | 200·00 (provisional) | Application pending | do. do. do. |
| | Applied for 3/1/68 | .... | do. do. do. |

*Petroleum Leases*

| No. | Area (Square Miles) | Expiry Date of Current Term | Holders |
|---|---|---|---|
| 1H | 89·4 | 2/2/88 | do. do. do. |
| 2H | 110·6 | 2/2/88 | do. do. do. |

## DRILLING

The positions of wells drilled for petroleum exploration in Western Australia to the end of 1967 are shown on Plates 17 to 19. Drilling was carried out during the year in the following permits:

### *PERMIT TO EXPLORE 27H*

Permit to Explore 27H is held by West Australian Petroleum Pty. Ltd. and covers part of the Perth Basin. The company completed 6 test wells (Badaminna No. 1, Cockburn No. 1, Dongara Nos. 4 to 6, and North Erregulla No. 1), and two stratigraphic wells (Bookara Nos. 2 and 3) on this permit during the year.

Dongara No. 4 was drilled 1¼ miles north of Dongara No. 2, and was completed as a gas producer in the Lower Permian Irwin River Coal Measures over the interval 5,639-5,642 feet. Gas was also recovered from a drill-stem test of the "Basal Triassic Sandstone". This was the fourth producing well to have been completed on the Dongara gas field. Two subsequent holes, Nos. 5 and 6, were dry and have been abandoned.

North Erregulla No. 1 was drilled to further evaluate the Cockleshell Gully Formation in the Erregulla area. It was abandoned as a dry hole, but small quantities of oil were obtained from drill-stem tests of the Kockatea Shale and the "Basal Triassic Sandstone" at depths of 9,580-9,613 feet and 10,535-10,570 feet respectively.

Further detais of the wells drilled on Permit 27H during the year are as follows:—

*Badaminna No. 1*

Type: Test well.
License to Prospect: 182H.
Latitude and longitude: 31° 20′ 30″ S, 115° 40′ 02″ E.
Elevation: G.L. 120 feet, R.T. 136 feet.
Commenced: 31st January, 1967.
Completed: 24th February, 1967.
Total depth: 8,000 feet.
Bottomed in: Lower Jurassic.
Status: Dry, plugged, and abandoned.

*Bookara No. 2*

Type: Stratigraphic well.
Latitude and longitude: 29° 09′ 59″ S, 114° 54′ 30″ E.
Elevation: G.L. 31 feet, R.T. 36 feet.
Commenced: 24th August, 1967.
Completed: 9th September, 1967.
Total depth, 2,500 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

*Bookara No. 3*

Type: Stratigraphic well.
Latitude and longitude: 29° 06′ 27″ S, 114° 53′ 14″ E.
Elevation: G.L. 102 feet, R.T. 107 feet.
Commenced: 15th September, 1967.
Completed: 24th September, 1967.
Total depth, 1,764 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

*Cockburn No. 1*

Type: Test well.
License to Prospect: 180H.
Latitude and longitude: 32° 08′ 02″ S, 115° 44′ 05″ E.
Elevation: G.L. 8 feet, R.T. 24 feet.
Commenced: 17th May, 1967.
Completed: 30th June, 1967.
Total depth: 10,020 feet.
Bottomed in: Lower Jurassic.
Status: Dry, plugged, and abandoned.

*Dongara No. 4*

Type: Test well.
License to Prospect: 111H.
Latitude and longitude: 29° 13′ 46″ S, 114° 58′ 49″ E.
Elevation: G.L. 201 feet, R.T. 216 feet.
Commenced: 27th February, 1967.
Completed: 24th March, 1967.
Total depth: 5,963 feet.
Bottomed in: Lower Permian.
Status: Gas well, completed over the interval 5,639-5,642 feet in Irwin River Coal Measures. Production test on a ½-inch choke yielded 1.4 mmcf/day.

*Dongara No. 5*

Type: Test well.
License to Prospect: 111H.
Latitude and longitude: 29° 11′ 14″ S, 114° 58′ 54″ E.
Elevation: G.L. 91 feet, R.T. 105 feet.
Commenced: 19th October, 1967.
Completed: 3rd November, 1967.
Total depth: 5,933 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

*Dongara No. 6*

Type: Test well.
License to Prospect: 190H.
Latitude and longitude: 29° 11′ 41″ S, 114° 56′ 16″ E.
Elevation: G.L. 81 feet, R.T. 94 feet.
Commenced: 12th December, 1967.
Completed: 31st December, 1967.
Total depth: 5,115 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

*North Erregulla No. 1*

Type: Test well.
License to Prospect: 150H.
Latitude and longitude: 29° 14′ 44″ S, 115° 19′ 34″ E.
Elevation: G.L. 533 feet, R.T. 547 feet.
Commenced: 4th October, 1967.
Completed: 25th November, 1967.
Total depth: 11,300 feet.
Bottomed in: Lower Permian.
Status: Oil show, plugged and abandoned. Drill stem tests of the interval 9,580-9,613 feet in the Kockatea Shale recovered 20 gallons of oil, and of the interval 10,535 to 10,570 feet in the "Basal Triassic Sandstone" recovered 8 gallons of oil.

### *PERMIT TO EXPLORE 28H*

Permit to Explore 28H is held by West Australian Petroleum Pty. Ltd. and covers part of the Carnarvon Basin. The company completed 4 test wells (Chargoo No. 1, Gnaraloo No. 1, Kennedy Range No. 1 and Muiron No. 1) and two stratigraphic wells (Locker No. 1 and Peak Island No. 1) during the year, and one test well (Sandy Point No. 1) and one stratigraphic well (Observation Island No. 1) were still drilling at the end of the year. All the wells were dry. Details are as follows:

*Chargoo No. 1*

Type: Test well.
License to Prospect: 141H.
Latitude and longitude: 23° 35′ 51″ S, 113° 55′ 51″ E.
Elevation: G.L. 75 feet, R.T. 80 feet.
Commenced: 14th October, 1967.
Completed: 20th October, 1967.
Total depth: 1,404 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

*Gnaraloo No. 1*

Type: Test well.
License to Prospect: 140H.
Latitude and longitude: 23° 40′ 38″ S, 113° 47′ 28″ E.
Elevation: G.L. 152 feet, R.T. 157 feet.
Commenced: 30th October, 1967.
Completed: 10th November, 1967.
Total depth: 1,646 feet,
Bottomed in: Carboniferous.
Status: Dry, plugged, and abandoned.

*Kennedy Range No. 1*

Type: Test well.
License to Prospect: 153H.
Latitude and longitude: 24° 29′ 50″ S, 114° 59′ 19″ E.
Elevation: G.L. 968 feet, K.B. 980 feet.
Commenced: 1st December, 1966.
Completed: 23rd January, 1967.

Total depth: 7,305 feet.
Bottomed in: Lower Permian.
Status: Minor gas show, plugged and abandoned.

*Locker No. 1*
Type: Stratigraphic well.
License to Prospect: 173H.
Latitude and longitude: 21° 43′ 16″ S, 114° 45′ 35″ E.
Elevation: G.L. 9 feet, R.T. 12 feet.
Commenced: 13th June, 1967.
Completed: 10th July, 1967.
Total depth: 2,512 feet.
Bottomed in: Triassic.
Status: Dry, plugged, and abandoned.

*Muiron No. 1*
Type: Test well.
License to Prospect: 185H.
Latitude and longitude: 21° 39′ 04″ S, 114° 21′ 18″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 1st December, 1967.
Completed: 26th December, 1967.
Total depth: 5,857 feet.
Bottomed in: Jurassic.
Status: Dry, plugged, and abandoned.

*Observation No. 1*
Type: Stratigraphic well.
License to Prospect: 195H.
Latitude and longitude: 21° 44′ 28″ S, 114° 32′ 12″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 31st December, 1967.
Status: Drilling at 72 feet on 31st December.

*Peak Island No. 1*
Type: Stratigraphic well.
License to Prospect: 191H.
Latitude and longitude: 21° 36′ 17″ S, 114° 30′ 23″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 17th October, 1967.
Completed: 23rd November, 1967.
Total depth: 7,026 feet.
Bottomed in: Jurassic.
Status: Dry, plugged, and abandoned.

*Sandy Point No. 1*
Type: Test well.
License to prospect: 192H.
Latitude and longitude: 22° 25′ 50″ S, 113° 47′ 46″ E.
Elevation: G.L. 366 feet, R.T. 378 feet.
Commenced: 30th November, 1967.
Status: Drilling at 7,117 feet on 31st December.

*PERMIT TO EXPLORE 30H*

Permit to Explore 30H is held by West Australian Petroleum Pty. Ltd. and covers part of the Canning Basin. The company completed two dry test wells (Blackstone No. 1 and May River No. 1) in this area during 1967. Details are as follows:

*Blackstone No. 1*
Type: Test well.
License to Prospect: 124H.
Latitude and longitude: 17° 35′ 14″ S, 124° 21′ 01″ E.
Elevation: G.L. 202 feet, R.T. 213 feet.
Commenced: 23rd July, 1967.
Completed: 12th October, 1967.
Total depth: 10,005 feet.
Bottomed in: Lower Ordovician.
Status: Dry, plugged, and abandoned.

*May River No. 1*
Type: Test well.
License to Prospect: 181H.
Latitude and longitude: 17° 14′ 50″ S, 124° 05′ 01″ E.
Elevation: G.L. 56 feet, R.T. 67 feet.
Commenced: 6th June, 1967.
Completed: 1st July, 1967.
Total depth: 5,505 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

*PERMIT TO EXPLORE 217H*

Permit to Explore 217H is held by West Australian Petroleum Pty. Ltd. and covers the north-eastern part of the Carnarvon Basin. The company drilled 3 test wells (Pasco Nos. 1 to 3) and 7 stratigraphic wells (Airlie No. 1, Mardie No. 1, Sholl Island No. 1, Trimouille Nos. 1, 1A, and 1B and Yarraloola No. 1) on the permit during the year. A further stratigraphic well, Peedamullah No. 1, was still drilling at the end of the year. Pasco Nos. 1 and 3 were completed as oil wells, the others were dry.

The Pasco discoveries are at the southeastern end of the unnamed island immediately south of Pasco Island, 6 miles south of Barrow Island. The discovery well yielded 449 barrels per day of oil on a production test of the interval 5,742 feet to 5,744 feet in an Upper Jurassic sandstone. The well also flowed gas at 3 million cubic feet per day from a drill-stem test over the interval 5,663 feet to 5,725 feet. The second well was dry, but Pasco No. 3 was also completed as an oil well over the interval 5,980 to 5,984 feet. A production test of this interval flowed at about 90 barrels per day.

Details of the wells drilled on this permit area are as follows:

*Airlie No. 1*
Type: Stratigraphic well.
License to Prospect: 163H.
Latitude and longitude: 21° 19′ 30″ S, 115° 09′ 55″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 11th September, 1967.
Completed: 5th October, 1967.
Total depth: 7,279 feet.
Bottomed in: Upper Jurassic.
Status: Dry, plugged, and abandoned.

*Mardie No. 1*
Type: Stratigraphic well.
Latitude and longitude: 21° 20′ 54″ S, 115° 42′ 54″ E.
Elevation: G.L. 16 feet, R.T. 21 feet.
Commenced: 20th July, 1967.
Completed: 16th August, 1967.
Total depth: 728 feet.
Bottomed in: ? Palaeozic.
Status: Dry, plugged, and abandoned.

*Pasco No. 1*
Type: Test well.
License to Prospect: 158H.
Latitude and longitude: 20° 58′ 19″ S, 115° 19′ 30″ E.
Elevation: G.L. 25 feet, R.T. 39 feet.
Commenced: 20th April, 1967.
Completed: 25th May, 1967.
Total depth: 6,230 feet.
Bottomed in: Upper Jurassic.
Status: Oil well, completed over the interval 5,742 to 5,744 feet in the Upper Jurassic. A production test flowed 449 barrels oil/day on ½-inch choke; gas/oil ratio not measured. A drill-stem test of the interval 5,663 to 5,725 feet flowed gas at 3.0 mmcf/day.

*Pasco No. 2*
Type: Test well.
License to Prospect: 158H.
Latitude and longitude: 20° 57′ 41″ S, 115° 19′ 20″ E.
Elevation: G.L. 12 feet, R.T. 26 feet.
Commenced: 11th June, 1967.
Completed: 19th July, 1967.
Total depth: 8,009 feet.
Bottomed in: Upper Jurassic.
Status: Minor shows of oil and gas. Plugged and abandoned.

*Pasco No. 3*
Type: Test well.
License to Prospect: 158H.
Latitude and longitude: 20° 58′ 05″ S, 115° 19′ 51″ E.
Elevation: G.L. 33 feet, R.T. 50 feet.
Commenced: 24th July, 1967.
Completed: 16th August, 1967.



(3)—41571

Total depth: 8,041 feet.
Bottomed in: Upper Jurassic.
Status: Oil well, completed over the interval 5,980 to 5,984 feet in the Upper Jurassic. Production test flowed about 90 barrels oil/day on ½-inch choke.

*Peedamullah No. 1*

Type: Stratigraphic well.
License to Prospect: 187H.
Latitude and longitude: 21° 24′ 26″ S, 115° 37′ 50″ E.
Elevation: G.L. 18 feet, R.T. 23 feet.
Commenced: 24th December, 1967.
Status: Drilling at 525 feet on 31st December.

*Sholl Island No. 1*

Type: Stratigraphic well.
License to Prospect: 159H.
Latitude and longitude: 20° 57′ 00″ S, 115° 53′ 50″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 7th January, 1967.
Completed: 27th January, 1967.
Total depth: 4,172 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

*Trimouille No. 1*

Type: Stratigraphic well.
License to Prospect: 161H.
Latitude and longitude: 20° 24′ 11″ S, 115° 34′ 09″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 12th February, 1967.
Completed: 19th March, 1967.
Total depth: 7,990 feet.
Bottomed in: Lower Cretaceous.
Status: Minor oil show, plugged and abandoned.

*Trimouille No. 1A*

Type: Stratigraphic well.
License to Prospect: 161H.
Latitude and longitude: 20° 24′ 11″ S, 115° 34′ 09″ E.
Elevation: G.L. 16 feet, R.T. 30 feet.
Commenced: 21st March, 1967.
Completed: 3rd April, 1967.
Total depth: 2,250 feet.
Bottomed in: Tertiary.
Status: Minor oil show, plugged and abandoned.

*Trimouille No. 1B*

Type: Stratigraphic well.
License to Prospect: 161H.
Latitude and longitude: 20° 24′ 18″ S, 115° 34′ 16″ E.
Elevation: G.L. 12 feet, R.T. 16 feet.
Commenced: 20th May, 1967.
Completed: 2nd June, 1967.
Total depth: 750 feet.
Bottomed in: Tertiary.
Status: Dry, plugged, and abandoned.

*Yarraloola No. 1*

Type: Stratigraphic well.
License to Prospect: 186H.
Latitude and longitude: 21° 25′ 07″ S, 115° 45′ 52″ E.
Elevation: G.L. 58 feet, R.T. 63 feet.
Commenced: 27th November, 1967.
Completed: 20th December, 1967.
Total depth: 892 feet.
Bottomed in: Carboniferous.
Status: Dry, plugged, and abandoned.

*PERMIT TO EXPLORE 228H*

Permit to Explore 228H is held by West Australian Petroleum Pty. Ltd. and is farmed out to French Petroleum Co. (Aust.) Pty. Ltd. and Australian Aquitaine Petroleum Pty. Ltd. It is situated in the central Perth Basin. One well, Beharra No. 2, was drilled on the permit during the year. Details are as follows:

*Beharra No. 2*

Type: Test well.
License to Prospect: 177H.
Latitude and longitude: 29° 30′ 55″ S, 115° 01′ 15″ E.
Elevation: G.L. 92 feet, R.T. 107 feet.
Commenced: 11th January, 1967.
Completed: 28th January, 1967.
Total depth: 6,313 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

*PERMIT TO EXPLORE 251H*

Permit to Explore 251H is held by West Australian Petroleum Pty. Ltd. and is farmed out to Gewerkschaft Elwerath. This company drilled one dry well, Yulleroo No. 1, on the concession during 1967. Details are as follows:

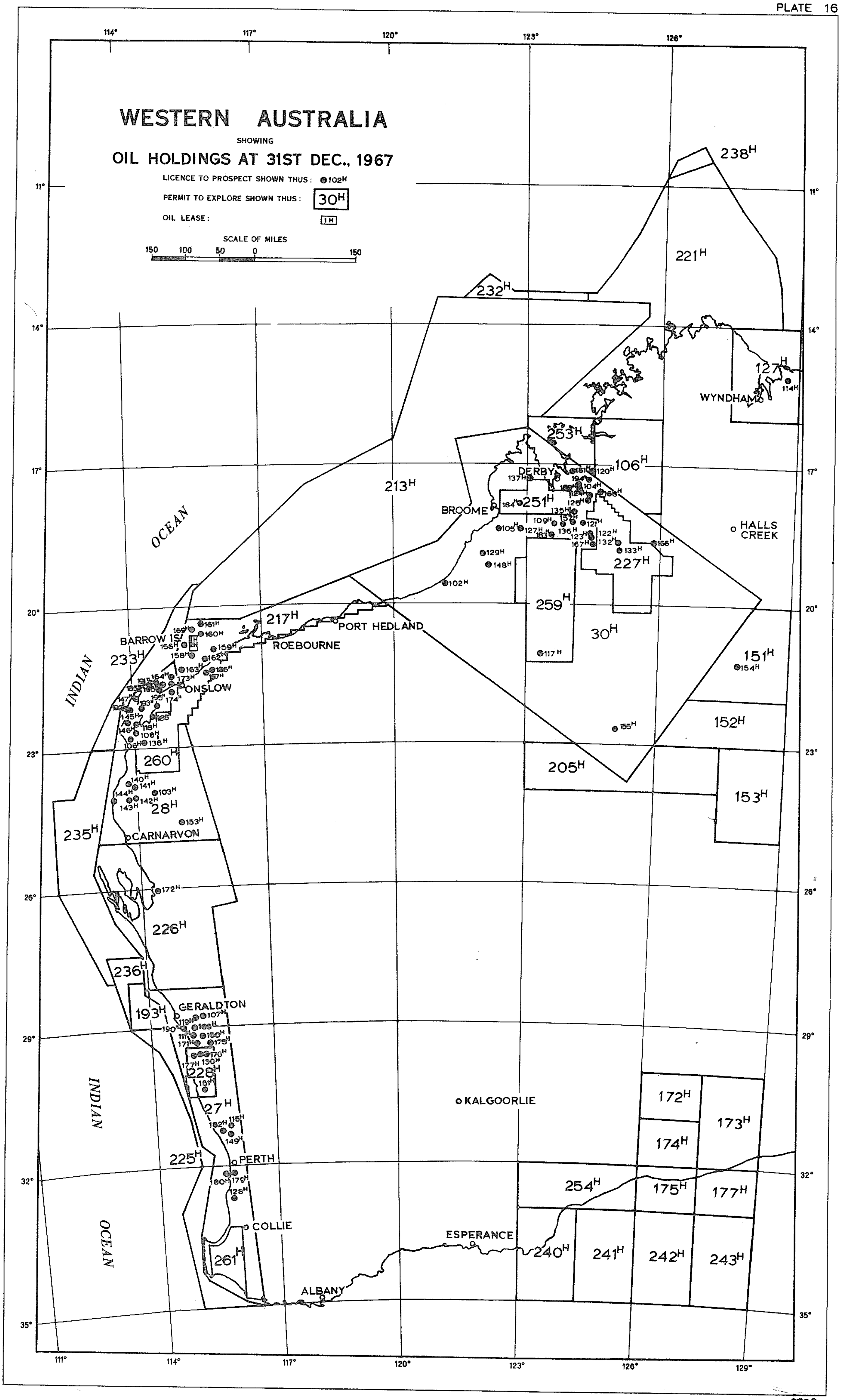
*Yulleroo No. 1*

Type: Test well.
License to Prospect: 184H.
Latitude and longitude: 17° 51′ 16″ S, 122° 54′ 25″ E.
Elevation: G.L. 164 feet, R.T. 181 feet.
Commenced: 21st May, 1967.
Completed: 13th November, 1967.
Total depth: 15,018 feet.
Bottomed in: Upper Devonian.
Status: Minor gas show, plugged, and abandoned.

*PETROLEUM LEASE 1H*

The following table summarises the development wells completed on Barrow Island (Petroleum Lease 1H) during 1967:

| Well | R.T. | G.L. or F.F.* | T.D. | Commenced | Completed |
|---|---|---|---|---|---|
| A18 .... | 99 | FF 89 | 2560 | 28/6/67 | 1/7/67 |
| A38 .... | 54 | FF 144 | 2517 | 30/12/67 | 2/1/68 |
| B14 .... | 74 | FF 64 | 2405 | 5/7/67 | 8/7/67 |
| B15 .... | 63 | FF 53 | 2308 | 7/9/67 | 16/9/67 |
| B16 .... | 78 | FF 67 | 2345 | 29/7/67 | 3/8/67 |
| B21 .... | 63 | FF 53 | 2511 | 20/8/67 | 23/8/67 |
| B23 .... | 56 | FF 45 | 2415 | 27/8/67 | 31/8/67 |
| B25 .... | 53 | FF 42 | 2290 | 6/12/67 | 15/12/67 |
| B32 .... | 48 | GL 37 | 2414 | 19/11/67 | 24/11/67 |
| B34 .... | 49 | FF 37 | 2427 | 24/11/67 | 28/11/67 |
| E12 .... | 155 | FF 145 | 2348 | 6/4/67 | 10/4/67 |
| E16 .... | 135 | FF 125 | 2636 | 15/12/67 | 19/12/67 |
| E21 .... | 204 | FF 194 | 2312 | 19/3/67 | 23/3/67 |
| E23 .... | 119 | FF 108 | 2365 | 27/12/67 | 30/12/67 |
| F12 .... | 142 | FF 132 | 2303 | 24/1/67 | 30/1/67 |
| F16 .... | 183 | FF 172 | 2344 | 20/1/67 | 25/1/67 |
| F18 .... | 148 | FF 138 | 2403 | 24/3/67 | 28/3/67 |
| F21 .... | 165 | GL 155 | 2336 | 1/2/67 | 4/2/67 |
| F23 .... | 213 | FF 203 | 2350 | 10/1/67 | 14/1/67 |
| F27 .... | 148 | FF 138 | 2342 | 12/3/67 | 18/3/67 |
| F32 .... | 162 | FF 152 | 2316 | 6/1/67 | 9/1/67 |
| F34 .... | 176 | FF 165 | 2318 | 13/1/67 | 18/1/67 |
| F38 .... | 100 | FF 90 | 2275 | 23/12/67 | 26/12/67 |
| F41 .... | 187 | FF 176 | 2307 | 5/2/67 | 10/2/67 |
| F43 .... | 112 | FF 101 | 2228 | 2/1/67 | 5/1/67 |
| F54 .... | 135 | FF 125 | 2885 | 2/3/67 | 12/3/67 |
| F61 .... | 114 | FF 184 | 2277 | 11/2/67 | 15/2/67 |
| G12 .... | 126 | FF 115 | 2456 | 8/7/67 | 12/7/67 |
| G14 .... | 122 | FF 112 | 2427 | 4/8/67 | 6/8/67 |
| G18 .... | 180 | FF 169 | 2403 | 24/2/67 | 27/2/67 |
| G21 .... | 124 | FF 114 | 2548 | 1/8/67 | 3/8/67 |
| G23 .... | 98 | FF 87 | 2457 | 16/8/67 | 19/8/67 |
| G25 .... | 130 | FF 120 | 2428 | 10/8/67 | 13/8/67 |
| G27 .... | 145 | FF 135 | 2402 | 21/3/67 | 24/3/67 |
| G32 .... | 109 | FF 99 | 2487 | 24/7/67 | 27/7/67 |
| G34 .... | 144 | FF 134 | 2457 | 13/8/67 | 16/8/67 |
| G36 .... | 169 | GL 158 | 2396 | 28/3/67 | 5/4/67 |
| G38 .... | 184 | FF 174 | 2415 | 15/3/67 | 20/3/67 |
| G41 .... | 141 | FF 131 | 2525 | 17/8/67 | 20/8/67 |
| G43 .... | 126 | FF 115 | 2420 | 31/8/67 | 3/9/67 |
| G45 .... | 134 | FF 123 | 2338 | 27/6/67 | 29/6/67 |
| G47 .... | 183 | FF 172 | 2350 | 12/3/67 | 15/3/67 |
| G52 .... | 130 | FF 119 | 2488 | 13/7/67 | 17/7/67 |
| G54 .... | 160 | FF 149 | 2427 | 17/7/67 | 20/7/67 |
| G56 .... | 165 | FF 154 | 2396 | 6/4/67 | 8/4/67 |
| G57 .... | 163 | FF 153 | 2357 | 13/6/67 | 19/6/67 |
| G58 .... | 148 | FF 138 | 2309 | 28/2/67 | 6/3/67 |
| G61 .... | 143 | FF 132 | 2555 | 10/8/67 | 13/8/67 |
| G63 .... | 126 | FF 115 | 2454 | 7/8/67 | 10/8/67 |
| G65 .... | 160 | FF 149 | 2397 | 20/7/67 | 24/7/67 |
| G67 .... | 134 | FF 124 | 2310 | 22/2/67 | 27/2/67 |
| G72 .... | 157 | FF 146 | 2496 | 12/7/67 | 15/7/67 |
| G74 .... | 140 | FF 130 | 2436 | 8/7/67 | 11/7/67 |
| G78 .... | 104 | FF 94 | 2257 | 17/2/67 | 21/2/67 |
| G81 .... | 99 | FF 89 | 2470 | 20/6/67 | 23/6/67 |
| G83 .... | 91 | FF 81 | 2403 | 1/7/67 | 5/7/67 |
| G84 .... | 91 | FF 81 | 2390 | 3/9/67 | 12/9/67 |
| G85 .... | 90 | FF 79 | 2310 | 24/6/67 | 27/6/67 |
| G87 .... | 80 | FF 70 | 2215 | 7/3/67 | 12/3/67 |
| H18 .... | 81 | FF 71 | 2548 | 6/8/67 | 10/8/67 |
| H47 .... | 105 | FF 95 | 2575 | 14/8/67 | 17/8/67 |
| H58 .... | 140 | FF 130 | 2545 | 4/8/67 | 7/8/67 |
| H78 | 141 | FF 130 | 2619 | 24/7/67 | 29/7/67 |
| K18 .... | 164 | FF 154 | 2518 | 12/12/67 | 15/12/67 |
| K25 .... | 196 | FF 186 | 2547 | 5/12/67 | 9/12/67 |
| K27 .... | 172 | FF 162 | 2561 | 28/11/67 | 3/12/67 |
| K38 .... | 179 | FF 169 | 2487 | 27/12/67 | 30/12/67 |
| K45 .... | 190 | FF 180 | 2518 | 9/12/67 | 12/12/67 |
| K47 .... | 194 | FF 183 | 2517 | 3/12/67 | 6/12/67 |
| K56 .... | 142 | FF 131 | 2457 | 30/12/67 | 4/1/68 |
| K72 .... | 140 | FF 130 | 2547 | 25/8/67 | 27/8/67 |
| K74 .... | 164 | FF 154 | 2488 | 22/8/67 | 24/8/67 |
| K76 .... | 163 | FF 153 | 2487 | 5/7/67 | 8/7/67 |
| K78 .... | 183 | FF 172 | 2417 | 24/3/67 | 27/3/67 |
| K81 .... | 107 | FF 97 | 2607 | 28/7/67 | 31/7/67 |
| K83 .... | 119 | FF 109 | 2487 | 19/8/67 | 21/8/67 |


WESTERN AUSTRALIA
SHOWING
OIL HOLDINGS AT 31ST DEC., 1967
LICENCE TO PROSPECT SHOWN THUS: 102H
PERMIT TO EXPLORE SHOWN THUS: 30H
OIL LEASE: 1H
SCALE OF MILES
150 100 50 0 150
INDIAN OCEAN
BARROW IS.
ONSLOW
ROEBOURNE
PORT HEDLAND
BROOME
DERBY
WYNDHAM
HALLS CREEK
CARNARVON
GERALDTON
PERTH
COLLIE
ALBANY
ESPERANCE
KALGOORLIE
238H
221H
232H
213H
127H
253H
106H
251H
227H
259H
30H
151H
152H
153H
205H
217H
233H
260H
28H
235H
226H
236H
193H
228H
27H
225H
261H
172H
173H
174H
175H
177H
254H
240H
241H
242H
243H

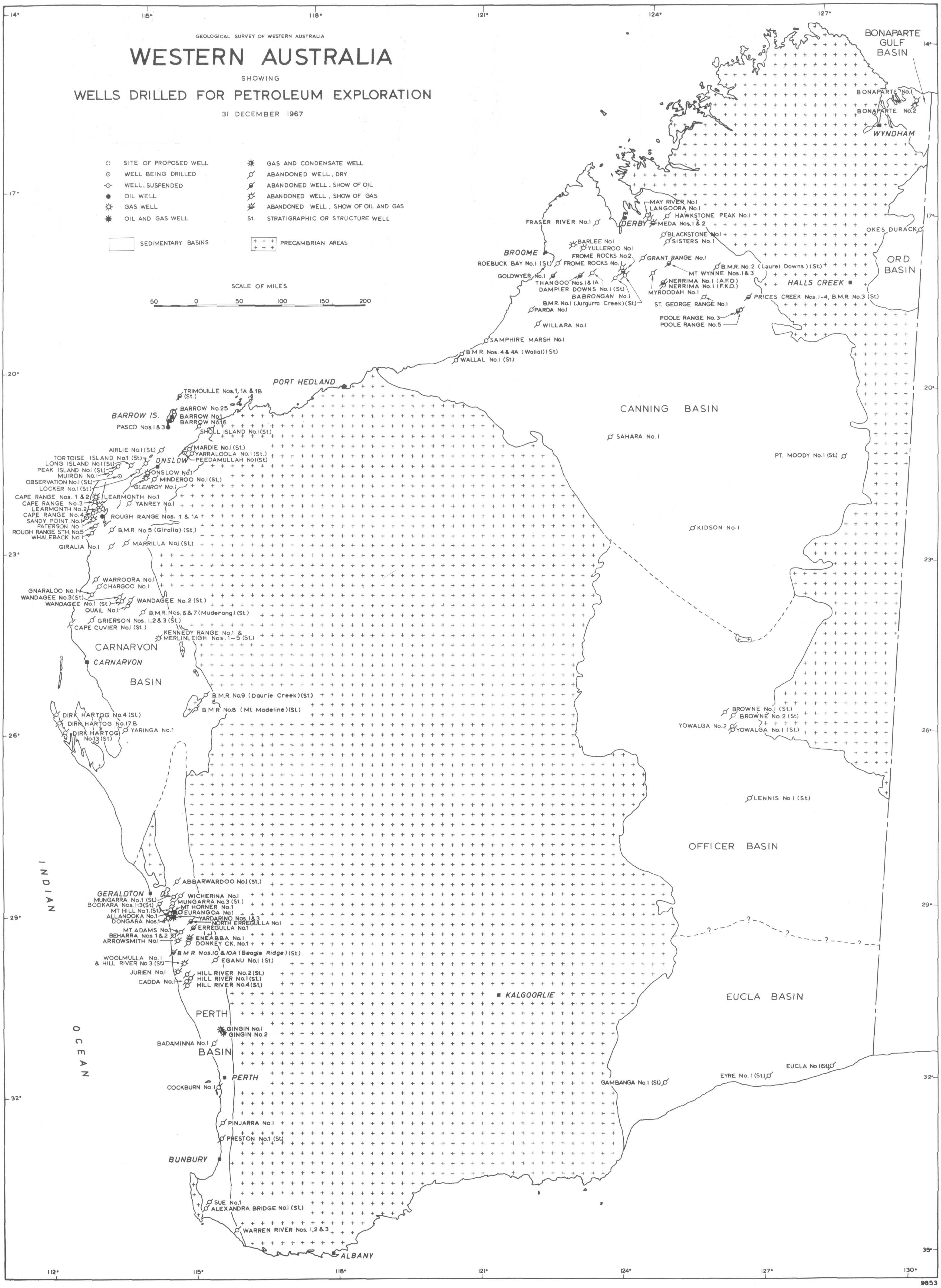
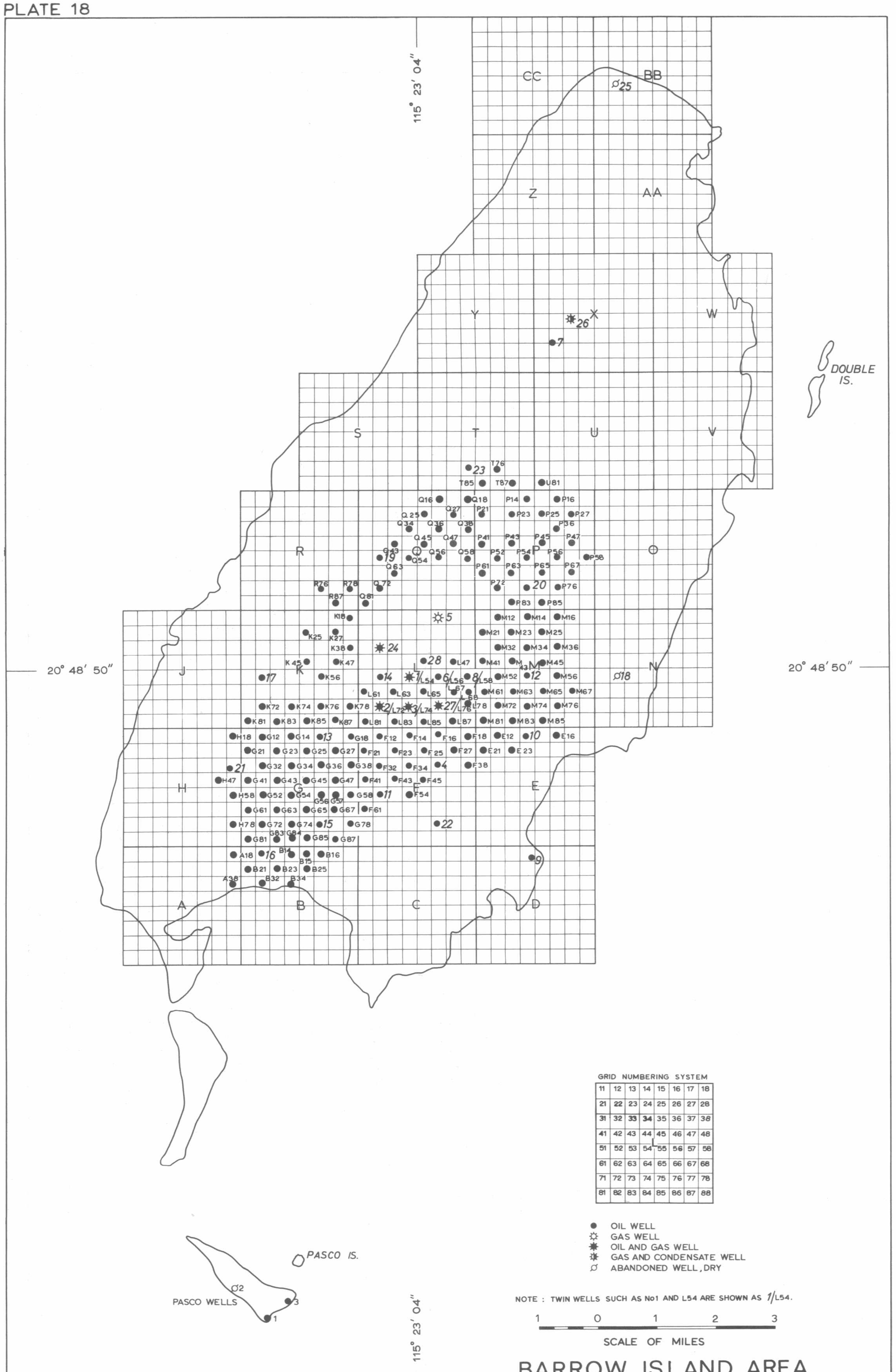



PLATE 17

9653

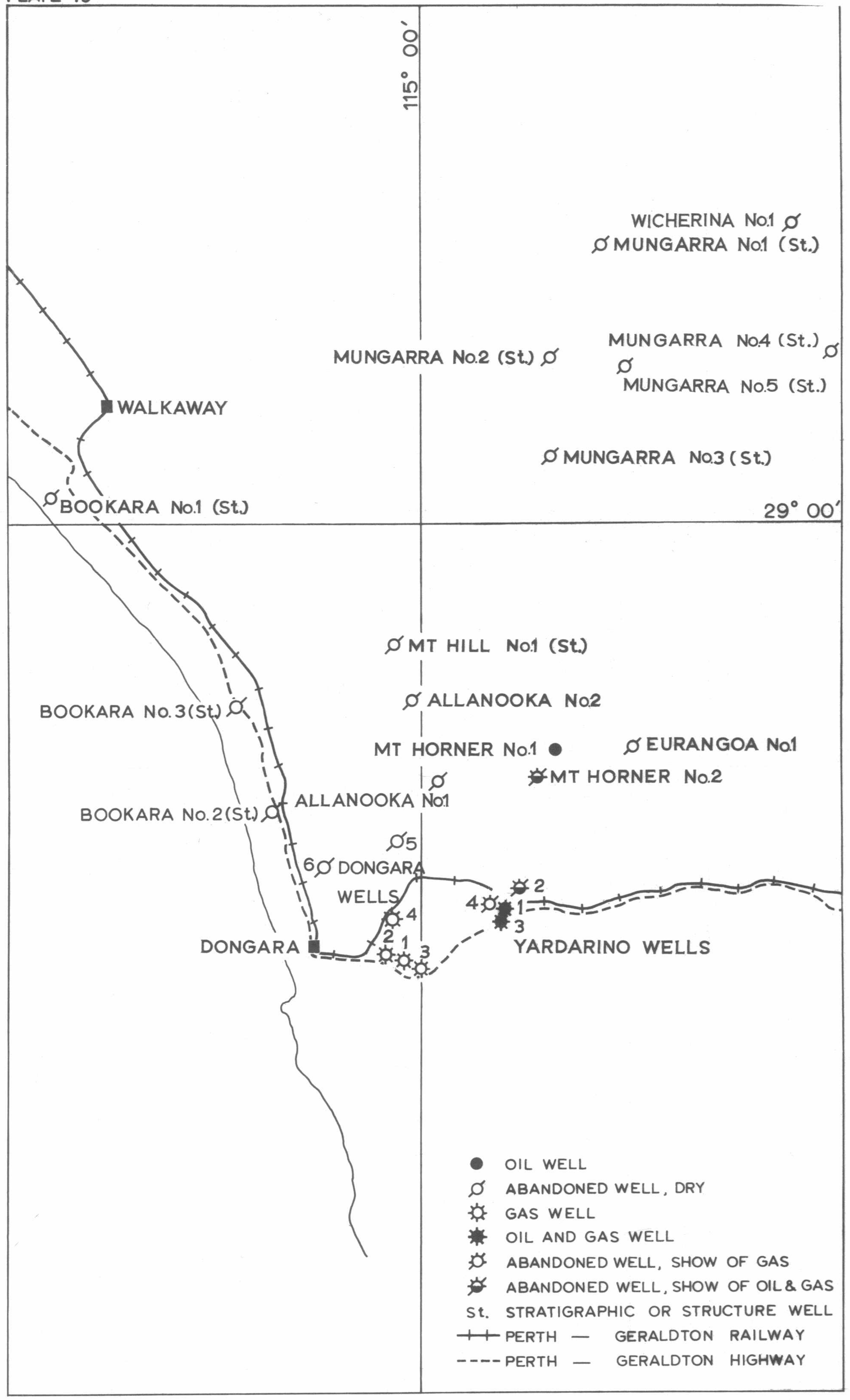
PLATE 18




BARROW ISLAND AREA
SHOWING WELLS DRILLED FOR PETROLEUM

9994

PLATE 19




DONGARA AREA
SHOWING WELLS DRILLED FOR PETROLEUM

0 4 8
SCALE OF MILES

9655

| Well | R.T. | G.L. or F.F.* | T.D. | Commenced | Completed |
|---|---|---|---|---|---|
| K85 .... | 161 | FF 151 | 2519 | 2/7/67 | 5/7/67 |
| K87 .... | 193 | FF 183 | 2434 | 27/2/67 | 2/3/67 |
| L47 .... | 170 | FF 160 | 2455 | 18/5/67 | 21/5/67 |
| L54 .... | 180 | FF 170 | 2400 | 9/2/67 | 13/2/67 |
| L56 .... | 218 | FF 207 | 2505 | 22/5/67 | 25/5/67 |
| L58 .... | 220 | FF 210 | 2466 | 30/5/67 | 3/6/67 |
| L61 .... | 194 | FF 184 | 2434 | 19/2/67 | 22/2/67 |
| L63 .... | 190 | FF 179 | 2406 | 12/2/67 | 16/2/67 |
| L65 .... | 209 | FF 199 | 2404 | 29/1/67 | 9/2/67 |
| L67 .... | 201 | FF 191 | 2456 | 25/4/67 | 29/4/67 |
| L68 .... | 190 | FF 180 | 2456 | 17/9/67 | 22/9/67 |
| L72 .... | 164 | FF 154 | 2348 | 10/1/67 | 15/1/67 |
| L76 .... | 227 | FF 217 | 2408 | 25/1/67 | 29/1/67 |
| L78 .... | 173 | FF 163 | 2426 | 9/4/67 | 12/4/67 |
| L81 .... | 155 | FF 144 | 2371 | 15/2/67 | 19/2/67 |
| L83 .... | 138 | FF 128 | 2300 | 16/1/67 | 23/1/67 |
| L87 .... | 182 | FF 172 | 2434 | 29/3/67 | 1/4/67 |
| M12 .... | 195 | FF 184 | 2502 | 4/6/67 | 9/6/67 |
| M14 .... | 162 | FF 151 | 2528 | 10/6/67 | 13/6/67 |
| M16 .... | 134 | FF 123 | 2560 | 24/6/67 | 26/6/67 |
| M21 .... | 151 | FF 140 | 2440 | 14/5/67 | 17/5/67 |
| M23 .... | 145 | FF 134 | 2488 | 5/6/67 | 8/6/67 |
| M25 .... | 173 | FF 163 | 2564 | 23/4/67 | 16/5/67 |
| M32 .... | 150 | FF 139 | 2440 | 11/5/67 | 14/5/67 |
| M34 .... | 112 | FF 102 | 2457 | 2/6/67 | 5/6/67 |
| M36 .... | 123 | FF 113 | 2547 | 11/6/67 | 14/6/67 |
| M41 .... | 152 | FF 141 | 2485 | 8/5/67 | 11/5/67 |
| M43 .... | 159 | FF 148 | 2487 | 27/5/67 | 30/5/67 |
| M45 .... | 122 | FF 112 | 2488 | 8/6/67 | 11/6/67 |
| M52 .... | 150 | FF 139 | 2517 | 3/5/67 | 6/5/67 |
| M56 .... | 129 | FF 119 | 2548 | 14/6/67 | 17/6/67 |
| M61 .... | 162 | FF 152 | 2456 | 22/4/67 | 25/4/67 |
| M63 .... | 175 | FF 165 | 2457 | 29/4/67 | 3/5/67 |
| M65 .... | 122 | FF 112 | 2564 | 16/4/67 | 19/4/67 |
| M67 .... | 101 | FF 190 | 2516 | 30/5/67 | 2/6/67 |
| M72 .... | 177 | FF 166 | 2455 | 16/4/67 | 22/4/67 |
| M74 .... | 136 | FF 126 | 2472 | 20/4/67 | 23/4/67 |
| M76 .... | 142 | FF 132 | 2501 | 10/4/67 | 16/4/67 |
| M81 .... | 170 | FF 160 | 2426 | 13/4/67 | 16/4/67 |
| M83 .... | 161 | FF 150 | 2494 | 2/4/67 | 5/4/67 |
| M85 .... | 136 | FF 126 | 2548 | 29/6/67 | 2/7/67 |
| P14 .... | 147 | FF 137 | 2487 | 19/9/67 | 23/9/67 |
| P16 .... | 168 | FF 158 | 2577 | 4/9/67 | 6/9/67 |
| P21 .... | 208 | FF 198 | 2547 | 9/10/67 | 12/10/67 |
| P23 .... | 196 | FF 185 | 2550 | 17/5/67 | 23/5/67 |
| P25 .... | 177 | FF 166 | 2577 | 15/9/67 | 19/9/67 |
| P27 .... | 135 | FF 125 | 2578 | 29/10/67 | 31/10/67 |
| P36 .... | 155 | FF 144 | 2577 | 31/8/67 | 3/9/67 |
| P41 .... | 192 | FF 181 | 2576 | 6/10/67 | 9/10/67 |
| P43 .... | 189 | FF 178 | 2578 | 9/10/67 | 12/10/67 |
| P45 .... | 134 | FF 124 | 2577 | 12/9/67 | 15/9/67 |
| P47 .... | 139 | FF 128 | 2578 | 7/11/67 | 9/11/67 |
| P52 .... | 195 | FF 184 | 2548 | 4/10/67 | 9/10/67 |
| P54 .... | 140 | FF 130 | 2578 | 28/9/67 | 1/10/67 |
| P56 .... | 112 | FF 102 | 2548 | 23/9/67 | 29/9/67 |
| P58 .... | 109 | FF 99 | 2578 | 20/12/67 | 22/12/67 |
| P61 .... | 172 | FF 161 | 2547 | 1/10/67 | 4/10/67 |
| P63 .... | 152 | FF 142 | 2517 | 17/10/67 | 20/10/67 |
| P65 .... | 124 | FF 114 | 2548 | 13/10/67 | 17/10/67 |
| P67 .... | 122 | FF 111 | 2577 | 20/10/67 | 22/10/67 |
| P72 .... | 167 | FF 156 | 2517 | 25/9/67 | 28/9/67 |
| P76 .... | 113 | FF 103 | 2547 | 28/8/67 | 31/8/67 |
| P83 .... | 165 | FF 155 | 2519 | 20/6/67 | 23/6/67 |
| P85 .... | 133 | FF 122 | 2547 | 17/6/67 | 20/6/67 |
| Q16 .... | 190 | FF 180 | 2547 | 4/11/67 | 11/11/67 |
| Q18 .... | 179 | FF 169 | 2576 | 21/10/67 | 25/10/67 |
| Q25 .... | 150 | FF 139 | 2534 | 29/10/67 | 1/11/67 |
| Q27 .... | 198 | FF 187 | 2547 | 16/10/67 | 22/10/67 |
| Q34 .... | 144 | FF 134 | 2541 | 1/11/67 | 4/11/67 |
| Q36 .... | 167 | FF 157 | 2578 | 23/10/67 | 28/10/67 |
| Q38 .... | 211 | FF 200 | 2577 | 3/10/67 | 6/10/67 |
| Q43 .... | 185 | FF 175 | 2557 | 25/10/67 | 29/10/67 |
| Q45 .... | 165 | FF 154 | 2548 | 22/9/67 | 25/9/67 |
| Q47 .... | 227 | FF 217 | 2547 | 12/10/67 | 15/10/67 |
| Q54 .... | 204 | FF 193 | 2547 | 16/11/67 | 19/11/67 |
| Q56 .... | 215 | FF 205 | 2547 | 11/11/67 | 16/11/67 |
| Q58 .... | 187 | FF 177 | 2548 | 12/10/67 | 14/10/67 |
| Q63 .... | 163 | FF 153 | 2487 | 19/11/67 | 22/11/67 |
| Q72 .... | 136 | FF 126 | 2458 | 22/11/67 | 24/11/67 |
| Q81 .... | 142 | FF 131 | 2487 | 25/11/67 | 28/11/67 |
| R76 .... | 130 | FF 120 | 2494 | 24/5/67 | 29/5/67 |
| R78 .... | 135 | FF 125 | 2518 | 28/11/67 | 1/12/67 |
| R87 .... | 208 | FF 197 | 2576 | 1/12/67 | 4/12/67 |
| T76 .... | 171 | FF 160 | 2642 | 4/11/67 | 6/11/67 |
| T85 .... | 191 | FF 180 | 2638 | 17/9/67 | 20/9/67 |
| T87 .... | 168 | FF 157 | 2567 | 7/9/67 | 12/9/67 |
| U81 .... | 165 | FF 154 | 2578 | 9/11/67 | 13/11/67 |

* FF = First flange. Datum adopted for the Barrow wells is 18·54 feet above mean sea level, or 23·44 feet above Indian spring low-water mark.

## GEOPHYSICAL OPERATIONS

*Gravity*

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

| Company | Permit | Basin | Party Months |
|---|---|---|---|
| West Australian Petroleum Pty. Limited | 27H | Perth | 2·5 |
| do. do. do. | 30H | Carnarvon | 4·0 |
| do. do. do. | 217H | Carnarvon | 2·0 |
| Australian Aquitaine Petroleum Pty. Ltd. | 151H | Canning | 0·8 |
| do. do. do. | 152H | Canning | 4·0 |
| do. do. do. | 205H | Canning | 0·4 |
| French Petroleum Co. (Aust.) Pty. Ltd. | 259H | Canning | 3·0 |

*Seismic*

During 1966 seismic surveys were conducted in the Perth, Carnarvon, Canning, Bonaparte Gulf, and Eucla Basins. This work was distributed as follows:

| Company | Permit | Basin | Party Months |
|---|---|---|---|
| West Australian Petroleum Pty. Limited | 27H | Perth | 1·5 (marine) |
| | | | 11·0 (land) |
| do. do. do. | 28H | Carnarvon | 3·0 (marine) |
| | | | 10·0 (land) |
| do. do. do. | 30H | Canning | 2·0 (land) |
| do. do. do. | 217H | Carnarvon | 3·0 (marine) |
| | | | 1·0 (land) |
| do. do. do. | 225H | Perth | 0·5 (marine) |
| do. do. do. | 233H | Carnarvon | 0·5 (marine) |
| Tenneco Australia Inc. .... | 175H | Eucla | 0·5 (marine) |
| do. do. .... | 177H | Eucla | 0·255 (marine) |
| do. do. .... | 240H | Eucla | 0·120 (marine) |
| do. do. .... | 241H | Eucla | 0·188 (marine) |
| do. do. .... | 242H | Eucla | 0·145 (marine) |
| do. do. .... | 243H | Eucla | 0·045 (marine) |
| do. do. .... | 254H | Eucla | 0·142 (marine) |
| Union Oil Development Corp. | 261H | Perth | 3·5 (land) |
| Marathon Petroleum Australia Ltd. | 260H | Carnarvon | 6·5 (land) |
| Gewerkschaft Elwerath .... | 251H | Canning | 2·0 (land) |
| Australian Aquitaine Petroleum Pty. Ltd. | 151H | Canning | 0·8 (land) |
| do. do. do. | 152H | Canning | 4·0 (land) |
| do. do. do. | 205H | Canning | 0·4 (land) |
| French Petroleum Co. (Aust.) Pty. Ltd. | 259H | Canning | 11·0 (land) |
| Arco Limited .... .... .... | 221H | Bonaparte | 4·0 (marine) |
| Canadian Superior Oil (Aust.) Pty. Ltd. | 235H | Carnarvon | 1·0 (marine) |

*Magnetic*

Aeromagnetic surveys were carried out during the year in the Carnarvon and Canning Basins. Details are as follows:

| Company | Permit | Basin | Line Miles |
|---|---|---|---|
| West Australian Petroleum Pty. Limited | 28H | Carnarvon | 1,167 |
| do. do. do. | 217H | Carnarvon | 3,830 |
| do. do. do. | 233H | Carnarvon | 1,481 |

## GEOLOGICAL OPERATIONS

Field geological studies were carried out by oil exploration companies in the Carnarvon and Canning Basins. Details are as follows:

| Company | Permit | Basin | Geologist Months |
|---|---|---|---|
| West Australian Petroleum Pty. Limited | 30H | Canning | 2 |
| do. do. do. | 217H | Carnarvon | 1 |
| Australian Aquitaine Petroleum Pty. Ltd. | 151–153H | Canning | 13·0 |
| French Petroleum Co. (Aust.) Pty. Ltd. | 259H | Canning | 6·5 |

## PRODUCING OPERATIONS

West Australian Petroleum Pty. Ltd. was granted Petroleum Leases 1H and 2H in January, 1967, covering the onshore and offshore areas respectively of the Barrow Island License to Prospect. Drilling during the year was confined to Lease 1H on the island itself. Two rigs were used to drill 163 development wells.

The first shipment of oil from Barrow Island was loaded on April 23, and by the end of December a total of 4,648,217 barrels of oil had been shipped. The average production during the year rose from 8,700 barrels a day in April to 25,700 barrels a day in December. It is predicted that when all the the primary 80-acre-spacing development wells are completed production will exceed 30,000 barrels a day.

Two water-injection wells were drilled in the central part of the field, together with one water-supply well. This pilot water-flood programme was designed to check laboratory studies of secondary recovery from the Windalia reservoir. A total of 26 water-injection wells have now been programmed for 1968.

Production details are summarised in the following tables.

OIL AND GAS PRODUCTION, 1967

| Company | Petroleum Lease and Field | Reservoir | Production | |
|---|---|---|---|---|
| | | | Oil (bbl) | Gas (mcf) |
| West Australian Petroleum Pty. Limited | 1H Barrow Is. | Windalia | 4,729,013 | 2,829,095 |
| | | Jurassic 6200 | 8,894 | 52,326 |
| | | Jurassic 6600 | 53,850 | 156,323 |
| | | Jurassic 6700 | 191,349 | 225,763 |
| Total .... .... .... | | | 4,983,106 | 3,263,507 |

OIL AND GAS DISPOSAL, 1967

| | Oil (bbl) | Gas (mcf) |
|---|---|---|
| Total production .... .... .... .... .... | 4,983,106 | 3,263,507 |
| Used in drilling .... .... .... .... .... | 5,835 | .... |
| Field fuel .... .... .... .... .... .... | 6,716 | 25,575 |
| Gas flared .... .... .... .... .... .... | .... | 3,237,932 |
| Percentage field utilization .... .... .... | 0·25% | 0·78% |
| Percentage gas flared .... .... .... .... | .... | 99·22% |
| Oil shipments .... .... .... .... .... | 4,646,948 | .... |

# TERTIARY STRATIGRAPHIC UNITS IN THE EUCLA BASIN IN WESTERN AUSTRALIA

**by D. C. Lowry**

ABSTRACT

The Tertiary stratigraphy of the Eucla Basin in Western Australia has been revised as a result of a recent study. Two previously described units, the Wilson Bluff Limestone and Nullarbor Limestone, are defined more precisely, and the Hampton Conglomerate is amended to Hampton Sandstone. Four new units are proposed. They are the Toolinna Limestone, a bryozoan Upper Eocene limestone in the southwest of the basin; the Abrakurrie Limestone, a bryozoan Lower Miocene limestone which underlies the Nullarbor Limestone near the centre of the basin; the Mullamullang Limestone Member, an algal limestone at the base of the Nullarbor Limestone; and the Colville Sandstone, a Lower Miocene sandstone in the northern part of the basin.

## INTRODUCTION

This paper gives definitions and preliminary descriptions of new stratigraphic units, and refines the definitions of existing units. A bulletin of the Geological Survey describing the stratigraphy of the Eucla Basin in greater detail is in course of preparation.

The Eucla Basin is occupied by a thin, almost horizontal sheet of Cretaceous and Tertiary strata. The foundations of the Tertiary stratigraphy were laid by Tate (1879) who measured a section at Wilson Bluff and recognised, in ascending order, a "White Polyzoal Limestone", a "Yellow Polyzoal Bed", and a "Crystalline Limestone". Some later workers grouped all the limestone as "Eucla Limestone", which they believed to be of Eocene (Maitland, 1911) or Miocene age (Maitland, 1919; Teichert, 1947; Fairbridge 1953). Others recognised the presence of beds of several ages: Crespin (*in* King, 1949) recorded Lower Miocene, "Upper Middle Miocene", and Upper Cretaceous, while Glaessner (1953) recognised Lower Miocene and "Late Eocene". Singleton (1954) named the upper "crystalline" limestone the Nullarbor Limestone and the lower chalky limestone the Wilson's Bluff Limestone, ignoring Tate's "Yellow Polyzoal Bed". Singleton's nomenclature has been widely used (McWhae and others, 1958; Ludbrook, 1958a, 1958b, 1963), although Ludbrook (1958a) supported the validity of Tate's three-fold subdivision, and pointed out that the confusion was largely due to lack of geological field work, and the neglect of Tate's observations.

Singleton (1954) failed to specify a type section for the Nullarbor Limestone and Wilson Bluff Limestone, but this ommission was corrected by McWhae and others (1958), who selected Wilson Bluff as the type section for the Wilson Bluff Limestone, and by Ludbrook (1958a), who favoured Tate's section at Wilson Bluff as the type section for both units. Unfortunately Tate did not specify precisely where his section was measured, but it seems likely that it was a composite section with the lower part measured beneath the Wilson Bluff trigonometrical station and the upper part measured about 100 yards to the west. The section is a poor one because in the upper part the exposures are either obscured or almost inaccessible. The best place to measure a section on the bluff is at its eastern end, 1.2 miles east of the trigonometrical station, and this is taken as the type section. The section lies in South Australia, about 2 miles east of the border with Western Australia.

Tate's "Yellow Polyzoal Bed" is now recognised as a distinct formation and is here named the Abrakurrie Limestone. Fairbridge (1953) recorded "*Lithothamnium* (algal) reefs" at Madura Pass, but this outcrop is part of an extensive biostrome which is here named the Mullamullang Limestone Member of the Nullarbor Limestone. Teichert (1947, p.115) examined corals from near Forrest which he described as "reef-building", and Fairbridge (1953) seems to have used this report as the basis for proposing the name "Forrest Reef Limestone Member". However it appears that Teichert used "reef-building" as a synonym for colonial, because I have found colonial corals scattered in the limestone near Forrest, but no sign of true reef development, and I therefore regard the name as invalid. The name Toolinna Limestone is proposed here for beds in the southwest of the basin which are laterally equivalent to the Wilson Bluff Limestone but which are sufficently distinct lithologically to warrant the status of a formation. For similar reasons the name Colville Sandstone is proposed for beds in the north of the basin which are laterally equivalent to the Nullarbor Limestone.

Singleton (1954) placed the Nullarbor Limestone and Wilson Bluff Limestone in the Eucla Group, omitting the Hampton "Conglomerate". However it is in keeping with the Australian Code of Stratigraphic Nomenclature to include in a group all the formations of a major depositional cycle, so the Hampton "Conglomerate" is here included in the Eucla Group, along with the Toolinna Limestone, Abrakurrie Limestone, and Colville Sandstone.

There has been little faulting in the Eucla Basin, and the formations are nearly horizontal. The thickest drilled sections of both the Tertiary and Cretaceous beds are in the Madura area, and marine seismic surveys indicate that the beds continue to thicken gently southwards across the continental shelf. The stratigraphic relations of formations of the Eucla Group are presented diagrammatically in Figure 6, and a cross section of part of the basin is shown in Plate 20.

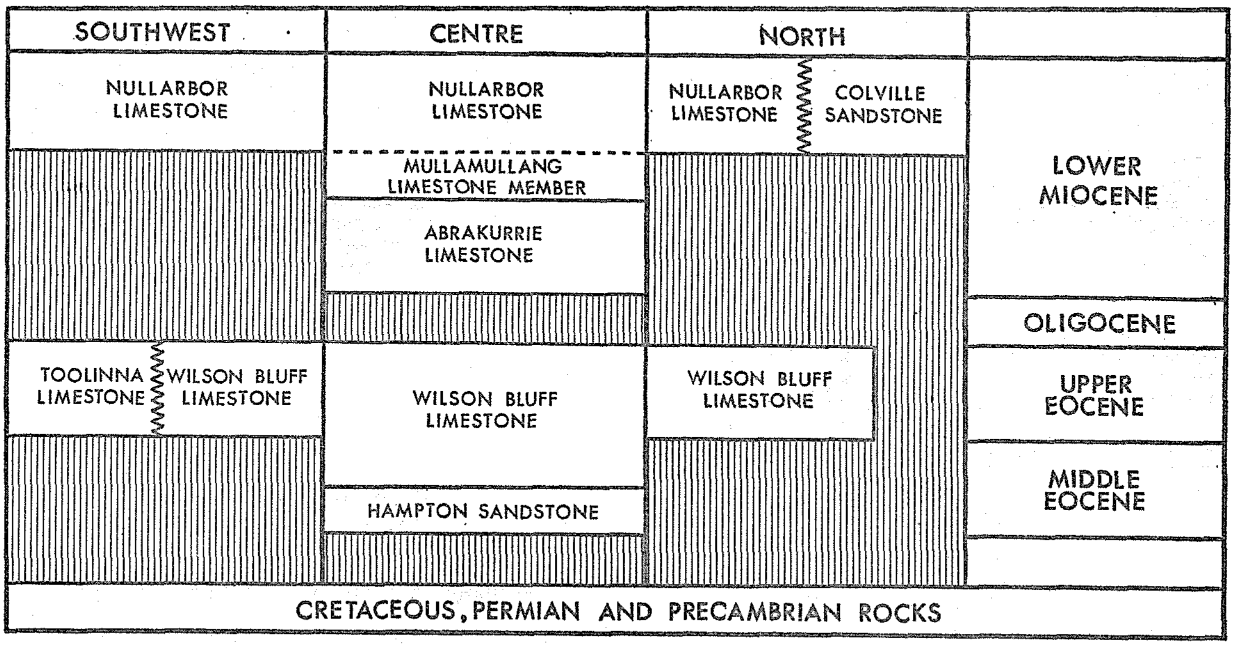



Figure 6—Stratigraphic relations within the Eucla Group, in the southwest, central, and northern parts of the Eucla Basin.

### HAMPTON SANDSTONE

The name "Hampton Conglomerate" was given by Fairbridge (1953) to the sandstone, calcareous sandstone and conglomeratic sandstone underlying the Tertiary "Eucla Limestone" in the Madura 1 bore. The name is apparently derived from the adjacent Hampton Range.

*Type section*

The type section is that encountered over the interval 903 feet to 928 feet 6 inches in the Madura 1 bore (31° 54′ 35″ S, 127° 00′ 20″ E). Fairbridge (1953) cited the interval 903 feet to 927 feet 3 inches, the combined intervals of the samples described by Maitland (1904). However, the driller's log indicates that the bed from 927 feet 3 inches to 928 feet 6 inches should also be included in this unit. The name is amended here to Hampton Sandstone because sandstone is the dominant lithology. The enclosing strata are Wilson Bluff Limestone above and Madura Shale beneath.

*Lithology*

The samples held by the Geological Survey of Western Australia comprise a lime-cemented medium to coarse-grained sandstone with iron-stained rounded to subrounded quartz grains from the interval 903 feet to 904 feet 8 inches, and medium to coarse-grained subangular to rounded iron-stained quartz sand from the interval 904 feet 8 inches to 927 feet 3 inches. Maitland (1904) described the lower sample as "coarse quartz, sand and gravel", but there is only about 5 per cent. conglomeratic material in the existing sample. The driller's log records:

903 feet-905 feet: very hard limestone conglomerate.

905 feet-927 feet 3 inches: coarse brown water-worn granite sand.

927 feet 3 inches-928 feet 6 inches: hard crystalline boulders.

*Thickness*

The thickness in the Madura 1 bore is 25 feet 6 inches according to the driller's log.

*Distribution*

The Hampton Sandstone does not crop out, and its extent is known only from bores. It was recorded in Eyre No. 1 to the south and Gambanga No. 1 to the west, but not in bores on the Trans Australian Railway to the north. Eastwards, it probably extends into South Australia, but if so, it is discontinuous because it was not present in Alliance Eucla No. 1.

*Stratigraphic relations*

The unit is overlain, probably conformably, by Wilson Bluff Limestone, and is underlain disconformably by the Cretaceous Madura Shale. It may pass laterally into the "Pidinga Clays and Sands" in South Australia (Ludbrook, 1958a).

*Fossils*

Casts of pelecypods are present in the sample from the interval 903 feet to 904 feet 8 inches.

*Age*

The Hampton Sandstone is probably the same age as the overlying lower part of the Wilson Bluff Limestone, that is, Middle Eocene (Ludbrook, 1963).

### WILSON BLUFF LIMESTONE

The name "Wilson's Bluff Limestone" was introduced by Singleton (1954) for chalky bryozoal limestone that underlies "crystalline" limestone in the Eucla Basin. The name was amended to Wilson Bluff Limestone by McWhae and others (1958).

*Type section*

The type section has not been accurately defined previously and it is here defined as the section exposed at the east end of Wilson Bluff (31° 41′ S, 19°, 02′ E.), 1.2 miles east of the trigonometrical station. The top of the formation is about 167 feet above sea level and is marked by an upward change from a hard white limestone with brachiopods to a friable porous bryozoan limestone. The formation extends below sea level and the base is not exposed.

The exposure on the west wall of Abrakurrie Cave (31° 39′ 20″ S, 128° 29′ 20″ E) is nominated here as a reference section because the contact with the overlying formation is better exposed and more accessible than at Wilson Bluff. The top of the formation in the cave is also marked by an upward change from a white hard limestone with large brachiopods to a yellow, friable, coarse, bryozoan limestone. The boundary lies about 159 feet beneath the surface of the plateau, and the formation extends below the lowest accessible part of the cave.

*Lithology*

The beds at Wilson Bluff are white chalky bryozoan limestones with chert nodules and minor glauconite.

*Thickness*

The type section is 167 feet thick, and the reference section 80 feet thick. In neither section is the base of the formation exposed. The thickest section drilled is in Eyre No. 1, which penetrated 1,073 feet of Tertiary limestone (Ludbrook, 1960) of which the lower 950 feet (approximately) is Wilson Bluff Limestone.

*Distribution*

The Wilson Bluff Limestone is developed throughout most of the Eucla Basin. It extends northwards beyond the Trans Australian Railway and eastwards into South Australia. Near the western margin of the basin it passes laterally into the Toolinna Limestone.

*Stratigraphic relations*

The Wilson Bluff Limestone overlies (probably conformably) the Hampton Sandstone in the Madura area, and disconformably overlies the Madura Shale in the northern part of the basin. To the west and southwest the upper part of the formation grades laterally into the Toolinna Limestone. It is overlain by the Abrakurrie Limestone in most areas, and the contact is interpreted as a slight disconformity where it is seen in Cocklebiddy Cave and in caves near Wilson Bluff. In the northern part of the basin, for example at Haig Cave (30° 45' S, 126° 23' E), the Abrakurrie Limestone is absent and the Wilson Bluff Limestone is overlain by Nullarbor Limestone.

*Fossils*

The Wilson Bluff Limestone contains a rich fauna of bryozoans, pelecypods, echinoids, brachiopods, and foraminifers.

*Age*

Foraminifera indicate an Upper Eocene age for the upper part of the formation, and a Middle Eocene age for the lower part (Ludbrook, 1963).

### TOOLINNA LIMESTONE

The name Toolinna Limestone is proposed here for porous bryozoan limestone that crops out in the southwestern part of the Eucla Basin. The name is taken from Toolinna Cove.

*Type Section*

The type section is the cliff at Toolinna Cove (32° 44' S, 125° 01' E), from about 60 feet above sea level to the top of the cliff. The lower part of the section was measured at the southwestern end of the cove, and the upper part along a precarious path up the cliff face. The beds in the lower 60 feet are regarded as Wilson Bluff Limestone, but the upper beds are designated as a separate formation because they are distinctly better sorted and coarser than the chalky beds at Wilson Bluff. The two lithologies are interbedded at Toolinna Cove, with the chalky beds dominant at the bottom and the porous beds dominant higher up. The boundary was chosen as the base of a thick current-bedded limestone bed which disconformably overlies a chalky bed at about 60 feet above sea level. The disconformity has a relief of at least 5 feet, but is probably of only local significance.

*Lithology*

The unit is a thick-bedded bryozoan limestone, and is commonly current-bedded. It is generally a medium to coarse-grained calcarenite, but in places the bryozoan fragments are large enough to form a fine calcirudite. In the lower 100 feet the beds are porous and friable, but in the upper part they are weathered to a hard tightly-cemented limestone.

*Thickness*

The type section is 180 feet thick, and the unit is thought to thicken to the southwest.

*Distribution*

The unit is exposed in the west and southwest of the basin, and it is possibly present in the subsurface in the north, close to the Eocene shoreline.

*Stratigraphic relations*

The echinoids and foraminifers clearly show that the Toolinna Limestone is laterally equivalent to the upper part of the Wilson Bluff Limestone.

Near Mount Ragged in the extreme southwest of the basin, the unit grades laterally into the Plantagenet Beds, and rests unconformably on Precambrian rocks. It is overlain disconformably by Abrakurrie Limestone towards the centre of the basin, and by Nullarbor Limestone towards the margin.

*Fossils*

The fossil content is similar to that of the Wilson Bluff Limestone, except that the planktonic foraminifers found in the chalky limestone are generally absent from the porous Toolinna Limestone. Crespin (1956) recorded numerous foraminifers in samples from a well near Booanya Rock in beds now regarded as Toolinna Limestone.

*Age*

Foraminifera indicate an Upper Eocene age (Crespin, 1956).

### ABRAKURRIE LIMESTONE

The name Abrakurrie Limestone is proposed here for the yellowish bryozoan limestone overlying the Wilson Bluff Limestone and underlying the Mullamullang Limestone Member of the Nullarbor Limestone in the central part of the Eucla Basin. The name is taken from Abrakurrie Cave. The unit was first described at Wilson Bluff by Tate (1879) as the "Yellow Polyzoal Bed", but it has not been formally named or defined before and the opportunity is taken here to select a type section superior to that at Wilson Bluff.

*Type section*

The type section is the western wall of Abrakurrie Cave (31° 39' 20" S, 128° 29' 20" E). The upper limit is the contact with algal limestone (Mullamullang Limestone Member) about 51 feet below the surface of the plateau, and the lower limit is the contact with hardened white limestone with abundant brachiopods (Wilson Bluff Limestone) about 159 feet below the plateau.

*Lithology*

The Abrakurrie Limestone is a medium to coarse-grained yellowish bryozoan calcarenite. The lower part is porous and friable, but weathering has made the upper part hard and tightly cemented. In places near the centre of the basin, for example at Twilight Cove and Mullamullang Cave, it is current-bedded. The lithology is very similar to the Toolinna Limestone, but preliminary studies by G. M. Philip indicate that each formation has a distinct echinoid fauna which can be used to distinguish them.

*Thickness*

The unit is 105 feet thick in Abrakurrie Cave, and is more than 322 feet thick in Mullamullang Cave. It was probably thickest south of Madura, but much has been removed by Pleistocene marine erosion. The depth to the base of the formation is unkown in the Madura area because it extends beneath the water table in caves, and in bores it is not possible to pick accurately the boundary with the Wilson Bluff Limestone.

*Distribution*

The unit is developed around Madura in the centre of the basin. It extends to Point Dover in the southwest, and beyond Wilson Bluff in the east. It probably does not extend as far north as the Trans Australian Railway.

*Stratigraphic relations*

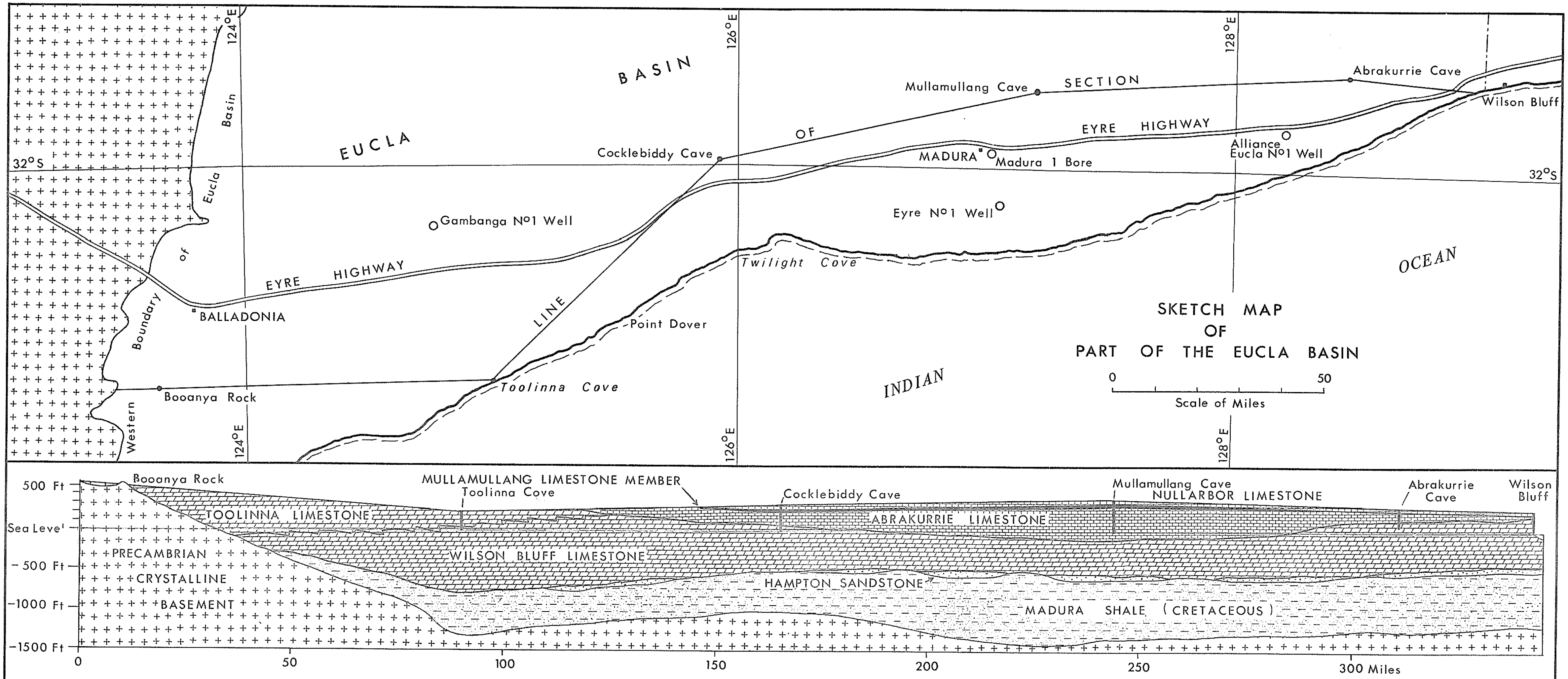
The Abrakurrie Limestone disconformably overlies the Wilson Bluff Limestone, and is overlain with apparent conformity by the Mullamullang Limestone Member.

*Fossils*

The unit contains abundant bryozoans, echinoids, pelecypods, and brachiopods.

*Age*

Echinoids indicate an Oligo-Miocene age (Philip, written communication, 1966), but typical Oligocene foraminifers are absent, and a lower Miocene age seems most likely.




VERTICAL EXAGGERATION X 100

SECTIONS EXPOSED AT EACH LOCALITY ARE INDICATED BY A HEAVY VERTICAL LINE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

## DIAGRAMMATIC CROSS SECTION OF THE EUCLA BASIN IN WESTERN AUSTRALIA

PLATE 20

9952

## NULLARBOR LIMESTONE

The term Nullarbor Limestone was introduced by Singleton (1954) for hard "crystalline" limestone which overlies the Wilson Bluff Limestone in the Eucla Basin. Ludbrook (1958a) nominated Wilson Bluff as the type section. Singleton's characterisation of the Wilson Bluff Limestone as chalky and friable and the Nullarbor Limestone as hard and tightly cemented was an over-simplification which led to the general belief that the Eucla Basin was everywhere covered by Nullarbor Limestone. The Toolinna Limestone and Abrakurrie Limestone are porous and friable where unweathered, but they also become hard and tightly cemented where subjected to prolonged weathering. For example the upper part of the scarp between Point Culver and Wilson Bluff is formed by 50 to 100 feet of hard, tightly cemented limestone which has the appearance of a single continuous formation, but this apparent uniformity is caused by weathering, the top of the scarp being formed in various places by Nullarbor Limestone, Abrakurrie Limestone, and Toolinna Limestone.

At Wilson Bluff, the bottom of the zone of weathering lies within the Abrakurrie Limestone, and Singleton (1954) apparently included the upper tightly cemented part of that formation in the Nullarbor Limestone and the lower friable part in the Wilson Bluff Limestone. However later workers have restricted the name Nullarbor Limestone to the foraminiferal calcarenite at the top of the cliffs and this practice is continued here.

*Type section*

The type section adopted is that exposed at the eastern end of Wilson Bluff, where the unit extends from the top of the Abrakurrie Limestone (239 feet above sea level) to the top of the cliffs. This section is a poor one because the formation lies within the zone of surface weathering ,and both the textural details of the limestone and its contact with the underlying formation are obscure. A reference section is nominated here as the 58 feet of foraminiferal and algal limestone exposed in the doline of Mullamullang Cave (31° 43′ S, 127° 14′ E), between the Abrakurrie Limestone and the surface of the plateau.

*Lithology*

The Nullarbor Limestone is a hard, tightly cemented, poorly-sorted calcarenite. Foraminifers and comminuted algae and echinoids are the most prominent constituents. Near the centre of the basin, the formation includes a biostromal algal limestone which is designated the Mullamullang Limestone Member.

*Thickness*

The unit is 46 feet thick at its type section at Wilson Bluff. Its thickness is very variable because it is the uppermost unit of the marine Tertiary sequence in the Eucla Basin, and its present thickness depends to a large extent on the amount of post-Miocene erosion. The thickest measured section in Western Australia is 75 feet in Haig Cave, but it is somewhat thicker in parts of South Australia, being 80 feet thick in Warbla Cave, 15 miles northeast of Wilson Bluff.

*Distribution*

The Nullarbor Limestone forms the surface of some 25,000 square miles of the Eucla Basin. It has been removed from the Roe Plains south of Madura by Pleistocene marine erosion (Ludbrook, 1958b), and from the southwestern part of the plateau by subaerial erosion.

*Stratigraphic relations*

The Nullarbor Limestone overlies the Abrakurrie Limestone with apparent conformity. The boundary is sharp, but there is no evidence of a period of erosion between deposition of the two formations. In the centre of the basin, the basal part is termed the Mullamullang Limestone Member, and in the northern part the formation grades laterally into the Colville Sandstone.

*Fossils*

The formation commonly contains abundant moulds of pelcypods and gastropods. There are scattered colonial corals near Forrest, and coralline algal nodules in the central part of the basin.

*Age*

Benthonic foraminifers indicate a Lower Miocene age (Ludbrook, 1963).

## MULLAMULLANG LIMESTONE MEMBER OF THE NULLARBOR LIMESTONE

The name Mullamullang Limestone Member is introduced here for the algal limestone that is developed at the base of the Nullarbor Limestone near the centre of the Eucla Basin. The name is taken from Mullamullang Cave.

*Type section*

The type section is that exposed in the doline of Mullamullang Cave (31° 43′ S, 127° 14′ E). The unit overlies hard bryozoan limestone of the Abrakurrie Limestone 58 feet below the surface of the plateau, and grades up into foraminiferal calcarenite about 37 feet below the plateau.

*Lithology*

The member is an algal limestone composed of nodules of coralline algae of the *"Lithothamnium"* type, enclosed in a poorly-sorted foraminiferal calcarenite.

*Thickness*

The unit is 21 feet thick in its type section, and reaches a thickness of about 35 feet where it is exposed on the Hampton Range, 25 miles southwest of Madura.

*Distribution*

The member occurs near the centre of the Eucla Basin, extending from Wilson Bluff on the east to beyond Cocklebiddy Cave on the west. The unit does not extend as far north as the railway.

*Stratigraphic relations*

The Mullamullang Limestone Member overlies the Abrakurrie Limestone with apparent conformity, and it grades up into the overlying part of the Nullarbor Limestone.

*Fossils*

Calcareous algae of the *"Lithothamnium"* type are dominant (see Figure 4 *in* Ludbrook, 1958b). The matrix contains comminuted algae, small algae, and foraminifers.

*Age*

The unit contains *Austrotrillina howchini,* a characteristic Lower Miocene foraminifer.

## COLVILLE SANDSTONE

The Colville Sandstone is proposed here for the beds of sandstone with minor claystone, limestone, and conglomerate that crop out in the northern part of the Eucla Basin. The name is taken from Lake Colville, 17 miles east of the type section.

*Type section*

The beds exposed in an east-flowing creek (21° 31′ S, 126° 23′ E) on the western side of a major depression 110 miles northwest of Loongana are taken as the type section.

*Lithology*

The dominant lithology of the type section is a medium-grained quartz sandstone. Thin calcarenite interbeds occur near the top and the bottom of the sequence. In other areas the formation also contains minor glauconitic sandstone, sandy shelly calcarenite, claystone, and conglomerate.

*Thickness*

The type section is 62 feet thick and the thickest known section of 77 feet is exposed in a creek 45 miles to the east. The base is not exposed in either section, and the maximum thickness is unknown.

*Distribution*

The Colville Sandstone is developed around the northern margin of the Eucla Basin.

*Stratigraphic relations*

The beds overlie tillite of probable Permian age near Lake Gidgi and the Carlisle Lakes, and surround an inlier of Proterozoic rocks near Lake Ilma (formerly "Lake Ell"). The beds grade laterally into the Nullarbor Limestone, and they are overlain by a variety of Quaternary deposits.

*Fossils*

The most common fossils are the heavy-shelled pelecypods *Ostrea* sp. and *Spondylus* sp.

*Age*

*Marginopora vertebralis* occurs at the base of the type section and *Austrotrillina howchini* has been found elsewhere. The beds are therefore Lower Miocene, the same age as the Nullarbor Limestone.

ACKNOWLEDGEMENTS

Fossils collected during the field work are being studied as follows: echinoids, Professor G.M. Philip; molluscs and brachiopods, Dr. N. H. Ludbrook; and Foraminifera, Bryozoa, and other groups, Dr. A. E. Cockbain. Some of their preliminary palaeontological data have been used in this report.

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# THE ORIGIN OF BLOW-HOLES AND THE DEVELOPMENT OF DOMES BY EXSUDATION IN CAVES OF THE NULLARBOR PLAIN

by D. C. Lowry

ABSTRACT

Narrow circular vertical shafts called blow-holes are common surface features in the limestone of the arid to semi-arid Nullarbor Plain. Blow-holes are formed by roof domes of shallow caves migrating upwards until they reach the surface. The domes develop in the vadose zone by frittering of the rock by exsudation.

## INTRODUCTION

The Nullarbor Plain is a stony treeless plain in the centre of an arid to semi-arid plateau of Tertiary limestone on the southern coast of Australia. This paper describes only the Western Australian plain, but the remarks on the genesis and morphology are believed to apply equally well to blow-holes in the adjoining part of South Australia. The name Nullarbor Plain strictly applies only to the treeless plain, but it is often used to include the scrub-covered area to the south, and sometimes (for example Jennings, 1963) to include the whole of the limestone plateau.

## DESCRIPTION OF BLOW-HOLES

Blow-holes are circular vertical shafts 1 to 6 feet in diameter and 5 to 35 feet deep. The surface of the plateau has a relief of about 20 feet, and consists of gentle rises with boulders and rare pavements of limestone, and intervening flat areas of accumulated clay. Blow-holes are found both on clay flats where they are set in a conical depression in the clay, and on rises where some are set in limestone pavements. Most of the shafts that are large enough to enter, are either blocked at the bottom by clay and rubble or lead to cramped rubbly caves. A few lead to larger caves, for example, Thylacine Hole, which covers an area of more than 2 acres.

## DISTRIBUTION

Blow-holes occur over the entire treeless plain and also in the scrub-covered area between the plain and the scarp that marks the southern edge of the plateau. Vehicle tracks criss-cross the plain, and by noting the frequency with which blow-holes are seen alongside the track it is possible to make a rough estimate of the areal density of blow-holes as well as the limits of their distribution. The data are plotted on Plate 21 and it suggests that there are 10,000 to 100,000 blow-holes scattered over an area of about 20,000 square miles.

## ROCK HOLES

Rock holes are another surface feature of the Nullarbor. They are roughly circular basins set in limestone pavements, and they hold water after rain. Pavements are often pock-marked with solution pans a few inches deep, and the pan in the lowest part of the pavement becomes preferentially enlarged because of the greater ponding of water. When the holes are big enough to hold water for a week or two after rain the rate of enlargement is probably increased further by the activity of algae and also by the scratching of men and animals trying to reach the last of the water.

## PREVIOUS THEORIES OF ORIGIN OF BLOW-HOLES

The earliest account of the blow-holes is probably that of Tate (1879, p. 111) who recorded "perpendicular vents called blow-holes up which there rushes on hot days a violent wind". Numerous other authors have mentioned them, and two possible origins have been proposed: Bolam (1923) suggested that they were formed by rock holes being deepened until they broke through into a cave, whereas King (1949) believed that the shafts were formed by corrosion and corrasion by descending vadose waters, presumably by the enlargement of a crack at the intersection of two vertical joints. Jennings (1963) also favoured this view and recorded conchoidal hollowings on the walls which he believed to be the eversional sculpturing of turbulent vadose water. It is conceivable that a few blow-holes were formed in the manner suggested by Bolam, but the great majority have features irreconcilable with either theory. A third theory is proposed herein; that they are formed by domes in the roofs of shallow caves migrating upwards until they reach the surface.

## SALIENT FEATURES OF BLOW-HOLES

Blow-holes have the following features:

Although aerial photographs commonly show a general joint-controlled pattern of elongate ridges of exposed limestone and intervening flat areas of colluvial clay, the rock outcrops rarely show jointing on a small scale. Instead the upper 10 to 15 feet of limestone is broken by irregular anastomosing cracks and seams of kankar and clay. The cracks are irregular in both horizontal and vertical exposures, and it seems unlikely that the intersection of two cracks could be rectilinear and vertical as would be necessary to initiate a blow-hole. Blow-holes rarely lie on cracks in limestone pavements, and instead most of them have circular rims unaffected by cracks (Plate 23A).

Some blow-holes occur in areas where the limestone is buried by colluvial clay up to 5 feet thick. The freshness of the exposure of the clay in the crater around these blow-holes shows that there is rapid erosion of the clay at the present time (Plate 23B). The clay appears to have once formed a continuous sheet over the top of the blow-holes, and it is difficult to see how they could have been formed by solution by vadose water.

Rock holes are not as common a feature as blow-holes, and they are restricted to large limestone pavements without cracks that would allow the seepage of water. Blow-holes on the other hand are not restricted to such pavements.

Rock holes often have irregular margins, for example Undawidgi Rock Hole in Plate 23C. Blow-holes however are usually markedly circular. A few rock holes are markedly circular and parallel-sided, but these may well be blow-holes that have become blocked by clay so that they now hold water.

Several blow-holes have little or no drainage entering them because they occur on ridges (for example, Plate 23A). Where blow-holes do receive surface drainage, it is not possible to demonstrate whether the drainage system developed as a result of the blow-hole, or vice versa.

Blow-holes commonly descend more than 10 feet before opening out into a cave, whereas no rock holes observed were more than 4 or 5 feet deep.

These features and their congruity with each of the possible origins are listed in Table 1. The conclusion is that the blow-holes have broken through to the surface from beneath and that their distribution is unrelated to jointing or surface drainage.

Table 1

FEATURES OF BLOW-HOLES AND ROCK HOLES, AND THEIR CONGRUITY WITH POSSIBLE BLOW-HOLE ORIGINS

| Features | Possible origin | | |
|---|---|---|---|
| | Deepened rock hole | Joint opening | Enlarged cave roof dome |
| Blow-holes rarely occur on joints | yes | no | yes |
| Some blow-holes are covered by clay | no | no | yes |
| Rock holes are restricted to large rock pavements; blow-holes are not .... .... .... .... | no | yes | yes |
| Rock holes often have irregular shapes; blow-holes are circular | no | ?no | yes |
| Some blow-holes receive little drainage .... .... .... .... | no | no | yes |
| Rock holes are shallower than blow-holes .... .... .... .... | no | yes | yes |

## ROOF DOMES IN CAVES OF THE NULLARBOR PLAIN

If blow-holes break through from beneath, an examination of quarries and caves should reveal incipient blow-holes that have not reached the surface. In fact, almost all the shallow caves that are entered by way of a blow-hole have domes in the roof which would become blow-holes if they extended further upwards. These domes have received very little attention by previous writers on Nullarbor caves: Tate (1879, p.111) seems to be the only writer to mention them. He recorded that the roof "in many places rises nearly to the surface in the form of inverted pot holes". The walls of the domes are close to vertical and the tops are approximately hemispherical. They range in diameter from 6 inches to 6 feet, and are usually in the range 18 inches to 3 feet. The walls have concentric sculpturing due to the truncation of subhorizontal layers of clay, kankar, and limestone having differing resistances to weathering. The "evorsional" sculpturing on the walls of blow-holes is probably usually due to the same cause.

Three widely separated caves can be used to illustrate the occurrence of domes. Decoration Cave lies at the northern limit of the Nullarbor Plain, 50 miles northeast of Forrest. A blow-hole 2 feet in diameter leads to a chamber 60 feet long, 25 feet wide, and 8 feet high. The chamber has a flat earth floor 35 feet below the surface, and the walls are covered with old calcite stalactites and flowstone. The entrance shaft (Plate 24A; Figure 7) has several domes connected with it, and the roof near the entrance shaft has a cluster of domes. It appears that a cluster of domes migrated upwards until the central one reached the surface.

A second example is Lynch Cave near Loongana (see Figure 8). The entrance is a blow-hole and like the entrance of Decoration Cave, there are several domes associated with it. The cave has an abundance of old calcite stalactites and flowstone, some of which are truncated by domes. This shows that these domes formed later than the calcite, and are one of the last-formed features of the cave.

Telegraph Cave, 24 miles east of Caiguna, is small (Figure 9) and has numerous domes. The entrance is partly the result of collapse, and it is likely that it was caused by weakening of the rock by a cluster of domes reaching almost to the surface.

It might be argued that domes are only associated with caves large enough to enter, or that domes only form after the cave develops an entrance. These possibilities can be discounted by examining some of the quarries along the Eyre Highway and the Trans-Australian Railway. The best exposures are in the Loongana quarry where there are domes developed above small cavities in porous rubbly limestone (Plate 24B).

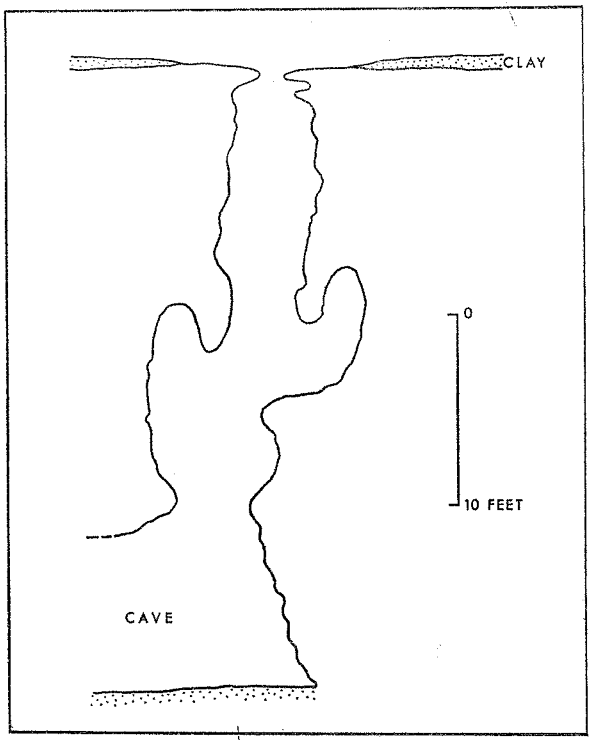



Figure 7—Vertical section of entrance to Decoration Cave.

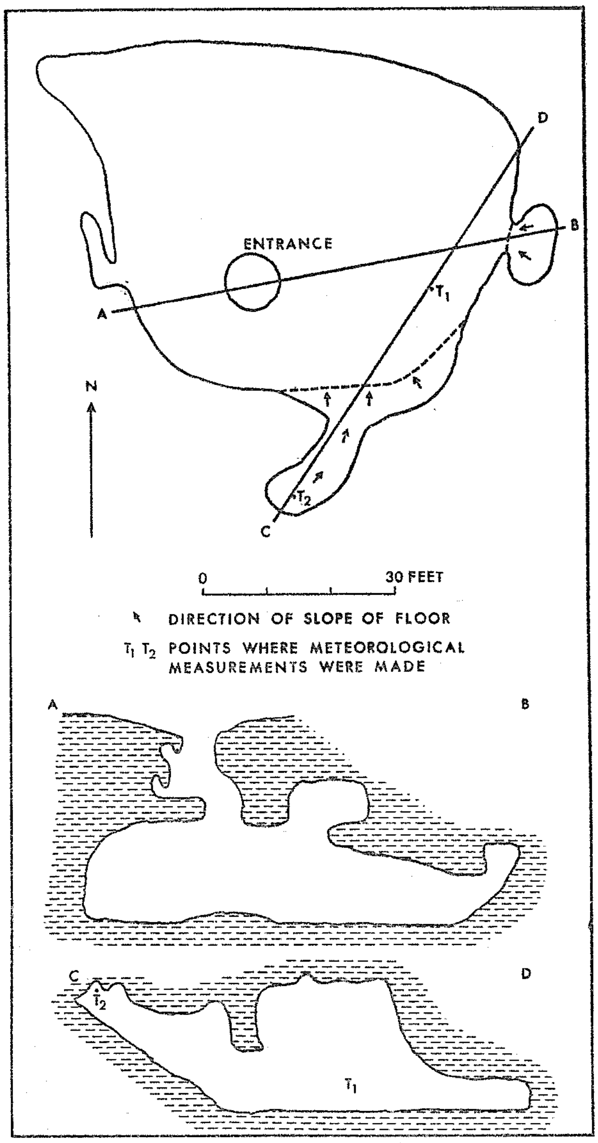



Figure 8—Plan and sections of Lynch Cave.

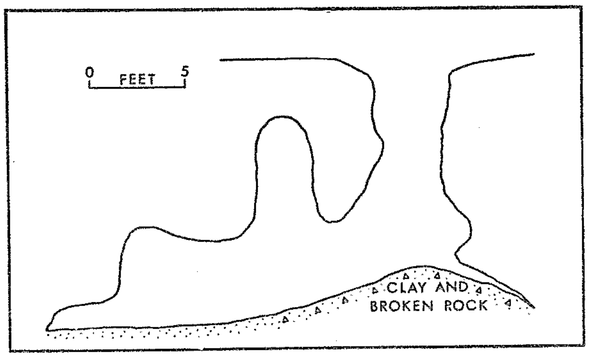



Figure 9—Vertical section of Telegraph Cave.

## DEVELOPMENT OF THE DOMES

If blow-holes are formed by the upward migration of domes, the problem is to find the mechanism. Domes have been recorded in the roofs of limestone caves elsewhere in the world, but none of the postulated origins fits the domes in the roofs of caves of the Nullarbor Plain. Probably the best known description of roof domes is that of Bretz (1942) who showed that the domes he studied were caused by solution by water in the phreatic zone. This theory cannot account for the domes described above: truncation of calcite formation and fresh erosion around the entrances of some blow-holes shows that the domes have developed relatively recently, yet the water table is at present about 300 feet below the plain and it is most unlikely that it could have been near the surface of the plain during the development of the domes.

King-Webster and Kenny (1958) believed that colonies of bats excavated domes in the roofs of caves in Trinidad, but this cannot apply to domes in the small shallow caves of the Nullarbor Plain because bats rarely live in them, and there are no guano piles beneath the domes.

Solution by vadose water as postulated by Bretz (1942) for dome-pits in caves in North America is eliminated because the tops of the domes have no visible fissures, and the walls of the domes are dry.

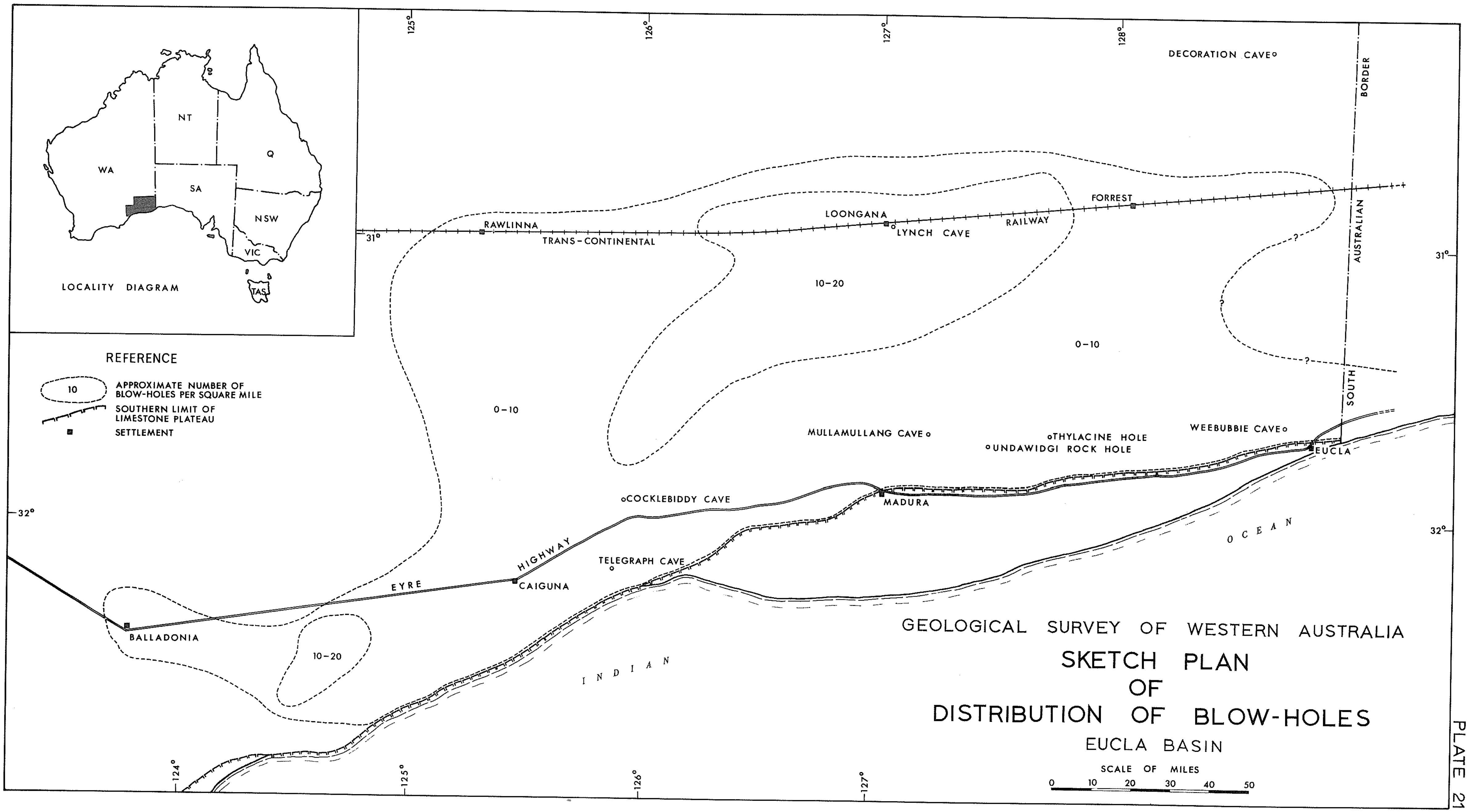
There do not appear to be any other published theories that can explain the development of domes in Nullarbor caves, and it is proposed here that the domes form by the frittering of the rock by the process of exsudation.

## EXSUDATION

Exsudation (see Hume, 1914; Jutson, 1918) is the process whereby the surface grains of a rock are wedged off by the growth of crystals in pores near the surface. The crystals grow because of evaporation of saline interstitial water. Buckley (1951) discussed the force exerted by a growing crystal, and cited several examples of rock disintegration caused by it.

Exsudation has an important modifying influence on the morphology of deep caves of the Nullarbor Plain. Jennings (1963) recorded scalloping ("tafoni") on the walls of Weebubbie Cave, and Lowry (1964) recorded similar weathering occurring at the present time in Cocklebiddy Cave and suggested that it was due to exsudation. Recently-discovered Mullamullang Cave shows very great modification by exsudation; for half a mile from the entrance the floor is covered with drifts of dust, sand, and rock flakes (Anderson, 1964) which I believe to be frittered from the roof. Wigley and Hill (1966) also recorded minor exsudation features in other parts of the cave. Thus exsudation is well-established in the deep caves, and it seems to be the most probable mechanism for the development of domes in the shallow caves.

There are at least three requirements for exsudation to take place in caves: the rock must be sufficiently porous; the interstitial fluid saline; and evaporation occur at the rock surface, that is, the




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

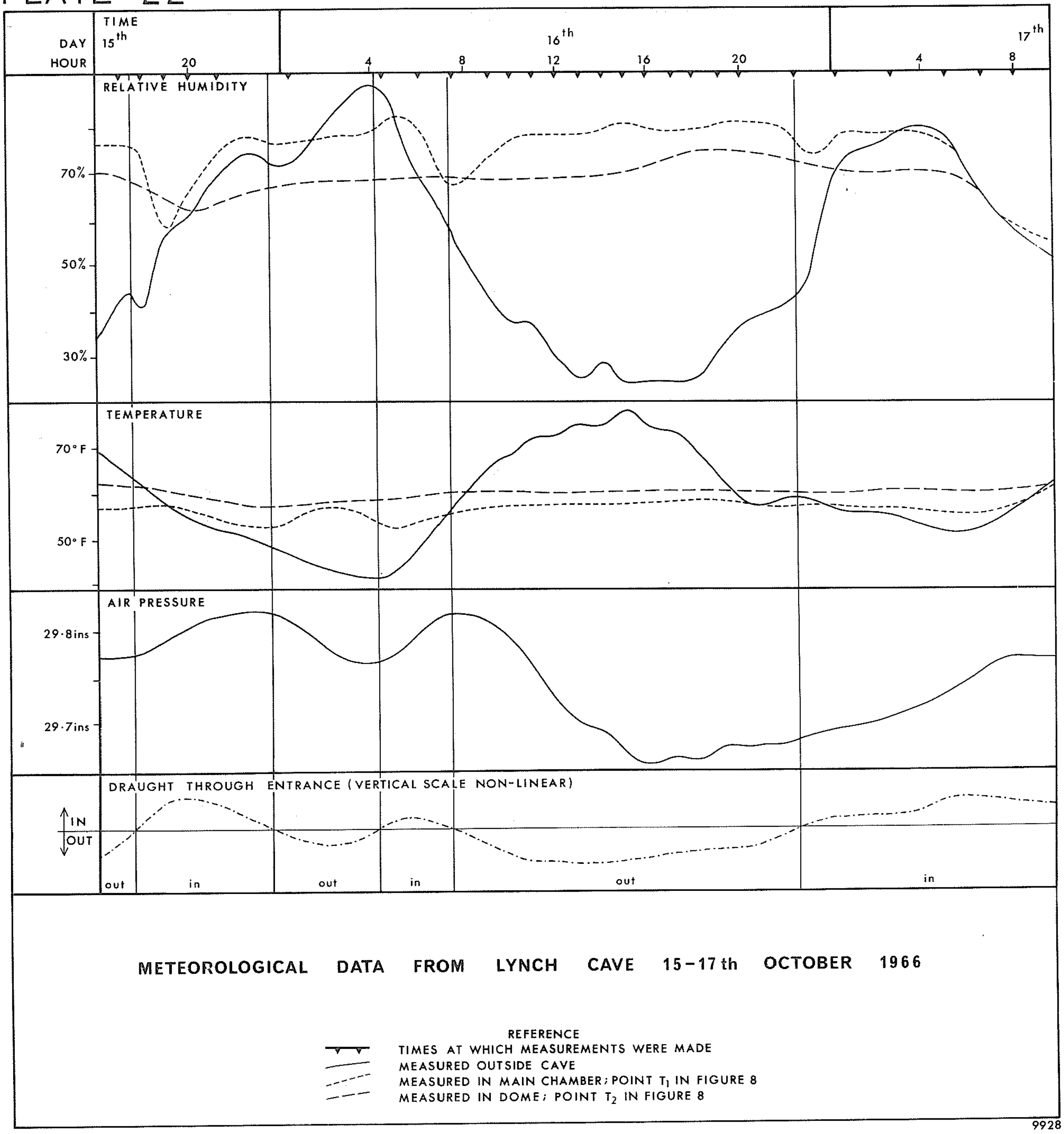
SKETCH PLAN OF DISTRIBUTION OF BLOW-HOLES

EUCLA BASIN

PLATE 21

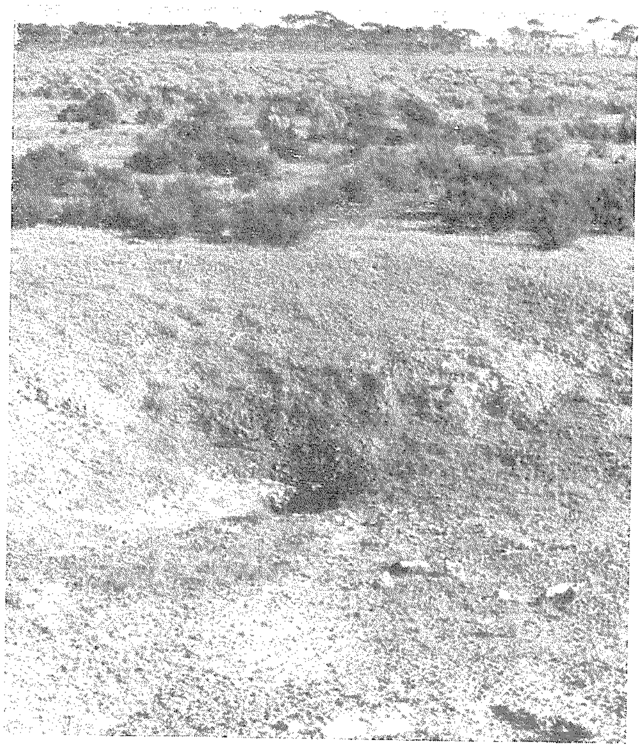
0066

# PLATE 22




METEOROLOGICAL DATA FROM LYNCH CAVE 15–17th OCTOBER 1966

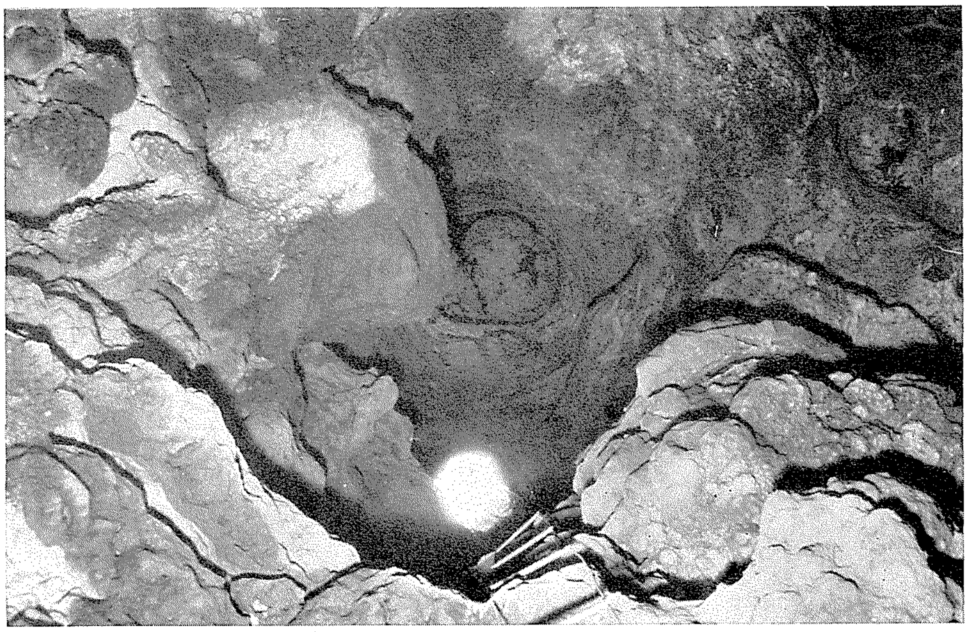

A. Typical blow-holes situated on a limestone ridge. Note the circularity of the rims; F 1177.



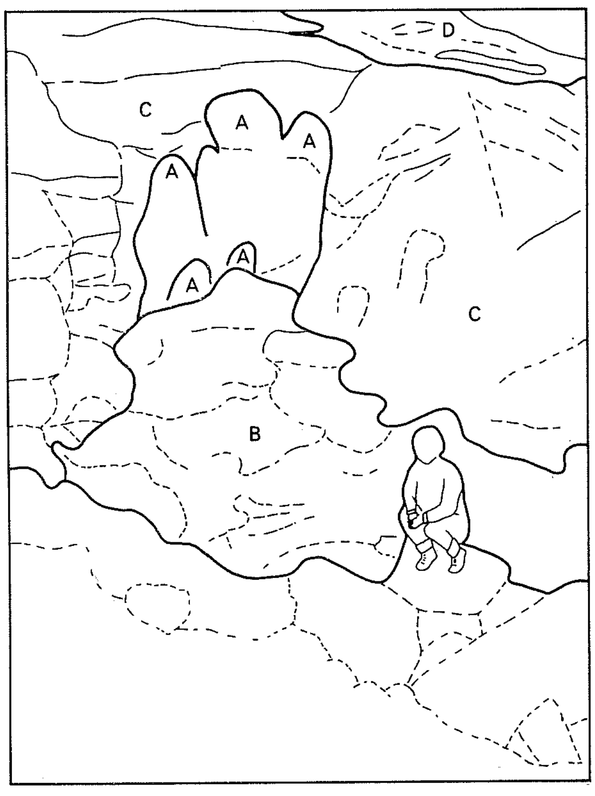
B. Blow-hole surrounded by a rapidly eroding layer of clay 3 feet thick; F 1178.

C. Undawidgi Rock Hole showing irregular margins and a typical large limestone pavement; F 1179.

PLATE 24



A. View looking up Decoration Cave blow-hole entrance. Ladder rungs are 6 inches wide. The dome appears in section in Figure 7; F 1181.




B. Loongana Quarry. A cluster of domes (A) are developed above a zone of porous rubbly limestone (B). Note the irregular jointing of the limestone (C) and the superficial layer of clay and kankar (D); F 1183.

air is not saturated with water vapour. These requirements are met by the conditions in the shallow caves of the Nullarbor Plain.

The limestone in which most of the domes are developed (the Nullarbor Limestone) is usually described as crystalline, but I believe that the limestone is porous and permeable enough to allow sufficient movement of water through the rock to supply the growing crystals. A thin-section of the wall of one of the domes in Lynch Cave showed that the rock had a porosity of about 5 per cent.

Rainfall on the Nullarbor Plain varies from about 12 inches near the coast to about 7 inches near the Trans-Australian Railway. This low rainfall results in the accumulation of cyclic salts in the soil (notably halite and gypsum), and water seeping into the underlying rock can be expected to be saline. This is confirmed by the occurrence of halite deposits in some of the caves.

Evaporation at the surface of the dome can also be expected because there exists a widespread shallow zone of small interconnected cavities in which there are air movements. This will be discussed in detail in the next section.

One implication of the exsudation hypothesis is that one could expect to find a cone of disintegrated rock beneath each dome. It must be admitted that such a cone is present in only a few instances (one example is beneath a shallow dome in Thylacine Hole, 25 yards southwest of the entrance). It is possible that flood waters, and perhaps strong draughts are responsible for removing debris beneath other domes. Solution by vadose water is probably ultimately responsible for removal of the debris; otherwise there would be a serious room problem created by the frittered rock occupying more space than the solid rock from which it was derived.

## AIR MOVEMENTS IN SHALLOW CAVES

The limestone of the Nullarbor Plain, in an interval about 10 to 40 feet below the surface, is riddled with tubes and small interconnected cavities. Jennings (1963) believed these tubes were the result of phreatic solution, but while this may be true for some tubes, I believe that many are due to solution by root exudates (Wall and Wilford, 1966), and that some other tubes and the irregular rubbly cavities are due to disintegration and solution of the rock in the vadose zone. Whatever the origin of the cavities, there are several indications that they are interconnected and ubiquitous.

One striking indication is the common occurrence of draughts in blow-holes. The draughts are estimated to reach 20 or 30 mph and give the blow-holes their name. The air pressure fluctuates under the combined influence of changing weather patterns, and a cyclical twice-daily change. Data presented in Plate 22, and in Wigley and others (1966) show that the daily fluctuations amount to about 0.1 inches of mercury (about 4 millibars). They claimed that the estimated volume of caves required to generate the observed draughts, is usually much greater than that accessible to exploration, and that this extra volume was due to the intergranular porosity of the limestone. They seem to have overlooked the more likely explanation that the extra volume is due to the small cavities mentioned above. The small cavities are found over the entire plain and are not restricted to the vicinity of blow-holes. Patches of rocks riddled with small cavities are exposed in dolines, coastal cliffs, and quarries (for example the Loongana quarry, Plate 24B). Furthermore, most percussion bores drilled on the Nullarbor Plain develop draughts before they reach a depth of 40 feet (Mr. M. Walsh, pers. comm.).

Little is known of the humidity of the air in the cavities, and thus it is uncertain how much evaporation can occur. Substantial evaporation must occur in cavities surrounding existing blow-holes, because there is a daily exchange of a large volume of air; the air blown out being more humid than the air sucked in. This is well shown by the data from Lynch Cave (Plate 22). However it is not certain that there is movement of air in cavities remote from blow-holes and other places where the zone of cavities is clearly connected with the atmosphere. It might be argued that in remote cavities, air movement would be so slight that the humidity would be high and exsudation negligible. This would mean that domes would develop only in the vicinity of existing blow-holes, and the exsudation hypothesis could not explain the development of the first blow-holes. This problem is not insuperable because it is quite likely that there is a small amount of air movement through the cracks and partly-blocked root holes that are seen in many limestone outcrops and which could well connect with cavities beneath. One indication that evaporation does occur throughout the cavities of the plateau is given by the data from Lynch Cave. During the observations there was a period when air blew out of the cave for 15½ hours instead of the average period of about 8 hours. The air blowing out reached a relative humidity of 78 per cent. 3 hours after the period commenced, and it remained virtually constant for the remainder of the period suggesting that the air in the cavities had that humidity for a great distance around the cave.

This evidence all points to a widespread shallow zone of cavities with air movements favourable to exsudation.

## AGE OF THE BLOW-HOLES

The limestone plateau emerged from the sea at the end of the Lower Miocene, and weathering produced a thick residual clay with a kankar horizon near the surface. Jessup (1961) studied soils in South Australia and believed that during the Pleistocene there was a period of wind erosion when calcareous clay was blown from the Nullarbor Plain eastwards into South Australia. Jessup did not try to correlate this event with an absolute or glacial chronology, but it seems likely that it was about the middle of the Pleistocene. Over much of the plateau the limestone is covered by thick residual clay and kankar but in the centre (the treeless Nullarbor Plain) and in the south there are numerous outcrops of limestone. This is very likely the source of Jessup's wind-blown clay. Blow-holes are virtually restricted to areas where the limestone surface has been exposed by this erosion. It seems likely that exsudation in caves would commence once the limestone surface was exposed and the air could move through the cracks. If so the domes would have started developing in approximately the middle Pleistocene. Another indication that blow-holes are no older than middle Pleistocene is that all skeletal remains found in caves with blow-hole entrances are of species of animals known to have lived on the mainland of Australia or Tasmania in historic times. Blow-holes are believed to have formed until the present time. As indicated earlier, several blow-holes appear to have broken through to the surface relatively recently, and the process of exsudation is believed to be occurring at present.

## THE SHAPE OF THE DOMES

One remaining problem for the exsudation hypothesis of dome formation is to find the mechanism whereby domes grow upwards instead of there being a general disintegration of the cave roof and walls. Two possible mechanisms are apparent. If the water from the surface is in the form of a vertical seepage confined to a small duct or zone, only the rock dampened by it will undergo exsudation and the dome will work back along the seepage towards the surface. Alternatively, warm air might collect in initial pockets in the roof so that evaporation occurred faster there than in the rest of the cave. The temperature of the rock walls of the cave would be roughly the mean daily or perhaps mean annual surface temperature, and warm air could accumulate either by the cave sucking in hot air during the day, or by sucking in cold air at night which would be warmed by the walls.

There are some observations which support the latter mechanism. In Lynch Cave, the air temperature was measured over a 40 hour period in the main chamber (at Point $T_1$ in Figure 3) and in a dome in the southern corner of the cave (at Point $T_2$). The data (Plate 22) show that the air in the dome was consistently warmer than in the

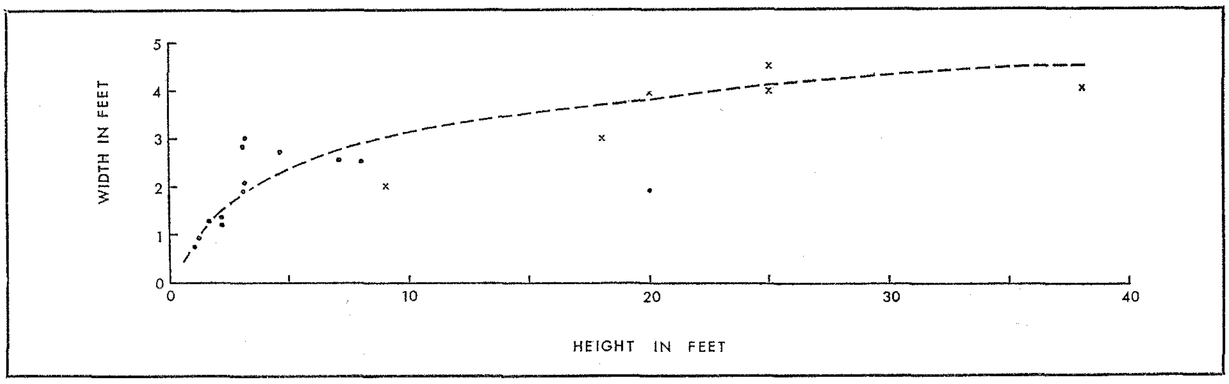



Figure 10—Plot of heights and widths of blow-holes (x) and domes (·).

main chamber. Similarly in Thylacine Hole, the air in a dome near the entrance felt significantly warmer than the air in the cave beneath the dome. However, the air in domes in many other caves was not noticeably warmer than in the rest of the cave, and it is not certain that trapping of warm air is a general characteristic of domes.

One feature of domes which might be indicative of the mechanism of their growth is the ratio of height to width. The few measurements that were made are plotted in Figure 10, and they seem to indicate that the height to width ratio increases as the dome grows. The processes of seepage and evaporation are potentially so complex that the significance of the ratio is not clear, although it would probably make a fruitful topic for further study.


ACKNOWLEDGEMENT

Dr. A. Richards kindly provided the whirling hygrometer used for humidity measurements.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## PROVISIONAL SUBDIVISIONS OF THE PRECAMBRIAN IN WESTERN AUSTRALIA, 1967


**compiled by R. C. Horwitz**


The accompanying chart (Plate 25) of provisional sub-divisions of the Precambrian in Western Australia is a revision of that published in the 1966 Annual Report. The chart emphasises the groupings in time of igneous events and sedimentation in Western Australia.

The previous geographic divisions of Phillips River and South West areas are deleted and replaced by a South Coast area and Perth Basin area. Some granites between Esperance and Israelite Bay appear to be analogous to those of Albany, dated at about 1,000 m.y. Areas surrounding the Perth Basin are characterised by repeated periods of folding and igneous activity throughout time.

## STRUCTURAL LAYERING OF THE ROCKS OF THE ARCHIPELAGO OF THE RECHERCHE


**by K. H. Morgan, R. C. Horwitz and C. C. Sanders**



ABSTRACT

The Archipelago of the Recherche, and adjoining mainland along the south coast of Western Australia, are made up of crystalline rocks that are believed to be Precambrian. Granite sheets and metamorphic rocks are layered and folded in a broad southwest plunging anticlinorium.


INTRODUCTION

The Archipelago of the Recherche is off the south coast of Western Australia near the port of Esperance. The one hundred or more small islands and rocks of the Archipelago are dotted along the continental shelf for over 100 miles.

PLATE 25


AGE OF UNIT

PROPOSED
PROPOSED (UNIT RESTS WITH A BASAL UNCONFORMITY)
PROBABLE RANGE WITHIN WHICH THE UNIT MAY FIT
POSSIBLE RANGE WITHIN WHICH THE UNIT MAY FIT
TENTATIVE POSITION OF TIME BOUNDARY

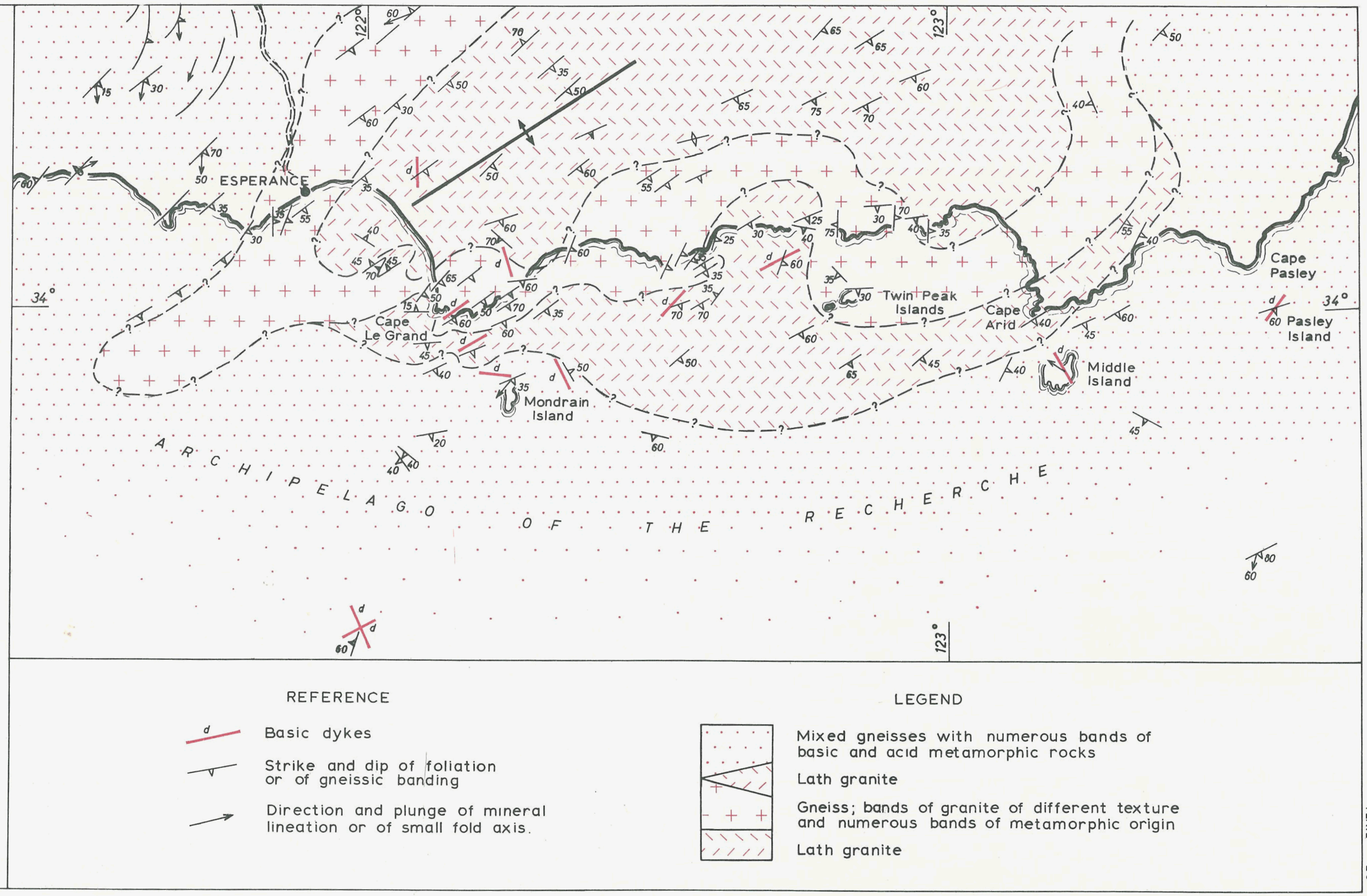
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# PROVISIONAL SUBDIVISION OF THE PRECAMBRIAN IN WESTERN AUSTRALIA 1967

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# SKETCH MAP OF SOLID GEOLOGY OF THE ARCHIPELAGO OF THE RECHERCHE REGION

SCALE OF MILES 15 0 15 30




1966

PLATE 26

The rocks of these islands are mainly crystalline and are believed to be Precambrian. To the east, some islands are capped by calcarenite which has been soaked by bird guano, leading to the development of phosphate deposits. These have been described by Woodward (1908, 1917) and by other geologists in unpublished reports.

Fairbridge and Serventy (1954) have given accounts of the physiography and rock types on these islands but little was known previously on the regional geology of the Precambrian of the Archipelago.

In April 1967, a week was spent in visiting several of the islands by boat and an ordered layered sequence of igneous and metamorphic rocks was recognised in the crystalline Precambrian rocks.

### PRECAMBRIAN

The accompanying sketch map (Plate 26) shows the solid geology of the Archipelago of the Recherche and the adjoining coastal area. In the ocean, strike and dip symbols denote an island that was visited; they were measured on lath-feldspar foliation in granites, and on compositional banding in gneisses.

The rocks are arranged in a layered sequence and folded. The deepest rock exposed is a grey porphyritic biotite granite with two feldspars, one of which is an alkali feldspar which is commonly in large pink laths.

Above this granite are gneisses made up of bands of granite of varying tone and texture with metamorphic rocks in large and small rafts.

Higher in the structural layering, lath granite is more abundant and, to the east of Esperance, there is a homogeneous sheet of granite which is about 15,000 feet thick. This homogeneous sheet is not developed to the west of Esperance where several bands of lath granite alternate with vari-textured crystalline rocks.

Above this granite there are mixed gneisses with numerous bands of metamorphic rocks, including hypersthene and garnet-bearing rocks. The bands are commonly basic, such as on the mainland coast 25 miles west of Esperance, or on Pasley Island, where field relationships indicate that the basic rocks are altered sills. On Middle Island there are granular quartz rocks which could be altered vein rocks.

Dolerite dykes cut the mixed gneisses. They are rarer in the lower part of the layering and very scarce in the granites. North of Cape Le Grand, basic dykes cut granite but they can be traced in the granite to some disconnected basic xenoliths. The dolerite and the granite are thus considered to be broadly contemporaneous.

The Precambrian history of the region can be summarised as follows:

(1) Deposition of sedimentary rocks and intrusion of basic igneous rocks. The age of this assemblage is believed to be Archaean because it appears to be the extension of the 2,800 m.y. old gneisses of the Oldfield River region to the west (dated by Richards and others, 1966) and with the Archaean rocks of the Norseman region, to the north.

(2) Regional metamorphism of these rocks. The age of this metamorphism is not known; it could be Middle Proterozoic.

(3) Intrusion of granite and, possibly towards the end of this igneous phase, intrusion of dolerite dykes. This igneous activity is tenatively assigned to the younger part of the Middle Proterozoic because it is equated with the Albany Granite on the grounds of similarity in rock types, trends, and relationship, and of provincial unity. The Albany Granite is dated by Turek and Stephenson (1966) as about 1,100 m.y. old.

(4) Folding in a broad anticlinorium.

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# SILVER-LEAD-GOLD-COPPER PROSPECT, M.C.38, KUNUNURRA AREA, WESTERN AUSTRALIA

by John Sofoulis

### ABSTRACT

Silver-lead-gold-copper mineralisation of M.C.38 is associated with lenticular quartz reefs intruding fractures within Hart Dolerite. Development on the mineralised reefs is insufficient to allow any accurate estimation of the amount and grade of ore available. Low-grade mineralisation may be distributed over a large proportion of the quartz reefs and it is likely that some of the reef sections could contain concentrations suitable for selective mining. The prospect could prove to be a profitable concern for small syndicate operation but the limited size of reefs and patchy distribution of ore are not suited to company scale operations. Silver, lead, and associated mineralisation similar to that of M.C.38 has been recorded from several other localities in the Kimberley Goldfield region. Although none of the deposits are economic, they indicate a widespread occurrence of this type of mineralisation and suggest further areas for future prospecting.

### INTRODUCTION

Seven lenticular quartz reefs, some of which contain patchy silver-lead-gold-copper and minor zinc mineralisation are included in M.C.38, pegged by Mr. P. Costeo in June 1967. The claim is about 13 miles west of the Kununurra townsite in the East Kimberley district.

A geological inspection of M.C.38 was made by the writer in October 1967.

### LOCATION AND ACCESS

M.C.38 lies in flat to gently undulating country adjoining the all-weather bitumen road that links Kununurra (the centre for the Ord Irrigation Scheme) with the port of Wyndham. The claim turn-off is 10 miles by road west of the western abutment of Bandicoot diversion dam, and the main excavations on the claim are about 600 feet north of the road. The road distance from M.C.38 to Wyndham is approximately 52 miles. The area lies within the Cambridge Gulf 1:250,000 Geological Sheet SD/52-14.

### GENERAL GEOLOGY

The geology of the region has been described by Dow and others (1964), and by Plumb and Veevers (1965). Proterozoic rocks referred to the Valentine Siltstone and Lansdowne Arkose of the Speewah Group comprise the main stratigraphic units exposed near the claim area. These formations are folded along northeast lines and have low to moderately steep dips to the southeast or northwest. The Speewah Group is commonly intruded as definite stratigraphic levels by extensive dolerite sills referred to the Hart Dolerite of post-Kimberley Group age (Upper Proterozoic).

The quartz reefs of the claim area are emplaced within a persistent sill of Hart Dolerite found in the basal part of the Valentine Siltstone. This sill is reported to be up to 6,000 feet thick in the adjacent Lissadell 1:250,000 Sheet area, (Plumb and Veevers, 1965).

Minor faulting, shearing, and jointing has affected the Hart Dolerite and associated sediments. A major fault west of the Dunham and Ord Rivers, known as the Ivanhoe fault, lies approximately 4 miles east of the claim. It dislocates both Proterozoic and Palaeozoic rocks and is defined by a prominent scarp of northeast trend. The quartz reefs of M.C.38 occupy faults and joints within the Hart Dolerite, and may be related to the same Palaeozoic or post-Palaeozic period of tectonism. Significant lead - zinc - silver mineralisation of Palaeozoic or post-Palaeozoic age has been recorded from the West Kimberley area (Halligan, 1965).

## DOLERITE HOST ROCKS

The Hart Dolerite is the host rock for the mineralised quartz reefs. It forms low rocky outcrops, pavements, and loose rounded boulders. The loose boulders are associated with red loamy soil adjacent to outcrops, or with black soils related to drainage lines. Dolerite in adjacent areas forms low, rounded boulder-strewn hills generally less than 50 feet high. Most of the dolerite boulders and outcrops are fresh, dark green, crystalline rocks ranging from fine to medium-grained dolerite and quartz-dolerite to coarse-grained gabbro and probably granophyre. Plumb and Veevers (1965) described dolerite from this area containing andesine or labradorite and pigeonite or diopsidic augite. Magnetite is a common accessory whilst olivine, biotite, quartz, epidote, and hypersthene may also be present as minor constituents.

Sheared Hart Dolerite crops out within the claim area marginal to the intrusive quartz reefs. Elsewhere the dolerite is hard, fresh, and massive with a prominent ophitic or sub-ophitic fabric. No sulphide minerals were observed in fresh dolerite specimens although lead and silver mineralisation was detected in an assay of oxidised dolerite taken from a contact zone (Sample 12819). Elsewhere in this region the Hart Dolerite locally contains small amounts of pyrite and chalcopyrite.

## MINERALISED QUARTZ REEFS

Several discrete lenticular quartz bodies with west-northwest to northwest trend are emplaced within the Hart Dolerite of the claim area and crop out over a distance of some 900 feet to form an echelon series aligned northwesterly (see Plate 27). These lenticular reefs range from small bodies 70 feet long and 10 feet wide to 200 feet long and 50 feet wide.

All of the reefs crop out as low pavements and solid bodies with up to 4 feet of relief, and have prominent joints parallel with their strike or at right angles to contacts with Hart Dolerite. A pre-existing fault or fracture pattern within the Hart Dolerite has provided suitable openings for the quartz intrusions (and subsequent mineralising fluids), and has been the dominant control for quartz reef distribution.

The lenticular quartz reefs are tabular or dome-like bodies, possibly connected in depth, and with irregular walls that range in dip from vertical to 30 degrees northeast. Usually the contacts are well defined and knife-sharp, but some are zones up to 2 feet wide and consist of quartz interlayed with dolerite and assimilated dolerite. Minor xenoliths are also present, and a larger block 20 feet long and 6 feet wide is included in the quartz reef of the southeastern part of the claim area.

All of the reefs consist of milky white massive quartz, commonly discoloured at the surface by orange-brown limonite staining. Blue-grey quartz crystals form interlocking half-rosettes growing inward from the walls of vugs and irregular openings. These crystalline growths are interlayed with white massive quartz to give a composite banding or layering effect. Some of the openings may have been up to 12 inches wide but most are lined with quartz crystal growths and the voids are now partly or completely filled.

The quartz reefs are separately designated on Plate 27 as reefs A-G.

## MINERALISATION

Significant mineralisation was observed only in reefs B, C, D, E, and F. The mineralised sections of the quartz reefs include silver, lead, gold, and copper, with minor amounts of antimony and zinc. The most common minerals are galena (lead sulphide), cerussite (lead carbonate), anglesite (lead sulphate), malachite (copper carbonate), and the yellow ochreous mineral bindheimite (a hydrous antimonate of lead). Neither gold, silver, nor zinc minerals were observed megascopically. Silver is probably associated with the lead minerals and is found in argentiferous tetrahedrite disseminated with the galena ores. Accessory copper minerals include azurite, chrysocolla, and a few grains of bornite, covellite, and chalcopyrite. An examination of crushed analytical material showed that the main zinc mineral is hemimorphite with a little sphalerite.

These complex silver-lead-gold-copper ores are not confined to any defined lode but are found as fine disseminations and as irregular enriched patches distributed within the quartz reefs. The more significant patches of mineralisation are indicated on Plate 27.

Most of the enriched ore is associated with the crystal-lined vugs described above, the ore material filling or partly filling the remaining spaces between the quartz crystal growths. Secondary copper minerals (mainly malachite) also occur in vugs as well as forming thin coatings along joints and partings of surface or near-surface layers. Below the surface layers the copper mineralisation is weaker and the copper minerals are mainly chalcopyrite, covellite, and bornite, found as minor disseminations with galena. The galena is disseminated in the quartz or may be in massive form or in coarse cubic crystals and bunches (up to 18 inches across) often with curved crystal faces.

Yellow ochreous bindheimite is associated with copper and lead carbonates (and partly altered galena) in some of the more oxidised surface ores.

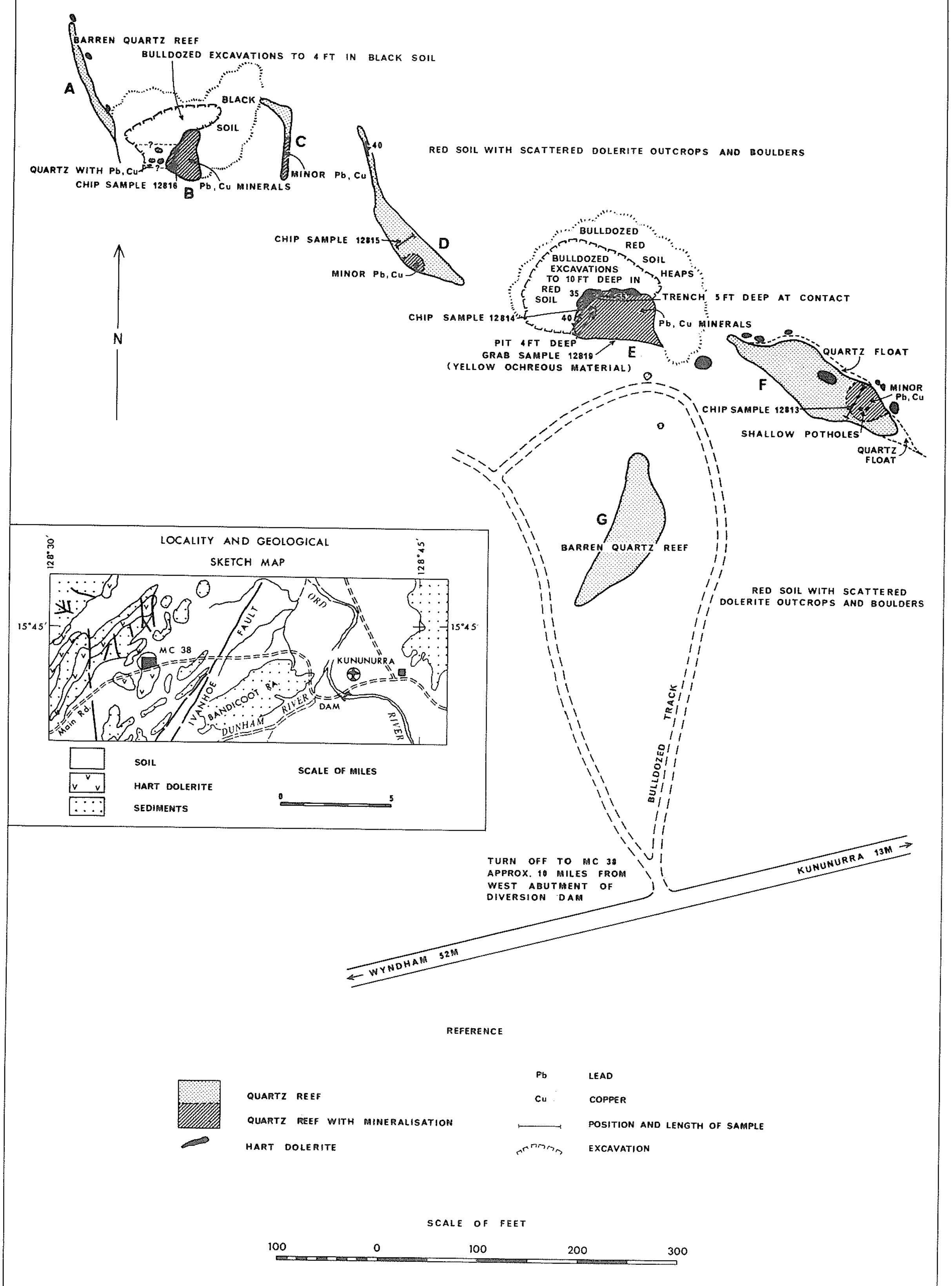
## DEVELOPMENT

The claim holder and one employee are currently working the claim. A bulldozer was used in the removal of overburden and scrubby growth, and in the construction of an access track from the bitumen road. Some black soil and red soil patches marginal to some of the mineralised sections of the quartz reefs were excavated to 10 feet deep to expose the irregularly dipping walls of ore bodies B and E, and some trenches have now been opened up on the best mineralised sections. Several shallow trenches, potholes, and small costeans scattered over other mineralised parts of the quartz reefs have been merely exploratory diggings for locating zones of more concentrated mineralisation.

Approximately 120 tons of silver-lead-gold-copper ore have been won from the claim and are stockpiled at the site ready for shipment. The ore has been hand-sorted into two separate piles of approximately 60 tons which represent first and second grade ore. Most of this ore was won from small gossanous surface-enriched zones and deeper cuts (to 5 feet deep) sunk into the mineralised sections of quartz reefs B and E.

## SAMPLING AND ASSAY RESULTS

Samples collected from M.C.38 were analysed by the Government Chemical Laboratories. Samples 12816 and 12814 were 20-foot chip samples taken from the exposed sections of the quartz reefs B and E. These reefs have provided most of the ores so far produced from this claim. Samples 12815 (20 feet) and 12813 (40 feet) were further chip




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# SKETCH PLAN OF QUARTZ REEFS MC 38 KUNUNURRA AREA, KIMBERLEY GOLDFIELD

BASED ON TAPE AND COMPASS SURVEY, J. SOFOULIS, OCTOBER, 1967.

Table 1

ASSAY RESULTS M.C.38 KUNUNURRA

| G.S.W.A. No. | Locality | Type of Sample | Silver Ag per long ton oz | dwt | grn | Gold Au per long ton oz | dwt | grn | Copper Cu per cent. on dry basis | Zinc Zn per cent. on dry basis | Lead Pb per cent. on dry basis | Calculated Value per long ton $Aust.* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12813 .... .... | Reef F | 40 ft. chip | 7 | 14 | 22 | | 2 | 5 | .37 | 1.25 | 8.87 | 40 |
| 12814 .... .... | Reef E | 20 ft. chip | 15 | 4 | 7 | 1 | 7 | 14 | .78 | .27 | 4.98 | 76 |
| 12815 .... .... | Reef D | 20 ft. chip | | 16 | 10 | | 2 | 14 | .84 | .05 | 1.03 | 15 |
| 12816 .... .... | Reef B | 20 ft. chip | 11 | 4 | 19 | | 2 | 10 | .51 | .23 | 10.40 | 48 |
| 12817 .... .... | 1st grade ore dump | Random chips | 96 | 4 | 14 | 1 | 1 | 14 | 4.04 | .76 | 34.80 | 286 |
| 12818 .... .... | 2nd grade ore dump | Random chips | 28 | 16 | 14 | 1 | 2 | 0 | 1.75 | .74 | 11.70 | 112 |
| 12819 .... .... | Margin of Reef F | Grab sample | 1 | 4 | 19 | | | 6 | .18 | .11 | 5.93 | 16 |

* Values approx., based on B.M.R. Metal and Mineral Prices as at 3/10/67 : Ag 154.4c/troy oz., Au $31.25/troy oz., Cu $1,000/ton, Zn $256/ton, Pb $210/ton. Assays : Government Chemical Laboratories, Perth.

samples taken across the width of the poorly mineralised sections of bodies D and F. The positions of all samples are shown in Plate 27.

Samples 12817 and 12818 were chip samples taken from the two hand-sorted stockpiles classified by the claim holder as first and second grade ores. Some yellow, ochreous, kaolinitic material (Sample 12819), locally showing relic ophitic fabric and believed to be decomposed Hart Dolerite, was included in the sampling as some of it was considered to be the yellow ochreous material (bindheimite) normally associated with oxidised lead ores. A geiger counter was used to test the yellow powdery material, the ore dumps, and mineralised portions of quartz reefs, but no significant radioactivity was detected.

Assay results are listed in Table 1.

Based on these assay results, hand-sorted ores from mineralised zones of reefs E and B, and stockpiled as first and second grade, have a mineral content equivalent to a calculated value of $285 and $112 per ton respectively. If a deduction of $30 to $50 per ton is allowed for production, handling, freight, and treatment costs, similar hand-sorted ores from reefs E and B would furnish a profit provided that equivalent grades could be maintained.

Sampled ore bodies D and F cannot be regarded as economic on the quoted assay values, because the disseminated nature of the contained mineralisation does not lend itself to concentration by hand-sorting methods. However it is considered that much of these low-grade ores could be beneficiated mechanically and upgraded by crushing, screening, and gravity concentration to yield a saleable product.

Some of the other untested reefs of this claim, and possibly some of the sheared dolerite marginal to the reefs, may contain sufficient disseminated mineralisation for beneficiable ore.

## OTHER PROSPECTS

Recent publicity given to M.C.38 has been mainly responsible for a number of claims being taken up on adjoining dolerite ground. Some of these locally contain small quartz reefs (up to 60 feet long and 15 feet wide) which have lead and copper showings similar to the reefs of M.C.38. However, because of the patchy distribution of mineralisation and limited size of reefs, none of the occurrences are considered to be economic, although small amounts of payable concentrates could be extracted as a part-time venture.

Blatchford (1927) reported on a quartz vein (associated with a granophyric phase of the Hart Dolerite) which contained silver-lead-copper mineralisation in the Speewah locality of the adjacent Lissadell 1:250,000 Sheet area. Preliminary investigations into the concentration and treatment of this ore were conducted by Moore (1927). However the prospect (known as Martin's, or Durack and Martin's Silver-Lead Prospect) was too small to be of economic significance, and the temporary reserve (T.R.457H) was allowed to lapse.

Further galena mineralisation (with associated fluorite) was reported from 5 miles north-northwest of the old Speewah homestead and from other areas in the East Kimberley. According to Dunnett and Plumb (1964), none of these deposits have economic potential.

Massive barite and a little copper mineralisation are found 6 miles west of M.C.38, in a vertical fault zone of quartz-breccia cutting Antrim Plateau Volcanics, 0.2 of a mile east of the 46-mile post (Wyndham-Kununurra road). This fault zone is up to 5 feet wide and is traceable northwesterly from the road for approximately half a mile.

Although the occurrence is not economic the common association of barite with silver-lead-zinc deposits suggests that the major faults shown on the Cambridge Gulf and Lissadell geological sheets could be worthy of more intensive prospecting.

## CONCLUSIONS AND RECOMMENDATIONS

Silver-lead-gold-copper mineralisation of M.C.38 is associated with lenticular quartz reefs intruding fractures within Hart Dolerite. Development on the mineralised quartz reefs is as yet insufficient to allow any accurate estimation of the amount and grade of ore available.

Surface indications, and small cuts and openings already made, suggest that although the quartz reefs are well defined, they are discontinuous in plan (and probably in depth) and that their contained mineralisation is patchy and irregular.

Low-grade mineralisation may be distributed over a large proportion of the quartz reefs and it is likely that some reef sections could contain concentrations suitable for selective mining.

High-grade ore is indicated from assays of the hand-sorted ore dumps derived from ore bodies E and B, and a high assay was obtained from the wall zone of ore body E. Although rich patches are present, there does not appear to be any defined zone capable of yielding a large quantity of direct shipping ore.

Concentration by hand-sorting or mechanical processes would therefore be necessary to maintain grades comparable with those already produced. The lower grade reefs with disseminated mineralisation are not amenable to hand-sorting and would require mechanical benefication to produce a saleable product.

The principal ore metal is expected to be lead (from galena) with variable gold and silver content and small amounts of copper and zinc.

A drilling programme would be required to delimit the mineralised sections of the quartz reefs or to prove high-grade zones suitable for selective mining.

The prospect could prove to be a profitable concern for a small syndicate operation but the limited size of reefs and patchy distribution of ore would not be suitable for company scale operations.

Suggested development would be to trench across the width of the mineralised sections to get an appreciation of grade and potential of these sections, as well as to provide workable faces for future open cut or selective mining operations.

The sale of ore to visitors and tourists is a profitable sideline which could develop with increased activity associated with the construction of the Ord River dam.

Silver-lead and associated mineralisation similar to that of M.C.38 has been recorded from several other localities in the East Kimberley region. Although none of the deposits are economic, they indicate the widespread occurrence of silver-lead-gold-copper-zinc mineralisation, and a possibility of finding a large deposit. Areas recommended for further prospecting are the major faults or shears cutting basic rock formations such as Hart Dolerite, Carson Volcanics, and Antrim Plateau Volcanics. These major faults and shears are shown on the available geological maps of the region.

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# STRATIGRAPHY OF THE DALES GORGE MEMBER OF THE BROCKMAN IRON FORMATION, IN THE PRECAMBRIAN HAMERSLEY GROUP OF WESTERN AUSTRALIA

by A. F. Trendall and J. G. Blockley

ABSTRACT

A composite type section 466.25 feet thick is selected for the basal Dales Gorge Member of the Brockman Iron Formation, in the Precambrian (about 2,000 m.y. old) Hamersley Group of Western Australia. The type section consists of diamond drill core from three holes and is illustrated completely by continuous strip photographs at a scale of one fifth. The member is divided into 33 numbered macrobands: macrobands BIF0 to BIF16 are made up of cherty iron formation banded (into mesobands) on a scale of inches; they alternate with macrobands S1 to S16, which are generally thinner and consist of shale, chert, and siderite. Within its outcrop area of about 20,000 square miles the macrobands are easily distinguishable in the field, and some criteria to assist recognition are given. Additional photographs show that mesoband correlation is simple where diamond drill core is available; the greatest distance between drill-holes is 51 miles. In natural exposures mesoband correlations have been made over 185 miles using the photographic type section, and quality of exposure rather than stratigraphic discontinuity is thought to be the limiting factor. The publication of such a detailed type section is justified only by the unusual lateral continuity of lithostratigraphic detail. Previously published work on the Dales Gorge Member is related to the type section, and it is suggested that all future work should specify stratigraphic position by reference to the equivalent position on the type section in feet above the base. Most of the type section will be permanently stored by the Geological Survey of Western Australia; some, included in the core of an additional section (analogous to a paratype in biological taxonomy) will be housed in the United States National Museum, Washington. Blue asbestos has been mined from the Dales Gorge Member, and it is the host for all of the larger iron ore bodies of the Hamersley Range area, including Mt. Tom Price and Mt. Whaleback, together containing over 1,000,000,000 tons of high-grade hematite.

INTRODUCTION

Between 1961 and 1966 extensive diamond drilling was carried out in the lower part, now called the Dales Gorge Member, of the Brockman Iron Formation, by the Australian Blue Asbestos Co. under subsidy from the Western Australian Government. The drilling formed part of a crocidolite exploration programme and comprised 60 holes in the Wittenoom Gorge area (lat. 22° 10′ S, long. 118° 20′ E.), 10 holes at Yampire Gorge, about 15 miles to the east-southeast, and 2 holes at Junction Gorge, about 35 miles farther in the same direction. Between 1964 and 1967 the Geological Survey of Western Australia pursued a special study of the geology of crocidolite in the Hamersley Range area, and core from the drilling contributed valuable evidence. The progress of the study has been reported by Trendall (1965; 1966a), by Ryan and Blockley (1965), and by Blockley (1967); a final report is in preparation (Trendall and Blockley, in preparation). This present paper is concerned solely with the stratigraphy of the Dale Gorge Members; its purposes are:

(1) to define the Dales Gorge Member in accordance with the requirements of the Australian Code of Stratigraphic Nomenclature (Geological Society of Australia, 1964),

(2) to provide a continuous photographic record of the core designated as the type section. This is intended to act as a display of the lithology of the member, a means of precise but simple specification of stratigraphic position within it, and as a means of stratigraphic location either in core or in field exposure,

(3) to record the positions, within the member, of selected features which are identifiable on the ground, or of which descriptions have already been published.

It is specifically *not* our purpose to provide here a full description of the lithology, petrography, chemistry, or diagenetic development of the Dales Gorge Member. Nor do we discuss its general geological significance; an account of the general geology of the Hamersley Range area has been given by MacLeod (1966) and a recent summary has also been provided by Trendall (1968).

## PREVIOUS DEFINITIONS

The Brockman Iron Formation of the Hamersley Group was formally defined by MacLeod and others (1963, p. 48-9), with a type locality at Mt. Brockman (lat. 22° 28′ S, long. 117° 18′ E), and a measured thickness of about 2,200 feet some 30 miles to the south-southwest. Ryan and Blockley (1965) later divided the formation into five members. They named the lowest of these the Dales Gorge Member, with a type section in Wittenoom Gorge.

Although Ryan and Blockley's establishment of the Dales Gorge Member was not made in a type of publication acceptable for formal definition by the Australian Code of Stratigraphic Nomenclature the name has already appeared in acceptable publications (Trendall, 1966a; 1966b) and in other restricted but publicly available forms (Daniels, 1967). Nevertheless, for our present purposes the Dales Gorge Member is accepted as a currently informal name and is here formally defined as would be required for an original appearance (Geological Society of Australia, 1964, paragraphs 19, 21, 22, and 28); the definition below supersedes all others, and accurately defines the base of the Brockman Iron Formation.

## PRESENT DEFINITION

The Dales Gorge Member is defined as the basal member of the Brockman Iron Formation (MacLeod and others, 1963). It usually forms about a quarter of the full thickness. It consists of magnetite-bearing, cherty banded iron formation, iron-rich shales including tuffaceous stilpnomelane varieties, and banded chert-siderite rocks. Massive riebeckite and crocidolite occur locally.

## TYPE SECTION

The composite type section of the Dales Gorge Member is here selected as the core between 856.95 and 1,298.6 feet drilling depths in Hole 47A (lat. 22° 20′ S, long. 118° 14′ E) of the Australian Blue Asbestos Co.'s drilling at Wittenoom Gorge, continuing down from 303.5 to 328.75 feet in Hole Y1 (lat. 22° 25′ S, long. 118° 27′ E) at Yampire Gorge; except that the parts of Hole 47A between 1,052.9 and 1,063.0 feet (mainly the S11 macroband, 269.5 to 259.85 feet from the base of the type section) and 1,227.65 to 1,230.25 feet (within BIF3 macroband, 94.9 to 92.4 feet from the base of the type section) are replaced by 375.6 to 385.25 feet and 540.8 to 543.3 feet respectively of the core of Hole EC10 (lat. 22° 20′ S, long. 118° 20′ E).

The core forming this type section is completely illustrated at an approximate scale of one fifth by Plates 28 to 36 of this paper, with footages marked upwards from the designated base. Although comparative photographs are included of representative core lengths from the two overlying members of the Brockman Iron Formation informally defined by Ryan and Blockley (1965), successively the Whaleback Shale Member and the Joffre (formerly Mindy Mindy) Member, these are not formally defined here.

## RECOMMENDED SPECIFICATION OF STRATIGRAPHIC POSITION

We have reluctantly used the foot rather than the metre as our basic length unit since all previously published literature on Hamersley Range area stratigraphy has done so, as well as all drilling logs and records. However, a division of feet into tenths rather than inches is not only neater (Figure 11), but is easier to accommodate to the scale variation of the photographs. We therefore suggest that in future work stratigraphic position within the Dales Gorge Member be specified by reference to correlative position on the photographic type section here provided, and that this in turn be specified by its distance above the base in feet and tenths. An accuracy of a twentieth of a foot may be necessary at times, but no finer subdivision is normally needed. Examples appear throughout this paper. It should be noted that a 5 in the second decimal place does not imply a greater accuracy than one twentieth of a foot.

## DERIVATION OF NAME

The member is named from Dales Gorge (lat. 22° 28′ to 29′ S, long. 118° 33′ to 35′ E) where clean exposures of the lower part of the member in the floor and sides of the gorge form possibly the finest natural exposures of Precambrian banded iron formation in existence.

## LITHOLOGY AND SUBDIVISION

Ryan and Blockley (1965) based their subdivision of the member on the analysis by Trendall (1965) of company drilling records. He (p. 56) defined three scales on which the iron formation could be described as banded:

Coarse *macrobanding:* alternations, on a scale of feet, between two constrasted lithologies, banded iron formation and "shale". The term "shale" was used as an abbreviation of "shale with subordinate cherts and carbonate", and it was later emphasized (Trendall, 1966b), p. 1453) that the term was a provisional one. In the field such macrobands are normally intensely weathered and on hillsides are marked by grassy talus slopes between cliffs of resistant banded iron formation (Plate 37D).

Medium-scale *mesobanding:* the conspicuous striped succession of chert, magnetite, and other types, with an average thickness of less than an inch, within the banded iron formation macrobands, clearly displayed on Plates 28 to 36.

Small-scale *microbanding:* an alternation, within chert mesobands only, of regularly repetitive laminae of even thickness (usually in the range 0.5 to 2.0 mm) defined by a greater or lesser content of some iron-rich mineral within the chert. Microbands are not distinguishable at the scale of this type section.

It is not our present purpose to describe in greater detail the lithology or petrography of any of the constituents of these three scales of banding.

Trendall (1965, Plate 32) represented 31 macrobands in the lower part of the Brockman Iron Formation: 16 "shale" macrobands, consecutively numbered upwards, separated by 15 similarly numbered banded iron formation macrobands, such that banded iron formation 1 overlay "shale" 1, and so on. In our present definition of the Dales Gorge Member we follow Ryan and Blockley (1965) in accepting and extending this macroband subdivision, by adding banded iron formation 0 as a basal macroband below Trendall's "shale" 1, and by adding banded iron formation 16 as a topmost macroband above Trendall's "shale" 16. The positions of these 33 macrobands in the type section of Plates 28 to 36 are marked on the Plates and are summarised in Figure 11.

Accurate macroband boundaries must be arbitrary, and we have chosen to accept the appearance and disappearance of magnetite as marking the lower and upper limits of BIF macrobands. These limits are not always those that would be closen by a field geologist working on weathered exposures and using mainly broad textural and compositional differences between macroband types.

We find that terms of the form "S13 macroband" and "BIF2 macroband", usually abbreviated to "S13" and "BIF2", are convenient designations of the macrobands, and we therefore propose to abandon the unsatisfactory term "shale".



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## LIMITS AND STRATIGRAPHIC RELATIONSHIPS

The lower and upper boundaries of the Dales Gorge Member are marked clearly on Plate 28 (0 feet) and Plate 36 (466.25 feet) respectively. The member overlies the Mt. McRae Shale with perfect conformity. Cherty iron formation occurs in the upper part of this shale, and to this extent the boundary is arbitrary, but it has been selected at the base of a thick banded iron formation macroband at a point approximating to where a field geologist would map the junction of the Mt. McRae Shale and the Brockman Iron Formation following MacLeod and others (1963) and using gross topographic expression as a guide. This is well shown by Plate 37C. The Whaleback Shale Member (Ryan and Blockley, 1965, informal name) overlies the Dales Gorge Member with perfect conformity. The Whaleback Shale Member has chert in its lower part, but the top of the Dales Gorge Member is similarly selected at an accurately determinable level approximating to a common major topographic expression of stratigraphy.

## DISTRIBUTION AND THICKNESS

Since the type section is composite its thickness of 466.25 feet represents the true thickness of the member at no specified locality. Trendall (1965) studied thickness variations of 31 macrobands with a mean total thickness of 366.4 feet, in selected boreholes in the Wittenoom area, and also gave details of the effect of stratigraphic sample size in assessing thickness variation. Ryan and Blockley (1965, Table 2) reported a mean thickness of 452.2 feet for all 33 macrobands representing measurements over the whole outcrop area. The thickest section so far measured is one of 607 feet at Mt. Brockman (lat. 22° 28′ S, long. 117° 18′ E) and the thinnest one of 280 feet at Seven Mile Creek (lat. 23° 13′ S, long. 117° 33′ E). The average regional thickness variation of the Dales Gorge Member is of the order of 7 feet per mile, but random local variation of the same order is superimposed on the regional pattern.

A smoothly curved line encircling the present outcrop of the Brockman Iron Formation and extending no more than 10 miles outside it, encloses an area of about 20,000 square miles, with a maximum extent in latitude of 20° 53′ to 23° 30′ South and in longitude 116° 03′ to 120° 30′ East. This is the minimum depositional area of the Dales Gorge Member. A similar smooth curve encircling the outcrop of the basal Marra Mamba Iron Formation of the Hamersley Group encloses 33,000 square miles, and the formation-scale continuity of the Hamersley Group makes it more reasonable to accept this as a closer approach to the original Dales Gorge Member depositional area. However, the Marra Mamba Iron Formation has a crudely crescentic outcrop, and if the depositional area is assumed to have extended between the horns of the crescent an area close to 50,000 square miles must be accepted.

## LATERAL STRATIGRAPHIC CONTINUITY

MacLeod and others (1963) drew attention to the remarkable lateral persistence of all formations of the Hamersley Group. All 33 macrobands of the Dales Gorge Member are, given adequate exposure (Plate 37 D), easily distinguishable in the field over almost the entire outcrop area. Within BIF macrobands the ease with which individual mesobands (mainly cherts) can be correlated depends partly on the quality of material available and partly on the character of the mesoband sequence in the restricted thickness chosen for the attempt. In Plate 37, A to C, selected lengths of the type section are reproduced next to equivalent lengths of core from other holes in the Wittenoom Gorge area and also from two holes at Junction Gorge, 51 miles east-southeast of Hole 47A, the main contributor to the type section. It will be appreciated from these photographs firstly that we accept subjective lithological mesoband correlation, and secondly that the standard of correlation between bore-holes 51 miles apart is not sensibly inferior to that between boreholes 6 miles or less apart.

When core is not available, field mesoband identification can be achieved using the photographed type section and working outwards from the more easily identified macroband boundaries. A high standard of exposure is essential, together with some experience of the effects of surface processes on lithology. We have compared in detail the natural exposures of the upper part of BIF0 (roughly 33 to 44 feet on the type section) at Dales Gorge, at Woongarra Gorge (lat. 22° 52′ 30″ S, long. 117° 07′ 30″ E; 92 miles west-southwest of Dales Gorge), and on the foreshore at James Point (lat. 20° 58′ S, long. 116° 10′ E; about 185 miles northwest of Dales Gorge and 145 miles north-northwest of Woongarra Gorge). Some cherts or closely associated chert groups in this section are sufficiently distinctive for confident identification. Three examples are: the thick chert with a thin central magnetite parting at 36.3 to 36.8 feet, the group of three thin cherts at 39.9 to 40.0 feet, and the grey (on the photograph) chert group at 42.9 to 43.2 feet. By using such distinctive cherts as markers, and by measuring systematically between them, other cherts on the type section, which lack any identifying characteristic, can be correlated with equal confidence. However, where there are groups of poddy cherts, as at 40.3 to 40.6 feet, individual chert correlation is not possible.

In summary, we believe that mesoband correlation over the entire outcrop area of the Dales Gorge Member falls little below the standard which the examples of Plate 37, A to C demonstrate to exist over a distance of 51 miles. The publication of a photographic type section on the scale of that presented here is justified only by the spectacular continuity of the detailed lithostratigraphy of the Dales Gorge Member: potentially some 10,000 knife-sharp lithological boundaries are correlatable in all parts of the 20,000 square mile area.

## AGE

The age of the Woongarra Volcanics, a higher formation of the Hamersley Group, was given by Leggo and others (1965) as about 2,100 m.y. The base of these lavas lies some 3,000 feet (excluding sills) above the top of the Dales Gorge Member. Later detailed work by P. A. Arriens has revised the earlier age to a date very close to 2,000 m.y. (personal communication). If Trendall's (1965, p. 64)) estimate of 2,000 years per foot of iron formation is accepted, and if there is a negligible time gap between the Woongarra Volcanics and the sediments on which they rest, then the Dales Gorge Member was deposited in the interval between 7 and 6 m.y. prior to this age.

## SOME CRITERIA FOR FIELD RECOGNITION

Where it is exposed with the clarity and completeness illustrated in Plate 37D, it is easy from Figure 11 to relate macrobands BIF0 to BIF16 to the exposed cliffs, while the intervening S1 to S16 macrobands can be similarly counted upwards, with their thicknesses proportional to the heights of the grassy slopes. During field work over several years it has become possible to identify many macrobands by some individual peculiarity other than simple thickness where the Dales Gorge Member is poorly or partially exposed. Although it is not possible to list all such characters, a few of which received informal field names, their great importance in the field makes it useful to record some of the more striking ones.

### *The "bed of holes"*

Below the base of BIF0 the black shale visible in Plate 28 is about 2.5 feet thick. It is underlain by about 3 feet of cherty iron formation, 1 foot of shale and then by the upper part of a thicker band of iron-poor banded chert. Roughly central in the 3-foot thick band of cherty iron formation, and over a thickness of about 6 inches, carbonate nodules weather out to give ovoid holes about ½-inch long and 1 to 3 inches apart, elongate along the bedding. This "bed of holes" is an extremely reliable regional indicator of the base of BIF0, which lies about 4 feet above it.

*Maculate bands*

Of the four maculate bands in BIF1, MB1 to MB4, defined and described by Trendall (1966a) MB1 fortuitously appears clearly on the type section at about 48.4 to 49.1 feet (Plate 28). MB1 is persistently maculate and a useful regional confirmatory criterion of S1 just beneath it. It is recognisable at Woongarra Gorge, although immaculate at James Point.

*The "adit-roof riebeckite"*

The Yampire Gorge crocidolite mine (lat. 22° 23′ 15″ S, long. 118° 27′ 30″ E) of West Australian Blue Asbestos Fibres Ltd. was abandoned in 1946. Several adits at this easily accessible locality are cut into the lower part of BIF2 and are roofed by a conspicuous mesoband of tough massive blue riebeckite about 0.5 feet thick, the "adit-roof riebeckite", which appears at 77.5 to 77.95 feet on Plate 29. It is variously represented by a massive riebeckite or by a flat-modified chert (Trendall, 1965) in the Hamersley Range area.

*The "three-chert shale" (S3)*

The S3 macroband characteristically has three central chert mesobands (Plate 29, 86.0 to 86.85 feet). These are a reliable field indicator of S3 throughout the Dales Gorge Member outcrop area; before the numerical macroband nomenclature was used it was referred to informally as the "three-chert" shale".

*The S4 breccia*

Although it appears only inconspicuously on the type section, between 110.35 and 112.3 feet (Plate 30), the central part of S4 in the Wittenoom-Yampire-Dales Gorge area consists of a coarse breccia 1 to 2 feet thick, graded upwards. The angular fragments are of chert and shale and some reach a length of several feet. S7 and S16 are also locally brecciated, but to a lesser degree. The limits of the area of brecciation in S4 are not precisely known. The early name Calamina Member for S4 is now abandoned.

*The Yampire Riebeckite Zone*

BIF0 to BIF5, the lowermost six macrobands of banded iron formation, locally have abundant mesobands of massive riebeckite, and together constitute the Yampire Riebeckite Zone. Riebeckite is particularly abundant in BIF1 to BIF3 in the central part of the Hamersley Range.

*The Junction Gorge Riebeckite Zone*

This zone comprises BIF12 to BIF16, and is again locally characterised by abundant massive riebeckite mesobands.

*The Calamina cyclothem*

In some macrobands (notably BIF12 at roughly 295 to 301 feet, BIF15 at about 382 to 390 feet, and BIF16 at roughly 429 to 435 and 444 to 452 feet) there is a strongly cyclic sequence in which thick cherts are separated by thin magnetite-rich bands, with about 2 cycles to the foot. It forms a useful field criterion of recognition, as it is emphasized by weathering. It is proposed to call this cyclothem the Calamina cyclothem (Trendall and Blockley, in preparation).

*The central parting of BIF16*

BIF16 often lies at the top of cliffs, below a recessive smooth slope of the Whaleback Shale Member. Its identity can easily be checked by the presence of a thin, roughly central parting, which does not normally cause any break of slope in the vertical (joint-face) cliff. It is caused by a stilpnomelane-rich mesoband which appears at 439.9 to 440.1 on the type section (Plate 35).

## RELATIONSHIP OF PUBLISHED WORK TO TYPE SECTION

Since the nomenclature set out here is a modification of the earlier scheme of Ryan and Blockley (1965), itself a modification of that of Trendall (1965), there is no difficulty in relating the new type section to these publications. The various nomenclatures of Finucane (1939, 1964) and of the Australian Blue Asbestos Co. are related by the later report of Trendall (1966a, Plate 34). The descriptions of parts of the Dales Gorge Member by LaBerge (1966) were separately related to the present scheme by Trendall (1966b); the illustrations of S13 in that discussion (Figures 1 and 3) can be followed clearly on our present type section (320 to 328 feet), the idea of which was then referred to (Trendall, 1966b, p. 1454). The chert from which spherical bodies were photographed for publication by LaBerge (1967, p. 336 and Plate 3) must be in BIF13 close to 348.8 feet, but closer identification is not possible.

Although MacLeod and others (1963) did not subdivide the Brockman Iron Formation, MacLeod (1966, p. 73) later referred to the special significance of the lower 500 feet of the formation for hematite mineralisation, and (ibid., p. 105) referred to the shale above this limit at the Mt. Whaleback Shale Member. We propose to designate this member the Whaleback Shale Member in a future publication (Trendall and Blockley, in preparation). MacLeod was clearly well aware of the special status of that part of the Brockman Iron Formation below this shale, the part we now call the Dales Gorge Member, although he found it unnecessary to name it formally. The application of our type section is well illustrated by the fact that, without knowing the drillhole number of the core in MacLeod's (1966) Figure 16, we were able to identify the chert sequence in the central row of core (roughly marked 260 to 261 feet, and between 2.25 and 0.2 inches from the right hand edge of the photo) as that appearing between 318 and 319 feet on the type section, in BIF12.

It should be noted that the "Brockman Iron Formation" of Campana and others (1964, p. 6), consisting of "sixteen massive, hematite-rich layers (slightly magnetic at intervals) separated by more shaly partings and reaching an aggregate thickness of 400 feet", is the Dales Gorge Member, *not* the Brockman Iron Formation.

## REPOSITORY OF SECTIONS

*Type Section*

The photographed type section, with the exceptions of 92.4 to 94.9 feet and 259.85 to 269.5 feet is stored by the Geological Survey of Western Australia.

*Other Sections*

All the recovered core from Hole EC10 (lat. 22° 20′ S, long. 118° 20′ E.), representing 46.5 to 357 feet on the photographed type section, and comprising 301.5 feet of core, is stored by the United States National Museum, in Washington. Of this, 375.6 to 385.25 feet and 540.8 to 543.3 feet drilling depth form part of our designated type section. The stratigraphically equivalent intervals from Hole 47 (about 10 feet distant from 47A) will be stored with Hole 47A in Perth.

A large part of the core from Hole 63 (lat. 22° 19′ S, long. 118° 17′ 30″ E), representing approximately 42 to 289 feet, 344 to 361 feet and 436 to 466.25 feet on the type section, and comprising some 260 feet of core, is stored in the Department of Economic Geology of Adelaide University, South Australia; there are several shorter gaps in this core.

In addition to these two holes stored outside Western Australia, the Geological Survey of Western Australia also holds about 75 feet of core from Hole JG1, the furthest hole from Wittenoom, representing a span of about 47.5 to 120.5 feet on the type section; about 218 feet of core from JG2, equivalent to about 85.5 to 202.5 and 335 to 448 feet on the type section; and 314 feet of core from Hole 51 (lat. 22° 19′ S, long. 118° 18′ E) at Wittenoom, representing a span of 47 to 356 feet on the type section. This last hole has several broken sections, and has been extensively used for thin-sectioning and chemical analysis.

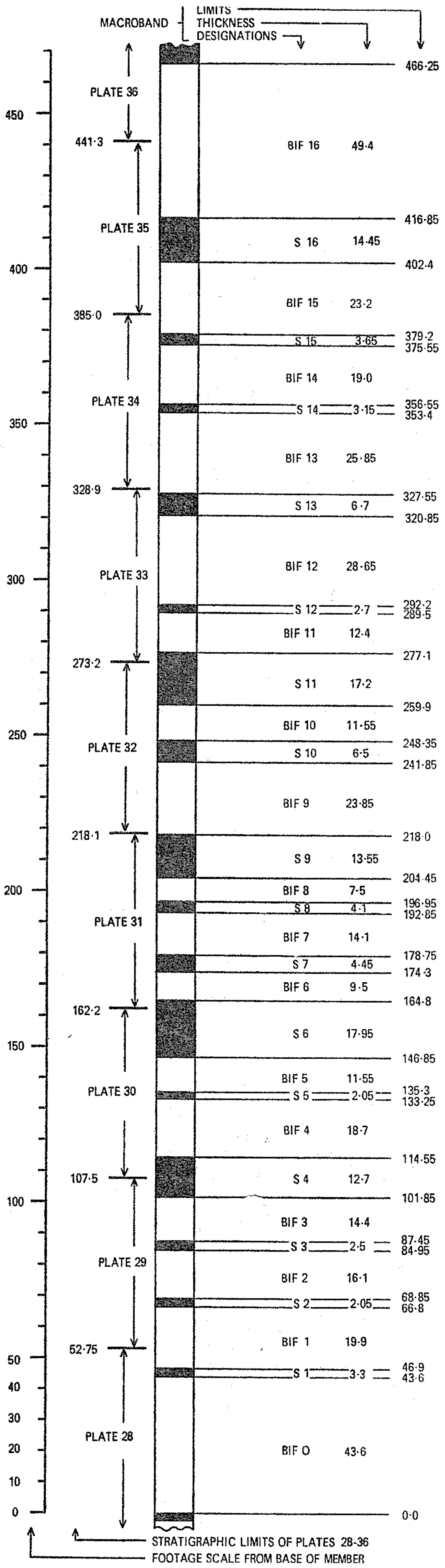


Figure 11—Summary of macrobands in the type section of the Dales Gorge Member. Black represents a mixture of shale, chert, and siderite; plain white is banded iron formation.

## CAPTIONS FOR PLATES

Note: The photographs of Plates 28 to 36 are of NX core, with a nominal diameter of $2\frac{1}{8}$ inches. To reduce parallax curvature all the core of Hole No. 47A was photographed with a 135 mm lens on 35 mm film from a point 12 feet vertically above each tray, with four frames to a tray. A 50 mm lens was used for Holes Y1 and EC10. Prints were made at a scale of one third and a slice about a tenth of an inch wide was cut from each side of the core photographs to give a final strip $\frac{1}{2}$-inch wide for mounting and reduction x3/5 for a published scale of about x1/5. White marks were painted on the core one foot apart so that slight inaccuracies in photographic processes would not matter. Thus the scale varies slightly above and below x1/5, in order to maintain the accurate relationship of the marked footages with true core length.

*Plate 28 (opposite).* The lowermost part of the type section of the Dales Gorge Member, with footages marked upwards from the base at 0 feet. This point defines both the base of the Dales Gorge Member of the Brockman Iron Formation and the top of the underlying Mt. McRae Shale. This Plate includes the BIF0, S1 and part of the BIF1 macrobands, the boundaries of which (see text) are marked. The poorer conditions of photography of the core from Hole Y1, below 24.4 feet, accounts for a change in appearance at this point. In general, paler mesobands in the BIF macrobands are chert, and darker mesobands are Q10 (Trendall, 1965) or magnetite. MB1 of Trendall (1966, p.76-78), with the drill passing close to a macule core, is conspicuous between about 48.4 and 49.1 feet.

*Plates 29-35.* The successive upward continuation of the type section of the Dales Gorge Member, with marked footages continuing from Plate 28. Refer to Figure 11 for the footage limits of each Plate and its coverage of the macrobands; macroband limits are also marked on the Plates. The main mesobands of massive riebeckite are marked by the letter R; although they have a bright blue colour in contrast with the black, dark grey, or dark green of the shales, the two rocks appear identical in these photographs.

*Plate 36.* The six left-hand columns are the uppermost part of the type section of the Dales Gorge Member, with the top (also the base of the Whaleback Shale Member) at 466.25 feet. The two central columns represent typical material from the Whaleback Shale Member, between approximately 719 feet (top of right-hand column) and 728 feet drilling depths in Hole 47A. The dark green or black shale and siderite has scattered white cherts. The close lithological resemblance between this and some macrobands of the Dales Gorge Member, for example S6, is obvious. The two right-hand columns, from approximately 544.5 (top of right-hand column) to 553 feet in the same hole, show the rather different lithology of the overlying Joffre Member. Many of the cherts are either red (hematite) or blue (riebeckite). Both the Joffre Member and Whaleback Shale Member are illustrated at the same scale as the Dales Gorge Member.

*Plate 37. A, B, C:*— In these three groups of three stratigraphically equivalent sections of the Dales Gorge Member the type section core is reproduced on the left of each group at the same scale as in the earlier Plates. The central and right-hand columns in each group are from equivalent levels of drill-holes at Eastern Creek and Junction Gorge, about 6 and 51 miles to the east-southeast respectively. Type section footages are marked on the type section itself in B and C. In B they are marked also on the right-hand column, to illustrate the recommended use of the type section to specify stratigraphic position after correlation. In A, type section footages are marked only on the right-hand column. The black lines between columns provide a correlative framework only. Careful comparison will reveal many details which can be correlated between columns; in some places there is closer resemblance across 51 miles than across 6 miles.

*D:*— Cliff exposure of the Dales Gorge Member on the northeast face of the prominent un-named hill about 2 miles north of Mt. Tom Price; photograph taken from Tom Price water supply tank, looking southwest. Macroband expression is clear between the base of the member (marked in three places by an arrow lettered B) and its top (similarly marked T in two places).


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S1
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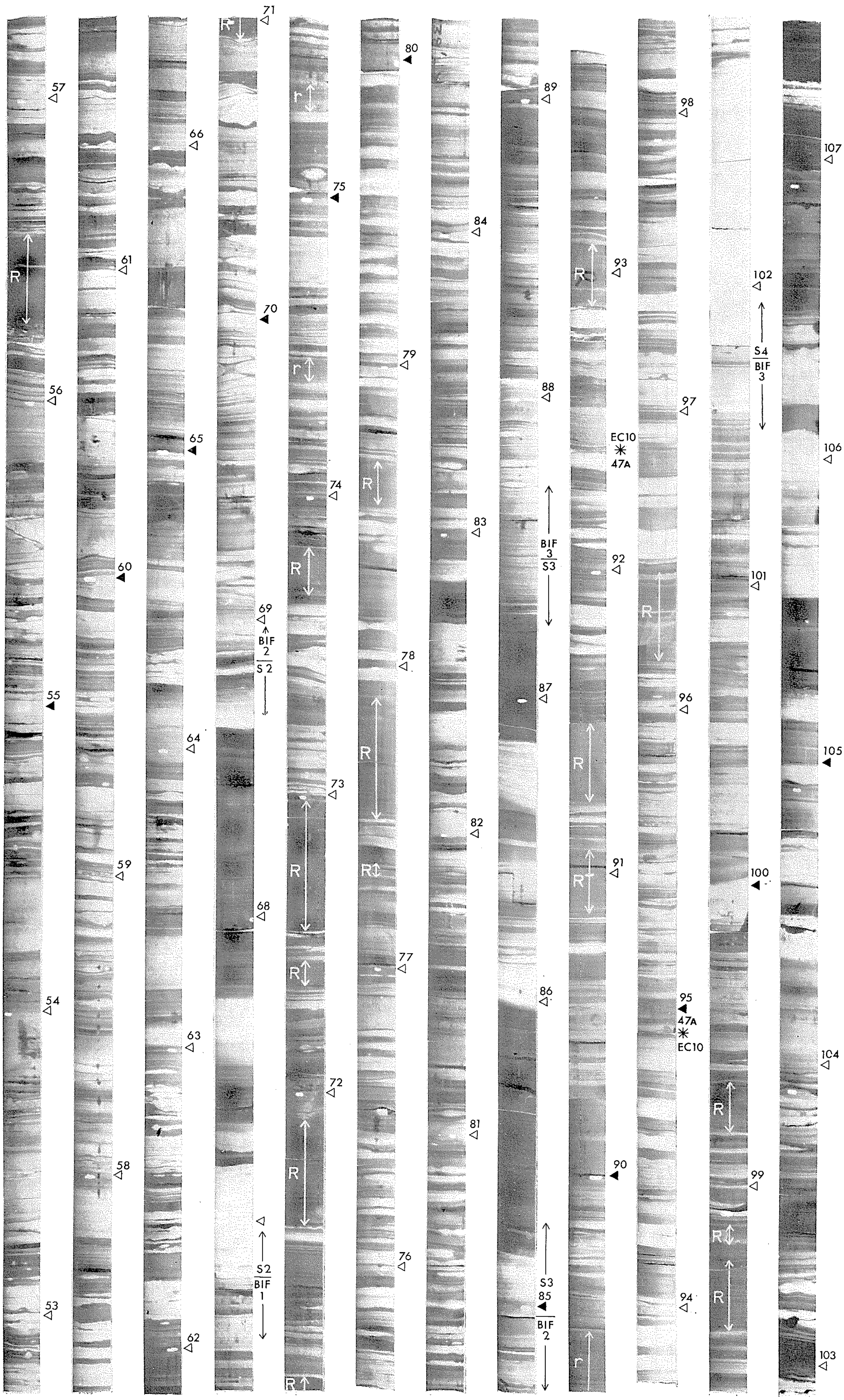
PLATE 29

52·75 — 107·5 FEET



107·5 — 162·2 FEET

PLATE 30

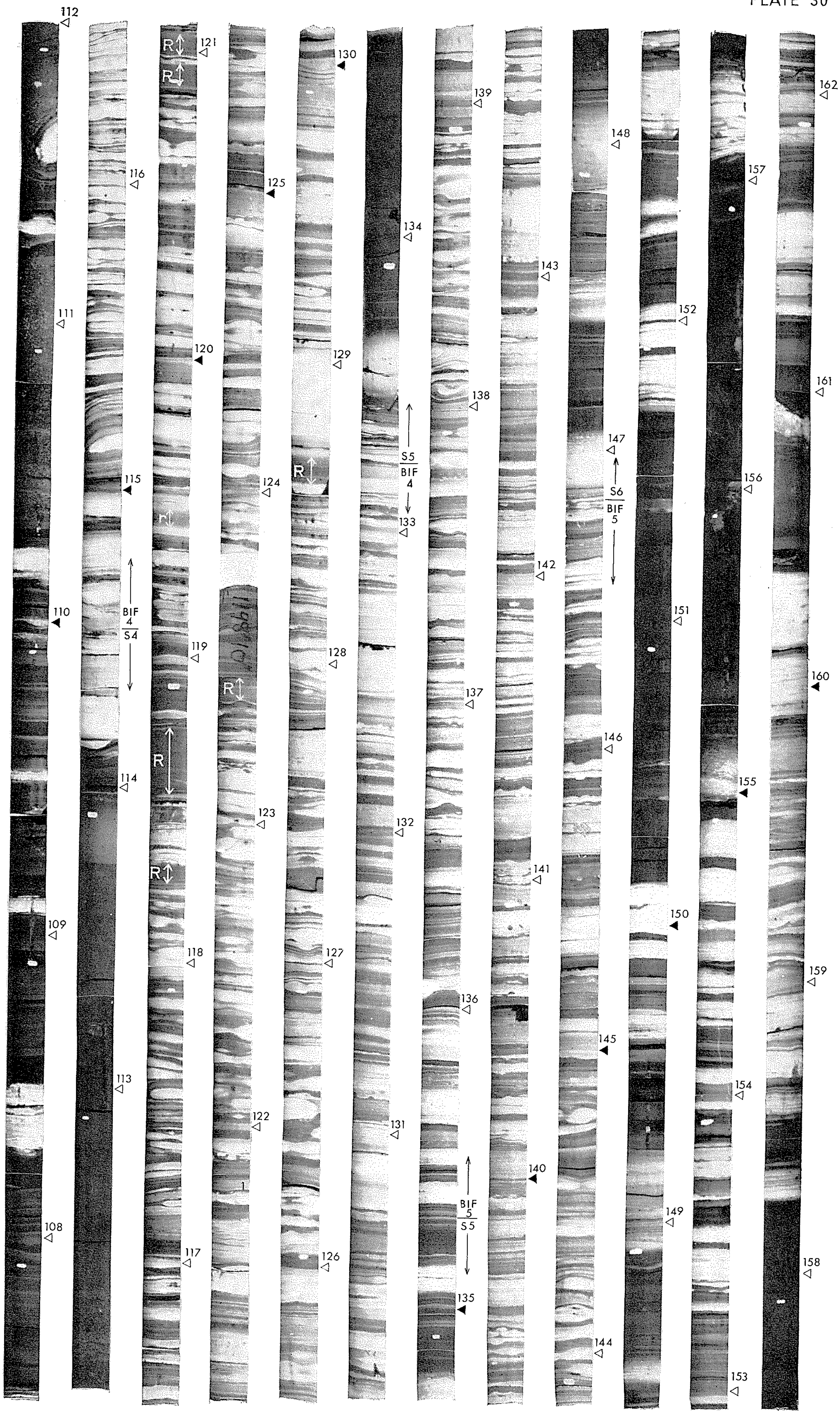


PLATE 31 162·2 — 218·1 FEET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BIF 10 / S10
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S11 / EC10 47A BIF 10
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47A EC10
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BIF 11 / S11
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S12 / BIF 11
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BIF 12 / S12
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BIF 13 / S13
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BIF 14 / S14
S14 / BIF 13
S15 / BIF 14
BIF 15 / S15
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BIF 16
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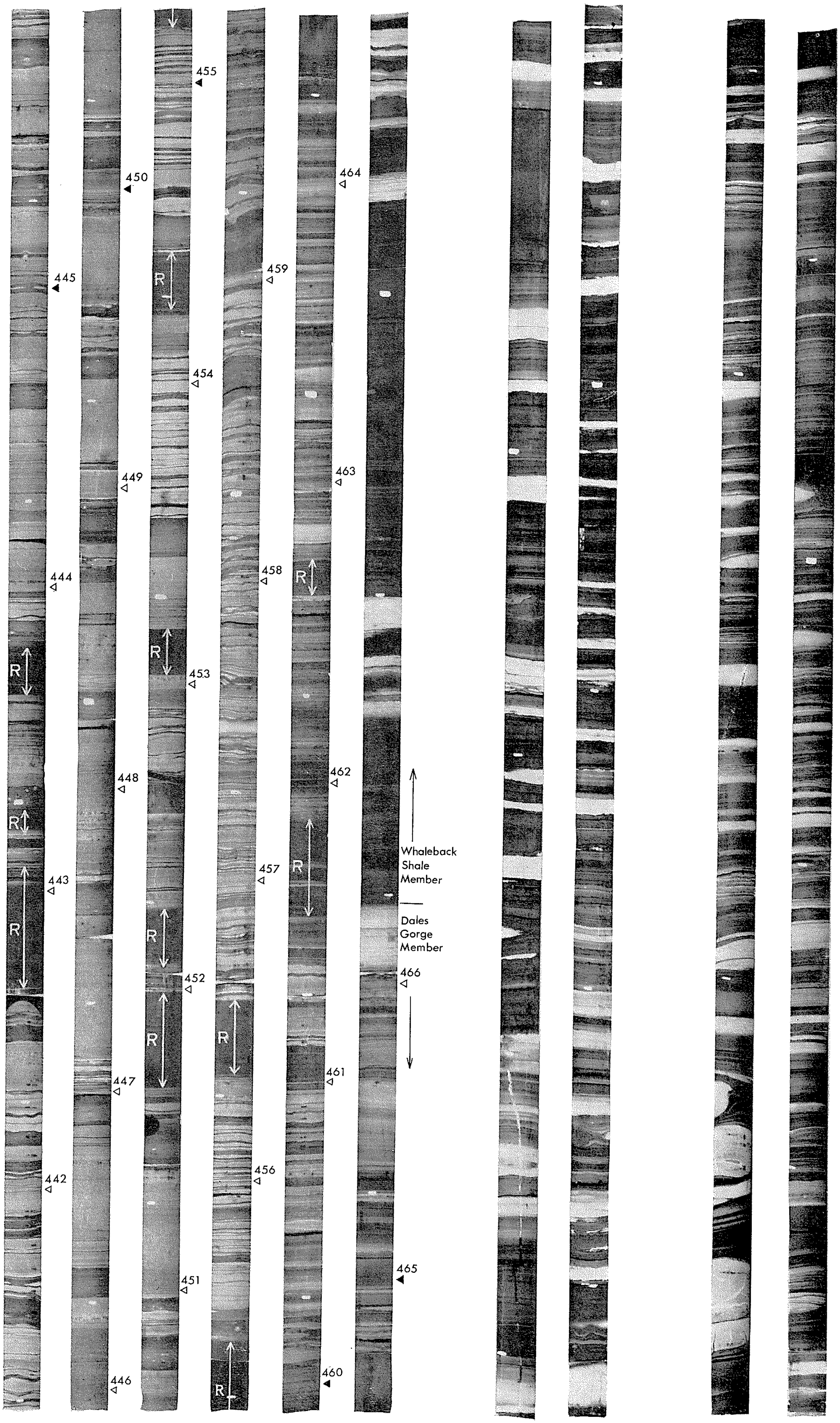
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Whaleback
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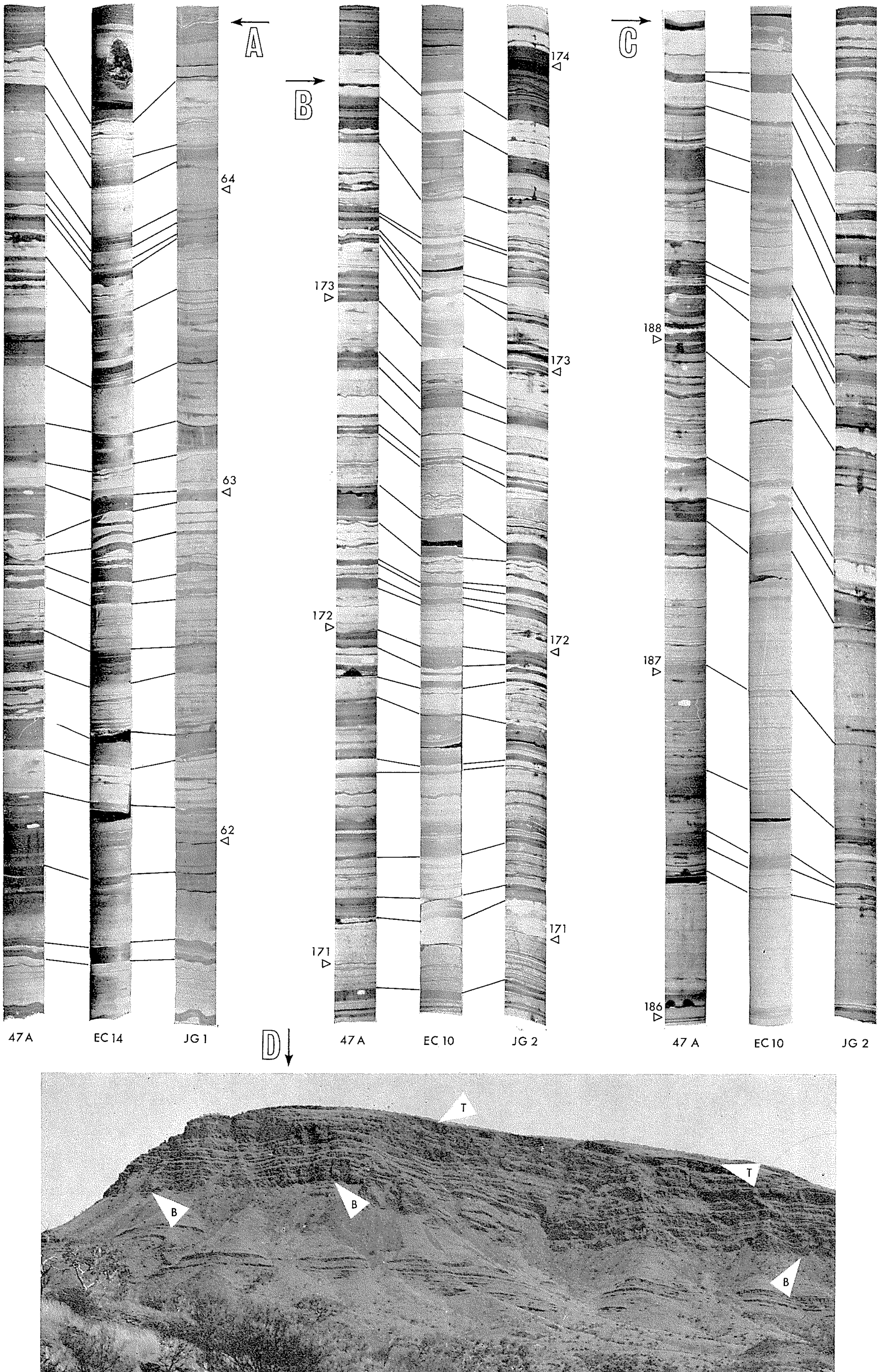
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EC 14
JG 1
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EC 10
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JG 2
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## ECONOMIC GEOLOGY

*Crocidolite*

The Dales Gorge Member locally contains blue asbestos deposits which are in part stratigraphically controlled. Although a full account of these is in preparation (Trendall and Blockley, in preparation) it is appropriate to note here the positions of the lower and upper mined seams at Wittenoom Gorge (Trendall, 1966b, Plate 34) at 49 to 50.5 feet and 69 to 70.5 feet.

*Iron ore*

The Dales Gorge Member is the host for the major hematite-geothite ore bodies of the Hamersley Iron Province (MacLeod, 1966, p. 73), including those of Mt. Tom Price and Mt. Whaleback, with a combined tonnage well in excess of one thousand million tons of high-grade ore. At Mt. Tom Price the macrobands can clearly be traced through the ore, and the ghost stratigraphy of the Dales Gorge Member here is of potential use both in structural mapping of the ore and in grade control in mining, as well as in allowing an accurate assessment of total volume change during the conversion of iron formation to hematite ore.

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# DIAMOND DRILLING AT THE THADUNA COPPER MINE, PEAK HILL GOLDFIELD, WESTERN AUSTRALIA

**by J. G. Blockley**

## ABSTRACT

At Thaduna, a copper lode about 2,000 feet long and 10 feet wide has been mined within a fault zone cutting Middle Proterozoic greywacke and siltstone. Ore shoots within the fault are controlled by split-shear structures developed on S-bends along the fault. Most of the mining has been confined to the oxidised part of the lode and several diamond drilling programmes have been aimed at testing the underlying sulphides. This drilling has shown that supergene sulphides averaging about 3.5% copper exist to depths ranging from 400 feet in the central part of the lode to 150 feet near the ends, but that the primary sulphide zone below this averages less than 1% copper and nowhere contains more than 2% copper. It is concluded that supergene enrichment is not taking place in the alkaline conditions of the present arid climate, but probably dates back to a more pluvial period in the Tertiary.

## INTRODUCTION

Between November 1966 and June 1967, the British Metal Corporation Pty. Ltd. drilled 10 diamond drillholes totalling 3,148 feet at the Thaduna copper mine. This drilling was subsidised on a dollar for dollar basis by the Mines Department, and the Geological Survey was asked to provide geological guidance for the work. Initially, assistance was given on the siting of the drillholes and examining sections of drill core sent to Perth. Later, British Metal Corporation requested a geological appraisal of the drilling programme with calculations of ore reserves. To collect sufficient information for this, several days were spent at Thaduna with B.M.C. staff, sampling and surveying the open cuts, and logging the remaining drill cores.

Before the present work the Thaduna lode had been tested by three other drilling programmes, between 1953 and 1964. The results of these were made available by the British Metal Corporation and used in the overall assessment of the lode's potential.

The objects of this report are to describe the geology and ore controls of the Thaduna mine, and to record for future reference the locations and results of all drillholes put down to test the lode. Calculations of ore reserves and core logs of the holes cannot be published at present, but are available to anyone entitled to the information.

## ACCESS AND FACILITIES

The Thaduna copper mine is situated at latitude 25° 30′ S, longitude 119° 43′ E. It is 130 miles by road from Meekatharra, the nearest rail head, and 35 miles east of the Great Northern Highway. Two graded gravel roads from the mine join the highway 90 miles and 106 miles respectively from Meekatharra. There is also a road connection to Wiluna, 90 miles to the southeast.

There are no postal services at the Thaduna mine, communication being by way of the Royal Flying Doctor Service radio network. Mail has to be collected from Meekatharra.

The Thaduna Copper Mines N.L. company has constructed a serviceable airstrip 3 miles southeast of the mine. The strip can take aircraft to the size of a D.C.3, but cannot be used after heavy rain.

Water for domestic and mining purposes is obtained from surface catchments and an underground bore situated in a creek bed. The surface water dries up during periods of drought and the mine then relies entirely on the bore which produces about 600 gallons per hour of rather brackish water.

Useful timber is scarce in the vicinity of the mine. Because of this, and the prevalence of termites, most construction is done in steel.

## HISTORY OF MINING AND DRILLING

The Thaduna copper lode was originally found by prospectors looking for gold. It was first reported in 1942 and worked in a small way by Mr. E. A. Wright as the Nabberu copper mine. Later, E. A. Walsh worked the deposit until 1953.

In 1952, Anglo-Westralian Mining Pty. Ltd. took an option on the property and carried out a programme of costeaning and diamond drilling. The option was relinquished in 1953 after two drillhole intersections had returned poor results.

The present company, Thaduna Copper Mines N. L., was formed in 1955 to work the leases. This company set about mining the lode by open-cut methods and soon became one of the State's largest producers of oxidised copper ore. It maintained this position until production ceased in 1966. All the company's production of 28,389 tons of ores and concentrates containing 2,244.64 tons of copper was sold to manufacturers of superphosphate as copper trace-element additive. The average tenor of the ore mined fell from about 6 to 7 per cent. to 3 to 4 per cent. during this period of production. In 1962, the company installed a flotation plant of a design suggested by the Kalgoorlie School of Mines in order to upgrade their product and increase its unit price and marketability.

In 1960 to 1962 the company carried out some deep mining from a shaft sunk in the floor of the northern open cut. Two shoots were mined from this shaft, each to a depth of about 160 feet. The stope on the Big Lode shoot was directly underneath the open cut and broke through in one place. The stope on the Black Lode shoot was just west of the open cut and broke through to the surface, apparently as the result of a collapse. Deep mining was abandoned when the workings collapsed after flooding.

New Consolidated Gold Fields (A/sia) Pty. Ltd. obtained an option on the Thaduna mine in 1962 and drilled 10 holes on the leases in the two following years. Eight of these holes were designed to test the known lode and two, GD9 and 10, were on a geochemical anomaly to the north. This work was done in conjunction with a regional geological, geochemical and geophysical survey. New Consolidated Gold Fields abandoned the option in 1966 after deep drillholes at Thaduna had shown the low grade of the primary mineralisation and after regional work had failed to find significant reserves of secondary ore.

Thaduna Copper Mines N.L. is now largely owned by the British Metal Corporation. The object of the present drilling was to prove sufficient supergene ore to justify capital expenditure on the mill, and thereby increase its efficiency in dealing with the graphite rich chalcocite ore.

In the four exploratory programmes carried out at Thaduna since 1953, 32 holes totalling about 14,000 feet have been drilled. Severe deflection of the deeper holes has been a constant problem, and two were abandoned when it became obvious that they would miss the lode. New Consolidated Gold Fields completed one deep hole only by constant wedging over the last few hundred feet. Most holes turn into the bedding of the sediments and this usually means that they curve to the south. The deflection can be compensated to some extent by starting the holes on a bearing north of the required azimuth, but if this is carried too far, the drill cuts the bedding planes in the opposite sense, and the holes then deflect to the north.

## GEOLOGY OF THE THADUNA LEASES

*Previous work*

The only published account of the geology of the Thaduna copper mine has been given by Low (1963, p. 112-117). Unpublished reports for Anglo-Westralian Mining Pty. Ltd. and New Consolidated Gold Fields (A/sia) Pty. Ltd. are now held by the British Metal Corporation and were made available to the Geological Survey. Rowston (1964) has reported on geophysical work done in the Thaduna area.

*Stratigraphy and rock types*

The copper mineralisation at Thaduna is in Precambrian rocks correlated by Horwitz (1966) with the Middle Proterozoic Bangemall Group. Four mappable stratigraphic units can be recognised on the leases, two of siltstone and two of greywacke. The lower siltstone unit, which is of undetermined thickness, is known only at the northern end of the leases beyond the area included on Plate 38. It is exposed in geochemical sample holes and in two diamond drillholes. Overlying this unit is the lower greywacke unit which consists of 2,500 feet of interbedded coarse, medium and fine-grained greywacke intercalated with beds of siltstone up to 100 feet thick. The upper 800 feet of the member is mainly of medium to coarse-grained greywacke which crops out more boldly than the finer-grained lower part.

The upper siltstone member is about 200 feet thick and is a good marker bed. Although its outcrop is poor, it forms a distinctive red-clay soil liberally covered with white quartz scree which can be traced through the leases. The upper greywacke unit is about 300 feet thick and comprises mainly medium to coarse-grained sediments with but few beds of siltstone. East of the mine area, it is overlain by more siltstone.

Lithologically the two greywacke units are almost identical, although the lower one has more intercalations of shale and siltstone. The rocks are made up of angular fragments of shale, lava, feldspar, and sparse, rounded quartz grains. Much of the fragmental rock material is probably of volcanic origin, the rocks being essentially resorted tuff (Trendall, 1967). The greywackes range from coarse turbidite with fragments 1½ to 2 inches across, to fine siltstones. The composition remains much the same regardless of the grain size. In good exposures the greywackes show many sedimentary structures such as cross-bedding, graded bedding, scours, slumps, and sedimentary breccias. Ripple marks and raindrop patterns are also found, but are much less frequent. In all, there is seldom any difficulty in determining the facings in well exposed greywacke.

The siltstone units consist of finely laminated purple shale and siltstone. The purple colour is due to fine hematite particles and is characteristic of many rocks within the Bangemall Group. The siltstone beds are finely cross-bedded and often show fine slump structures.

Although the foregoing description applies to the Thaduna leases, the whole copper-bearing belt from Lee's mine (M.C. 65P) 2 miles to the southwest, to the Green Dragon (M.L. 69P) 3½ miles northeast is underlain by similar rocks.

## STRUCTURAL GEOLOGY

### *Folding*

The Proterozoic sediments in the vicinity of the Thaduna mine have been folded about axes trending at 040° to 050° and plunging at 10 to 15° northeast. The folds are asymmetric with axial planes dipping at about 70° northwest.

Two synclines and one anticline have been established within the area of the leases while a second anticline is known to the southeast.

The westernmost fold, a syncline, has its west limb overturned, but the other folds are normal. The present tentative interpretation of the regional geology, is that the Thaduna mine is near the axis of a major anticlinorium which is flanked on its western side by overturned "drag" folds, but which has more open folds near its crest. On this interpretation, the rock assemblage seen on the leases is therefore the oldest which crops out in the area.

### *Faulting*

Three sets of faults are known in the copper-bearing area about the Thaduna mine. The major set trends at about 340° and has had a strong influence on the drainage pattern of the area. The other sets, striking north and east respectively, seem to be subsidiary to the major faulting. Mineralisation has been observed in faults of each set.

The copper lode on the Thaduna leases is within the prominent Thaduna fault, the best known example of the northwest trending set of faults. This fault has a measured displacement of 500 feet horizontally and about 200 feet vertically. The northeast block has moved northwest and down. The block of country west of the Thaduna fault has been tilted sufficiently to the west to bring the fold axes to a horizontal position.

## WALL ROCK ALTERATION

At Thaduna, the rocks within 50 feet of the lode are hydrothermally altered. Chlorite has been produced by the reaction of the original hematite and clay components, resulting in a marked colour change from purple to green. Calcite, introduced during the alteration, has considerably softened the sediments, allowing the wall rocks to weather deeply. Near the lode, the wall rocks are impregnated with graphite and are consequently coloured grey or black. In the weathered zone, the wall rocks consist mainly of kaolin.

## MINING GEOLOGY

The Thaduna copper lode is within the Thaduna fault. It is about 2,000 feet long and averages about 10 feet wide. In places, copper has penetrated into the wall rocks increasing the total width of mineralisation to a maximum of 70 feet. In this report the term "lode" is used to refer to mineralised material within the crush zone of the fault, whether or not it contains significant copper. The term is not used for mineralised wall-rock, although at times the copper content of this may approach an economic grade.

### *Composition of the lode*

For convenience of core logging and description, five types of lode material have been recognised, but graduations between the types are common.

(1) Graphitic schist: soft, black, very fissile material composed chiefly of carbon and crushed rock.

(2) Graphitic breccia: breccia with black, angular pieces of country rock set in a matrix of carbonates and crushed rock.

(3) Quartz-filled breccia: breccia with angular rock fragments, usually black, set in a matrix of quartz with minor carbonates.

(4) Siliceous lode: hard, dense, flinty quartz which is often grey or brown and may contain some rock fragments.

(5) Quartz: normally a typical, white, reef quartz.

The copper minerals present are: chalcopyrite and bornite in the primary zone; chalcocite and a little covellite in the secondary sulphide or supergene zone; and cuprite, malachite, azurite, and chrysocolla in the oxidised part of the lode.

There is insufficient information to calculate average grades of copper in all three zones. However, the richest lode material found to date in the primary zone contains only about 1.5 per cent. to 2 per cent. copper while the richer supergene ore averages 8 to 10 per cent. and the better oxidised ore 6 to 8 per cent. copper. The average grade of all oxidised ore won is about 4 per cent. copper which is higher than the average for supergene ore encountered in the drilling.

The mineral paragenesis of the lode can be set out as follows:

| Zone | Minerals Present | Lower Limit of Zone |
|---|---|---|
| Near surface .... .... | Chrysocolla.... .... .... | 10–20 feet |
| Oxidised zone .... .... | Malachite + azurite cuprite | 50–150 feet |
| Supergene zone .... .... | Chalcocite (+ covellite).... | 300–400 feet |
| Primary zone .... .... | Chalcopyrite + bornite .... | |

Despite the great depth of weathering found in the drillholes, only the upper few feet of the lode has been reduced in grade by surface leaching. It seems that in the prevailing alkaline weathering conditions copper cannot be transported far in solution. The mineral paragenesis shows that the present copper carbonates and oxides have resulted from the oxidation of supergene chalcocite. In fact in any shoot, there is little change in the grade of copper between the oxidised and supergene zones, indicating that there has been little migration of the copper during the present weathering processes. However, the fact that both the oxidised and supergene zones are both considerably richer in copper than the primary zone, shows that in the past there must have been considerable concentration of copper during oxidation of the lode. This suggests that the groundwaters of the time must have been much more acid than those affecting the lode at present. But the primary sulphide content of the lode is very low; (in fact the acid-producing mineral pyrite is quite rare), so the acidity probably derived from more abundant vegetation flourishing in a wetter climate. If so, then it is likely that the supergene copper zone is no younger than Tertiary in age.

The most characteristic feature of the Thaduna lode, and indeed of the other copper lodes worked in the same field, is the presence of carbon, either as the amorphous form, or as graphite. The carbon seems to have been introduced hydrothermally into the shear zone along with the copper minerals. The possibility of a carbonaceous sediment having been dragged along the shear is discounted for the reasons that:

(1) no primary carbon-bearing sediments have been recognised near the mine, either on the surface or in any of the drillholes;

(2) the wall-rocks of the lode are impregnated with carbon in a manner suggesting that it has been carried outwards from the lode channel;

(3) all the lodes in the Thaduna area carry a similar amount of carbon, suggesting it has a common deep-seated source rather than a local origin.

Although the carbon in the lode resembles graphite in its macroscopic properties, tests made on it during geophysical surveys of the area have shown it to be mainly amorphous carbon. The term "graphite" however has been retained in the rest of this report, partly because of local usage, and partly because it imparts a much more accurate description of the material as seen in the field.

*Ore controls within the lode*

Where seen south of the mine workings, the Thaduna fault is a simple, tight shear with only patches of copper mineralisation. Within the leases however, the fault swings through a large S-bend on which are superimposed smaller bends of the same type. On these bends, the shear splits into two or more branches and the intervening country rock is veined and brecciated.

Although the whole width of the resulting breccia zone may be mineralised, the ore shoots are usually restricted to the most intensely crushed parts. At the south end of the lode, two such shoots have been worked where the split sections of the main fault rejoin on either side of an S-bend. This situation is illustrated diagrammatically in figure 12. Here the fault A-D bends and splits between B and C. The section between B and C consists of large, broken slabs of country rock, but due to the wide separation of the marginal shears there has been little crushing of the rock. At a point such as B or C, the wedge of rock between the shears has been subjected to considerable stress in comparison to its bulk, and has been crushed. It is at these positions that the enrichments of copper are found.

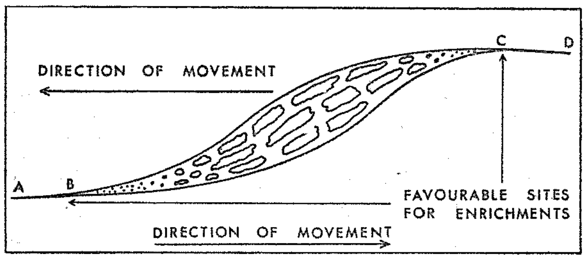


Figure 12—Diagram illustrating favourable positions for ore shoots on a split shear structure.

The better grade ore worked at Thaduna is almost always in "graphite schist" or "graphitic lode". Lode with a high content of silica seldom contains high-grade copper mineralisation. As all of the ore worked to date owes its copper content to secondary enrichment, it is likely that this process has taken place preferentially in the less siliceous and hence more permeable parts of the fault zone.

At the north end of the open cuts, two shoots known as the "Big Lode" and the "Black Lode" respectively, have been mined to a depth of about 160 feet. The controls of these shoots are not as apparent as with those to the south mainly because the present collapsed, waterfilled workings cannot be closely examined. From previous examinations, made when the workings were in a better condition, it is thought that the two shoots are on separate branches of the Thaduna fault. The Black Lode shoot is on the main through-going branch of the fault while the Big Lode is on an eastern branch which dies out to the north. The movement on this branch seems to have been taken up on link shears which join it to the western part of the structure. The shoots may have formed where these link-shears intersect each of the two branches.

## THE DIAMOND DRILLING PROGRAMME

Drilling done by New Consolidated Gold Fields in 1963 to 1964 showed the existence of good-grade chalcocite ore beneath the open cuts at depths of 350 to 400 feet below the surface. However, the holes intersecting the secondary sulphide ore were too widely spaced for reliable determination of the reserves, so the British Metal Corporation decided to drill a further 10 holes. Eight of the holes were planned to intersect the lode at about 200 feet vertical depth, and two were laid out to cut the more interesting central part at a depth of about 400 feet. Another three holes, financed entirely by B.M.C. are planned to test the extensions of the lode along strike.

The present drilling programme was laid out with the object of trying to prove a large body of supergene enriched ore. Consequently, no deliberate attempt was made to intersect each of the shoots known in the open cuts and it is therefore possible that the drillholes may have straddled some shoots. However, as the object of the programme was to prove an ore body suitable for open-cut mining, the policy of placing the holes at equal intervals to get an average grade for the whole lode was justified. Any deliberate attempt to intersect only the higher-grade shoots would have made the results impossible to interpret and useless for the aim of the project.

Table 1 gives the results of all holes drilled on the lode to date and the positions of the intersections in plan and section are shown in Plates 38 and 39. On these plates, holes drilled by the British Metal Corporation are shown as BD15 to 24. This numbering follows on from that used by New Consolidated Gold Fields who drilled 14 holes in the Thaduna area. Those holes of New Consolidated Gold Fields which are in the compass of the present report are shown on the plates with the prefix GD. The two intersections obtained by Anglo-Westralian Pty. Ltd. are shown on the longitudinal projection with the prefix AW. As the collar positions of these holes are uncertain, they have not been shown on the plan. Thaduna Copper Mines drilled several shallow holes, which are shown on the plates with the prefix TH. Apart from TH7 the positions of these holes are known only approximately.

The results of drilling and channel sampling can best be interpreted as indicating a series of North-pitching shoots within the lode. Holes GD2 and BD20 intersect one such shoot which is centred on channel sample S7 in the open cut. The mine manager, Mr. A. Rieck, reports that the shoots worked from the shaft in the northern open cut also pitched to the north. Individual shoots are in the order of 150 to 200 feet long and range in grade from 6.5 per cent. to 10 per cent. copper.

The average grade up the upper 200 feet of the lode as calculated from the drilling and sampling results, and excluding some very low-grade sections, is about 3.5% copper. Sufficient ore is indicated to justify a small open-cut mining venture if the high price of copper is maintained and the problems associated with concentrating the copper sulphides can be overcome.

Secondary enrichment extends to a depth of 350 to 400 feet in the central part of the lode, but is less than 150 feet deep at the south end and is also decreasing at the north end.

## REFERENCES


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Trendall, A. F., 1967 Petrography depositional environment of some Precambrian sedimentary rocks from Thaduna, Western Australia: West. Australia Geol. Survey Rec. 1967/23 (unpublished).

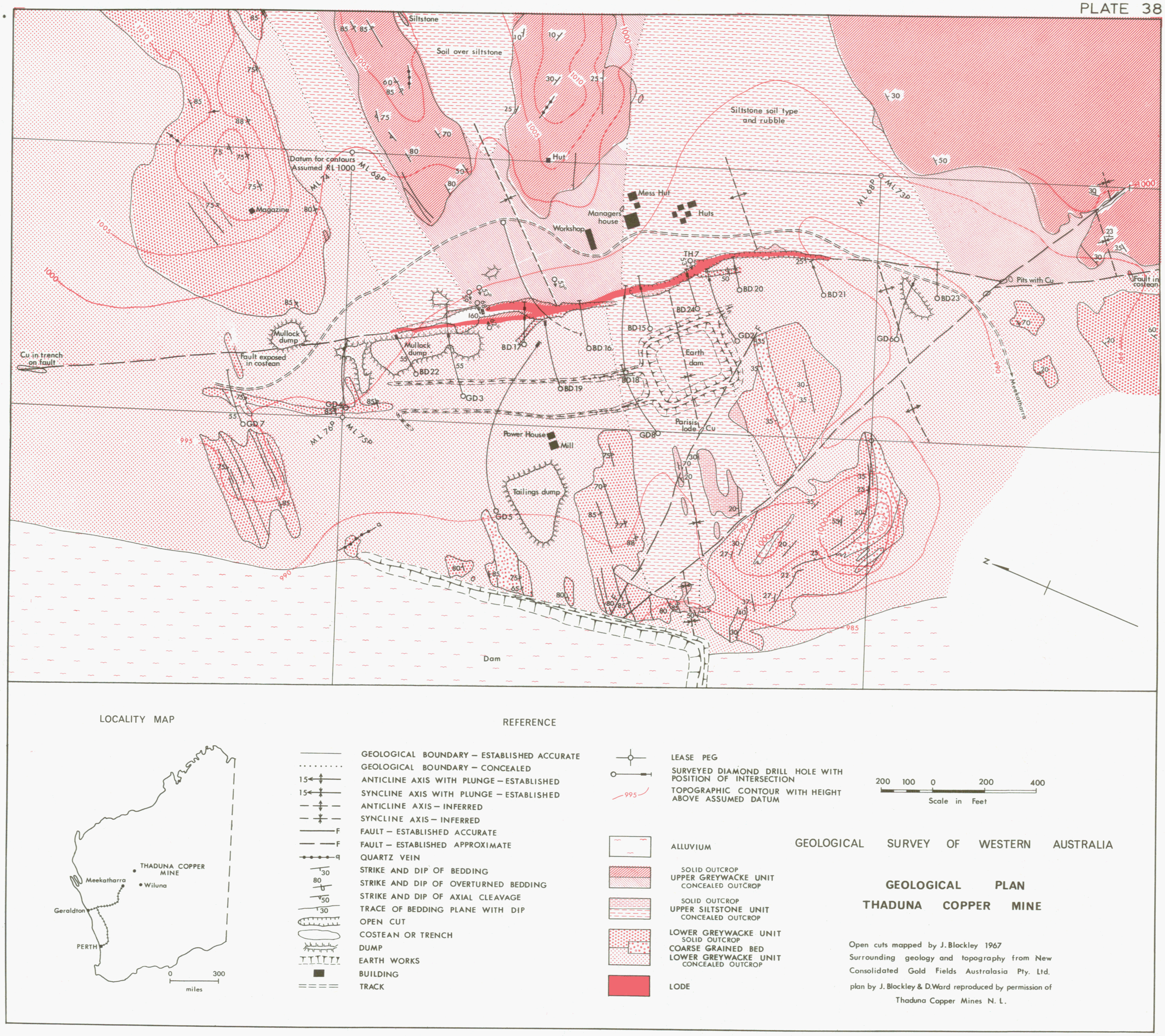
Siltstone
Soil over siltstone
Siltstone soil type and rubble
Datum for contours Assumed RL 1000
Magazine
Hut
Mess Hut
Managers house
Huts
Workshop
Pits with Cu
Fault in costean
Mullock dump
Cu in trench on fault
Fault exposed in costean
Earth dam
Parisis lode Cu
Power House
Mill
Tailings dump
Dam
Meekatharra
LOCALITY MAP
THADUNA COPPER MINE
Meekatharra
Wiluna
Geraldton
PERTH
0 300
miles
REFERENCE
GEOLOGICAL BOUNDARY – ESTABLISHED ACCURATE
GEOLOGICAL BOUNDARY – CONCEALED
ANTICLINE AXIS WITH PLUNGE – ESTABLISHED
SYNCLINE AXIS WITH PLUNGE – ESTABLISHED
ANTICLINE AXIS – INFERRED
SYNCLINE AXIS – INFERRED
FAULT – ESTABLISHED ACCURATE
FAULT – ESTABLISHED APPROXIMATE
QUARTZ VEIN
STRIKE AND DIP OF BEDDING
STRIKE AND DIP OF OVERTURNED BEDDING
STRIKE AND DIP OF AXIAL CLEAVAGE
TRACE OF BEDDING PLANE WITH DIP
OPEN CUT
COSTEAN OR TRENCH
DUMP
EARTH WORKS
BUILDING
TRACK
LEASE PEG
SURVEYED DIAMOND DRILL HOLE WITH POSITION OF INTERSECTION
TOPOGRAPHIC CONTOUR WITH HEIGHT ABOVE ASSUMED DATUM
ALLUVIUM
SOLID OUTCROP UPPER GREYWACKE UNIT CONCEALED OUTCROP
SOLID OUTCROP UPPER SILTSTONE UNIT CONCEALED OUTCROP
LOWER GREYWACKE UNIT SOLID OUTCROP
COARSE GRAINED BED
LOWER GREYWACKE UNIT CONCEALED OUTCROP
LODE
200 100 0 200 400
Scale in Feet
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL PLAN
THADUNA COPPER MINE
Open cuts mapped by J. Blockley 1967
Surrounding geology and topography from New Consolidated Gold Fields Australasia Pty. Ltd.
plan by J. Blockley & D. Ward reproduced by permission of Thaduna Copper Mines N. L.

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PLATE 39

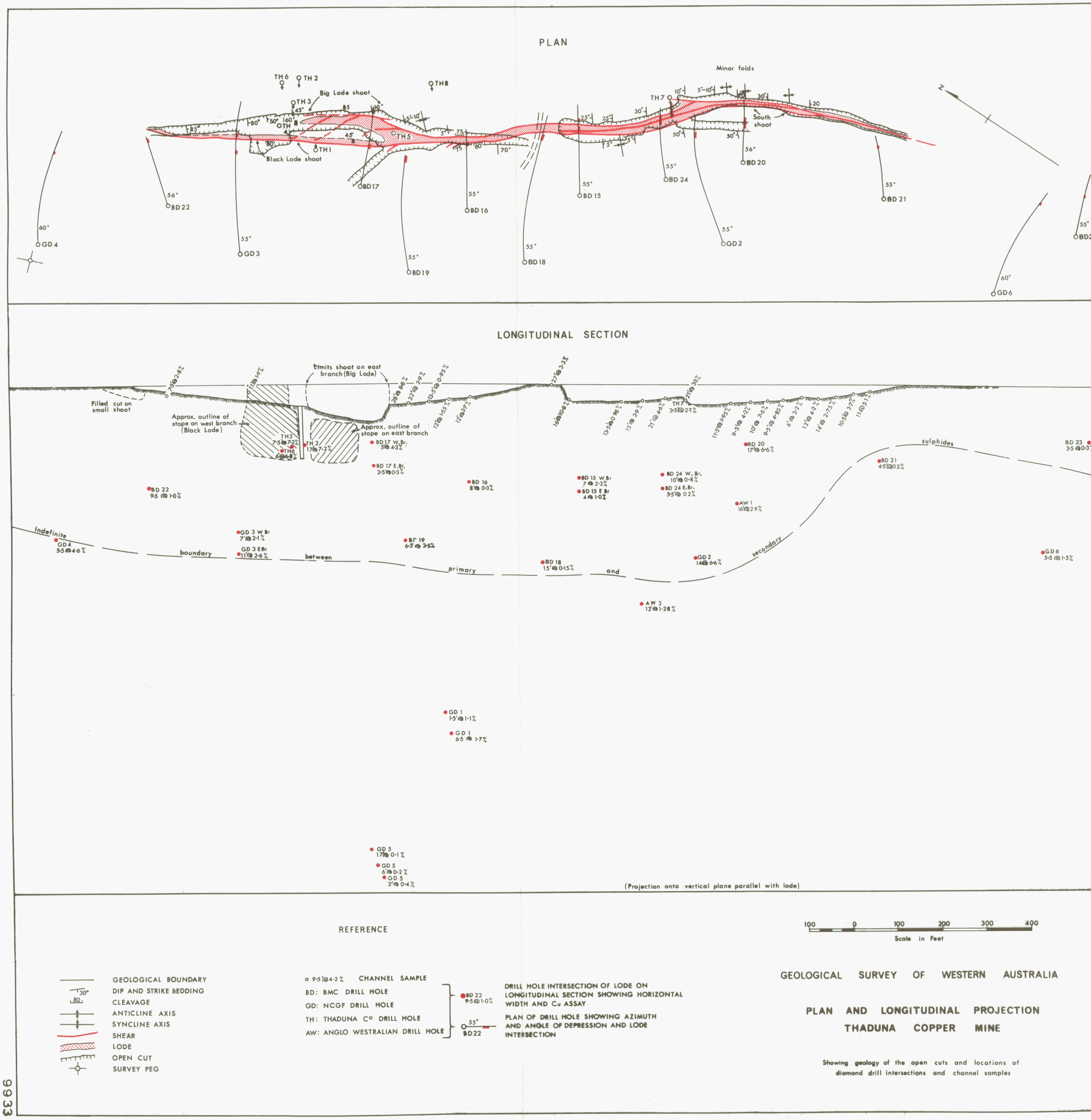
PLAN
Minor folds
Big Lode shoot
Black Lode shoot
South shoot
TH6
TH2
TH3
TH8
TH5
TH1
TH7
BD17
BD22
BD16
BD15
BD24
BD20
BD21
BD19
BD18
GD4
GD3
GD2
GD6
BD23
LONGITUDINAL SECTION
Limits shoot on east branch (Big Lode)
Filled cut on small shoot
Approx. outline of stope on west branch (Black Lode)
Approx. outline of stope on east branch
sulphides
Indefinite boundary between primary and secondary
BD 22 9·5 @ 1·0%
GD 4 5·5 @ 4·6%
GD 3 W Br 7' @ 2·1%
GD 3 E Br 11' @ 2·6%
BD 17 W. Br. 5' @ 4·3%
BD 17 E. Br. 2·5' @ 0·3%
BD 16 8' @ 0·3%
BD 19 6·3' @ 2·5%
BD 18 15' @ 0·15%
BD 15 W Br 7' @ 2·3%
BD 15 E Br 4' @ 1·0%
BD 24 W. Br. 10' @ 0·8%
BD 24 E. Br. 5·5' @ 0·2%
AW 1 16' @ 2·9%
GD 2 14' @ 6·6%
AW 3 12' @ 1·28%
BD 20 17' @ 6·6%
BD 21 4·5' @ 0·2%
BD 23 3·5 @ 0·3%
GD 6 5·5 @ 1·5%
GD 1 1·5' @ 1·1%
GD 1 6·5 @ 1·7%
GD 5 17' @ 0·1%
GD 5 6' @ 0·2%
GD 5 3' @ 0·4%
(Projection onto vertical plane parallel with lode)
REFERENCE
GEOLOGICAL BOUNDARY
DIP AND STRIKE BEDDING
CLEAVAGE
ANTICLINE AXIS
SYNCLINE AXIS
SHEAR
LODE
OPEN CUT
SURVEY PEG
9·5' @ 4·2% CHANNEL SAMPLE
BD: BMC DRILL HOLE
GD: NCGF DRILL HOLE
TH: THADUNA Co DRILL HOLE
AW: ANGLO WESTRALIAN DRILL HOLE
DRILL HOLE INTERSECTION OF LODE ON LONGITUDINAL SECTION SHOWING HORIZONTAL WIDTH AND Cu ASSAY
PLAN OF DRILL HOLE SHOWING AZIMUTH AND ANGLE OF DEPRESSION AND LODE INTERSECTION
100 0 100 200 300 400
Scale in Feet
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
PLAN AND LONGITUDINAL PROJECTION
THADUNA COPPER MINE
Showing geology of the open cuts and locations of diamond drill intersections and channel samples
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Table 1

SUMMARY OF DIAMOND DRILLING RESULTS

| Hole No. | Drilled by* | Date | Collar | | Lode Intersection | | Assays better sections | | | | Final depth (ft.) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Bear. | Dep. | From (ft.) | To (ft.) | From (ft.) | To (ft.) | %Cu | Hor. Width (ft.) | | |
| AW1 .... | A.W. .... | 1953 | .... | .... | .... | .... | .... | .... | 2·9 | 16 | .... | Poor core recovery |
| AW2 .... | A.W. .... | 1953 | .... | .... | .... | .... | .... | .... | .... | .... | 635 | Abandoned due to severe deflection |
| AW3 .... | A.W. .... | 1953 | .... | .... | .... | .... | .... | .... | 1·28 | 12 | .... | In primary sulphide |
| TH1 .... | T.C.M.... | 1959 | .... | 62° | 0 | 15 | 0 | 15 | Trace | .... | 160 | |
| TH2 .... | T.C.M.... | 1959 | .... | 53° | 162 | 190 | 162 | 190 | 7·2 | 17 | 190 | |
| TH3 .... | T.C.M.... | 1959 | .... | 68° | 141 | 161 | 141 | 161 | 7·2 | 7½ | 171 | |
| TH4 .... | T.C.M.... | 1959 | .... | 90° | .... | .... | .... | .... | .... | .... | 90 | No lode intersected |
| TH5 .... | T.C.M.... | 1959 | .... | 90° | 0 | 120 | 0 | 120 | 7·15 | .... | 120 | Drilled vertically down lode |
| TH6 .... | T.C.M.... | 1959 | .... | 59° | 170 | 182 | 170 | 182 | 6·8 | 6 | 185 | |
| TH7 .... | T.C.M.... | 1959 | .... | 53° | 20 | 56 | 20 | 56 | 5·5 | 20 | 70 | Oxidised lode |
| | | | | | 60 | 66 | 60 | 66 | 2·1 | 3½ | .... | Graphite lode |
| TH8 .... | T.C.M.... | 1959 | .... | 53° | .... | .... | .... | .... | .... | .... | 201 | No lode intersected |
| GD1 .... | N.C.G.F. | 1963 | 230° | 55° | 761 | 956 | 761½ | 762½ | 14·9 | 0·3 | 956 | Hole deflected badly and was running nearly parallel to the lode when stopped ; primary sulphides |
| | | | | | | | 890 | 894½ | 1·13 | 1½ | .... | |
| | | | | | | | 932½ | 956 | 1·67 | 6½ | .... | |
| GD2 .... | N.C.G.F. | 1963 | 050° | 55° | 460·7 | 482·9 | 463·5 | 482·9 | 6·6 | 14 | 550 | Secondary sulphides |
| GD3 .... | N.C.G.F. | 1963 | 055° | 55° | 341·7 | 346·7 | 341·7 | 346·7 | 1·8 | 3·5 | 598 | Oxidised copper minerals |
| | | | | | 395·0 | 404·7 | 395·0 | 404·7 | 2·06 | 7 | .... | West branch of lode } Secondary and primary sulphides |
| | | | | | 459·0 | 474·0 | 459·0 | 474·0 | 2·65 | 11·0 | .... | East branch of lode } Secondary and primary sulphides |
| GD4 .... | N.C.G.F. | 1964 | 055° | 60° | 402·0 | 415·5 | 407·0 | 415·6 | 4·6 | 5·5 | 517 | Secondary and primary sulphides |
| GD5 .... | N.C.G.F. | 1964 | 060° | 63° | 1234·5 | 1265 | 1234·5 | 1265 | 0·09 | 17 | 1351 | } Primary sulphides |
| | | | | | 1291 | 1302 | 1291 | 1302 | 0·19 | 6 | .... | } Hole running near-parallel to this lode |
| | | | | | 1326 | 1344 | 1326 | 1344 | 0·42 | 3 | .... | |
| GD6 .... | N.C.G.F. | 1964 | 079½° | 60° | 425·5 | 434 | 425·5 | 434 | 1·54 | 5·5 | 500 | Primary sulphides |
| GD7 .... | N.C.G.F. | 1964 | 035° | 60° | 402·7 | 430·3 | 402·7 | 430·3 | 0·01 | 18·5 | 481 | Disseminated pyrite in lode |
| GD8 .... | N.C.G.F. | 1964 | 040° | 65° | .... | .... | .... | .... | .... | .... | 736 | Abandoned due to deflection after several wedging attempts |
| GD9† .... | N.C.G.F. | 1964 | 050° | 60° | 449 | 556 | .... | .... | .... | .... | 752 | Lode comprises quartz-filled breccia—no copper |
| GD10‡ | N.C.G.F. | 1964 | 040° | 60° | 405 | 412 | 405 | 412 | 0·62 | 4·0 | 502 | Oxidised copper minerals |
| | | | | | 432 | 450 | 432 | 450 | 0·32 | 12·0 | .... | Oxidised copper minerals |
| BD15.... | B.M.C..... | 1966 | 058° | 55° | 261 | 279 | 254 | 266 | 2·35 | 7·0 | 351 | Includes some mineralised wall rock in assay section |
| | | | | | 296 | 302 | 295 | 302·5 | 1·0 | 4·5 | .... | |
| BD16.... | B.M.C..... | 1966 | 058° | 55° | 259 | 272 | 259 | 272 | 0·3 | 8·2 | 320 | |
| | | | | | 290·5 | 304 | Barren | .... | .... | .... | .... | |
| BD17.... | B.M.C..... | 1966 | 069° | 55° | 159 | 168·2 | 157 | 162 | 2·4 | 3·0 | 285½ | |
| | | | | | 224 | 228 | 224 | 228 | 0·3 | 2·2 | .... | Poor recovery in lode |
| BD17A | B.M.C..... | 1967 | .... | .... | 155 | 170 | 153·5 | 162 | 4·35 | 4·9 | 226 | Secondary sulphides |
| | | | | | 219 | 226 | Not assayed | | | | | Wedged from BD17 at 130 feet |
| BD18.... | B.M.C..... | 1967 | 054° | 55° | 471 | 523 | 487 | 508 | 0·15 | 15·0 | 587 | |
| BD19.... | B.M.C..... | 1967 | 053° | 55° | 431·5 | 446 | 431 | 440 | 2·5 | 6·3 | 458 | Secondary sulphides |
| BD20.... | B.M.C..... | 1967 | 053° | 56° | 196·5 | 231 | 196·5 | 219·5 | 6·65 | 19 | 253 | Secondary sulphides |
| BD21.... | B.M.C..... | 1967 | 053° | 55° | 205 | 214·3 | 205 | 211 | 0·2 | 4·5 | 250 | Pyrite in lode |
| BD22.... | B.M.C..... | 1967 | 041° | 56° | 274 | 286 | 272 | 289 | 1·03 | 9·5 | 294 | Primary and secondary sulphides |
| | | | | | | | 273 | 279 | 2·25 | 3·3 | .... | |
| BD23.... | B.M.C..... | 1967 | 068° | 55° | 154 | 159 | 154 | 159 | 0·3 | 3·5 | 250 | Oxidised |
| BD24.... | B.M.C..... | 1967 | 051° | 55° | 232·5 | 241 | 232·5 | 251 | 0·8 | 10 | 297½ | Oxidised |
| | | | | | 247 | 259 | Not assayed | | | | | |
| | | | | | 275 | 286 | 275 | 286·5 | 0·2 | 5·5 | .... | Oxidised |

* A.W. = Anglo-Westralian Corporation Pty. Ltd.
T.C.M. = Thaduna Copper Mines N.L.
N.C.G.F. = New Consolidated Gold Fields (A/sia) Pty. Ltd.
B.M.C. = British Metal Corporation Pty. Ltd.
† GD9 sited on a geochemical anomaly 1,775 feet north of GD7.
‡ GD10 sited on a geochemical anomaly 1,200 feet north of GD7.

# THE NAUTILOID CIMOMIA IN THE PLANTAGENET GROUP

by A. E. Cockbain


## ABSTRACT

The Upper Eocene nautiloid *Cimomia felix* (Chapman), of which *C. yorkensis* McGowran is a junior synonym, is described and figured from the Plantagenet Group in the Denmark-Esperance area. The five specimens come from four widely scattered localities and are all of small size.


## INTRODUCTION

Nautiloid cephalopods were first discovered in the Plantagenet Group by Jutson and Simpson (1916). The form they found has subsequently been named *Aturia clarkei* Teichert. More recently, Glenister and Glover (1958) have described *Teichertia prora* Glenister, Miller and Furnish from these strata. A third species was recorded, but not figured, by Chapman and Crespin (1934) as *Nautilus geelongensis*. What is probably the same species was identified by Teichert (*in* Clarke and Phillipps, 1955, p. 22) as "fairly close to the Victorian *Nautilus balcombensis* Chapman or *Nautilus geelongensis*".

This latter nautiloid from Western Australia has not been described or figured and the purpose of this note is to rectify this omission.

## SYSTEMATIC PALAEONTOLOGY

Phylum MOLLUSCA
Class CEPHALOPODA
Subclass NAUTILOIDEA
Order NAUTILIDA
Superfamily NAUTILACEAE
Family HERCOGLOSSIDAE
Genus CIMOMIA Conrad, 1866

Type species:
*Nautilus burtini* Galeotti 1837.
*Cimomia felix* (Chapman) 1915.
Plate 40; Figure 13.

1915 *Nautilus felix* Chapman, p. 357, pl. 6 fig. 14, pl. 7 fig. 15.

1934 *Nautilus geelongensis* (Foord); Chapman and Crespin p. 125.

?1955 "close to . . . *Nautilus balcombensis* Chapman or *Nautilus geelongensis*"; Teichert *in* Clarke and Phillipps p. 22.

1959 *Cimomia felix* (Chapman); McGowran p. 443 pl. 65 figs. 1-7, text fig. 10.

1959 *Cimomia yorkensis* McGowran p. 445 pl. 66 figs. 6-8; text fig. 11.

*Material:* From the Western Australian Museum collection,

65.1: from Lort River.
64.21: from Esperance.
67.353a: from Plantagenet Location 5293, 22 miles from Albany along Mt. Manypeaks road.

From the National Museum of Victoria collection (Jutson collection; *N. geelongensis* (Foord) of Chapman and Crespin 1934, p. 125), P26128 A & B: from near Albany.

*Dimensions* (in mm):

| Specimen No. | 65·1* | 64·21*† | 67·353a* | P26128A† | P26128B† |
|---|---|---|---|---|---|
| Maximum diameter | 34·0 | .... | 21·5 | .... | .... |
| Maximum width .... | 33·0 | .... | 17·5 | .... | .... |
| Height of last chamber | 15·5 | .... | 9·0 | .... | .... |
| Height of impressed area | 6·0 | .... | 4·5 | .... | .... |
| Chamber length .... | 4·0–7·5 | approx. 5·0 | 2·0–3·2 | .... | approx. 6·0 |
| Umbilicus diameter | 2·0 | .... | 1·5 | .... | .... |
| No. of chambers in final whorl | Body chamber +11 | Body chamber +4 | 16 | Body chamber +1 | 5·0 |

* Specimen distorted; axis of coiling is at 82° to plane of coiling in 65.1 and 67.353a and at a slightly larger angle in 64.21.

† Incomplete specimens.

*Description:* All specimens are preserved as internal moulds: the description is based on those in the W.A. Museum collection. Conch small, expanding fairly rapidly. Umbilicus small; it is impossible to determine whether or not it is perforate. Body chamber takes up about ⅓ of a volution in 65.1 (incomplete specimen) and one third to one half volution in 64.21. Whorl cross section broadly rounded ventrally, sides slightly flattened, umbilical walls steep. Siphuncle not preserved. Surface of internal mould smooth; in 65.1 there is a faint ridge on the mid-ventral line of the final chambers, in 67.353a, there is a shallow groove in this position. Suture line (Figure 13) slightly sinuous with broad ventral saddle and shallow lateral lobe; a small but distinct lateral saddle is present in the umbilicus in early chambers and on the umbilical shoulder in later chambers. Dorsal suture unknown.

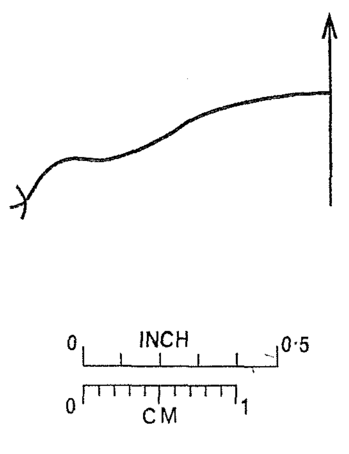


Figure 13—*Cimomia felix;* suture line form final whorl of specimen 65.1

*Remarks:* The only slightly sinuous suture line of these specimens suggests that they belong to the genus *Cimomia* rather than *Eutrephoceras.* Two Australian Tertiary species of *Cimomia* are known, namely *C. felix* (Chapman) and *C. yorkensis* McGowran. The main differences between these two species (McGowran 1959, p.446) are in height/width ratio of mature chambers, perforation of umbilicus, and position of subcentral siphuncle; in view of the known variability of these features in nautiloid populations it seems best to recognise only one species and suppress *C. yorkensis* as a synonym of *C. felix.* This is borne out by published figures (McGowran 1959, pl.65 figs. 2 & 3) showing the variation in chamber cross-sectional shape in young specimens of *C. felix.* The Plantagenet Group specimens closely resemble the young specimens from the Tortachilla Limestone figured by McGowran (1959, pl.65 fig. 1, 2). The only other published figures with which the Plantagenet Group specimens may be compared, are of young (and atypical) paratypes of *Cimomia tenuicosta* Glenister, Miller & Furnish (1956, pl.53 fig. 5, 6, 7) from the Upper Cretaceous Miria Marl in the Carnarvon Basin. It is possible that these paratypes do not belong to *C. tenuicosta;* the suture line resembles that of *C. felix* although the chamber cross section is more globose and lacks the lateral flattening of *C. felix.*

It is not clear what is the significance of the small size of the Plantagenet Group material. All five specimens studied come from a variety of lithologies (limestone, hard and soft siltstone). These nautiloids seem to be consistently smaller than other Australian Tertiary nautiloids previously described. Whether they are all young specimens or represent a new, small-sized species, cannot be established from the material available.

*Stratigraphical range:* In addition to the specimens from the localities mentioned above *C. felix* probably occurs near Quaalup homestead on the Gairdner River. The species is thus known throughout the Plantagenet Group outcrop in the Denmark-Esperance area.

*Cimomia felix* is of Upper Eocene Age, being known from the Tortachilla Limestone, Blanche Point Marls, and Browns Creek Clay (McGowran, 1959; Ludbrook, 1967). The Plantagenet Group is known to be of Upper Eocene age from dating by Foraminifera (McTavish, 1966; Cockbain, 1967). The presence of *C. felix* in the Plantagenet Group would support this Upper Eocene age.


ACKNOWLEDGEMENTS

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PLATE 40


*Cimomia felix* (Chapman)
Left: Specimen No. 65.1 from Lort River.
Right: Specimen No. 67.353a from Plantagenet Loc. 5293.

# EOCENE FORAMINIFERA FROM THE NORSEMAN LIMESTONE OF LAKE COWAN, WESTERN AUSTRALIA

by A. E. Cockbain

ABSTRACT

Three formations (Norseman Limestone, Cowan Dolomite, and Princess Royal Spongolite), in part laterally equivalent, crop out on the margins of Lake Cowan and are here designated the Eundynie Group. The original Miocene dating, on the basis of Bryozoa, of the Norseman Limestone has been questioned recently. Upper Eocene Foraminifera are identified for the first time from the Norseman Limestone and enable it to be correlated with the Toolinna Limestone, Wilson Bluff Limestone, and Plantagenet Group.

## INTRODUCTION

There are several small outcrops of rocks, usually assigned to the Tertiary, around the margin of Lake Cowan. The main rock types are limestone (silicified in part), dolomite, and spongolite; they have been named—Norseman Limestone (Gregory, 1916), Cowan Dolomite (Fairbridge, 1953), and Princess Royal Spongolite (Glauert, 1926) respectively. A variety of fossils has been recorded, chiefly from the Norseman Limestone; most of these fossils were referred to Victorian species and a Miocene age assigned to the beds. More recently, with the recognition of the Upper Eocene age of the Plantagenet Group, the Lake Cowan Tertiary rocks have been placed in the Eocene. However, no palaeontological evidence has been published to substantiate this age. The purpose of this paper is to record an Upper Eocene fauna from the Norseman Limestone.

## STRATIGRAPHY

The accompanying sketch map (Plate 41) shows the known Tertiary outcrops in the vicinity of Lake Cowan. An attempt has been made to place each outcrop in its correct formation on the basis of published evidence. Previous workers have considered the three formations to be in stratigraphic sequence:

(3) Princess Royal Spongolite

(2) Cowan Dolomite

(1) Norseman Limestone

The evidence for this succession is tenuous. Clarke and others (1948, p. 90) state that ". . . two small fossiliferous outcrops (Norseman Limestone) . . . underlie the unfossiliferous (Cowan) dolomite". The field evidence is equivocal and as the Norseman Limestone and Cowan Dolomite are at about the same elevation, and the dip, whilst not measured, is low, the two formations could be in part laterally equivalent. Concerning the Princess Royal Spongolite, Clarke and others (1948, p. 93) write ". . . The relation of the spongolite to the dolomite has not been seen but the base of the spongolite is about level with the top of the dolomite". On the other hand Hooper (1959, p. 8) concludes . . . "Thus the spongolite and shell bed limestone (i.e. Norseman Limestone) may be regarded as lateral facies laid down more or less at the same time".

In the absence of detailed mapping of the Tertiary rocks the relationship of these three formations cannot be determined with certainty. However it appears likely that they are, in part, lateral equivalents, with the Norseman Limestone being the nearshore facies and the Princess Royal Spongolite a more offshore (although not necessarily deeper water) facies. The spongolite occurrence at Princess Royal is at a slightly higher elevation than the surrounding Tertiary rocks and hence the Princess Royal Spongolite must overlap the Norseman Limestone and Cowan Dolomite. Whether the carbonate unit needs different names for the fossiliferous and unfossiliferous parts, future mapping must decide. It is here proposed that the Norseman Limestone, Cowan Dolomite, and Princess Royal Spongolite be referred to collectively as **the "Eundynie Group".**

## PREVIOUS WORK ON PALAEONTOLOGY OF THE LAKE COWAN GROUP

Of the three formations, the Cowan Dolomite is unfossiliferous, the Princess Royal Spongolite consists almost entirely of sponge spicules, and the Norseman Limestone is richly fossiliferous in places.

Lists of fossils from the Princess Royal Spongolite have been published by Hinde (1910, p. 9-20), Chapman and Crespin (1934, p. 126), Glauert (1926, p. 61), and Clarke and others (1948, p. 93), although most of these records are repetitions of those given by Hinde. Hinde (1910) stated that the formation was younger than the Cretaceous but was unable to be more specific on the evidence of the sponges.

The Norseman Limestone fauna has been recorded by Campbell (1906, p. 22), Maitland (1907, p. 61; 1908, p. 153), Gregory (1916, p. 320), Chapman and Crespin (1934, p. 126), Clarke and others (1948, p. 90-97), Crespin (*in* Clarke and others 1948, p. 99-100), and Hooper (1959, p. 4-6).

In determining the age of the deposit considerable reliance was placed on the Bryozoa by both Gregory and Crespin, who referred them to Victorian and South Australian species formerly believed to be of Miocene age. Since many of the sponge determinations are unreliable (de Laubenfels, 1953), and, as the Bryozoa require re-examination in the light of both modern bryozoan taxonomy and current views on Victorian Tertiary stratigraphy, there is no point in repeating these faunal lists here.

## FORAMINIFERA FROM NORSEMAN LIMESTONE

Examination of samples, in the Geological Survey collection, of Norseman Limestone from the type locality of the formation about 20 chains north-east of ML1, Norseman (Norseman run 4, photo 5475, quadrant C, x co-ord. 2.34, y co-ord. 0.36), enabled the following foraminifers to be identified: *Bolovina* sp. *Amphicoryna hirsuta* (d'Orbigny), *Quinqueloculina* spp., *Cibicides perforatus* (Karrer), *Elphidium* cf. *omotoensis* Dorreen, and *Spirillina* sp. The age of the limestone cannot be determined from this fauna.

In July 1967, samples were collected from Hooper's (1959) locality 3 on the southern side of Lake Cowan some 7 miles south-southeast of Binneringie homestead. The succession at this locality consists of a basal shelly limestone about two feet thick resting on Precambrian rocks and overlain by bryozoan limestone. Total thickness is estimated to be about 30 feet. The byrozoan limestone is current-bedded in places and the strata dip eastwards at a low angle. Hooper (1959) recorded two shell beds at this locality but only one was noted in the present investigation.

A small creek marks the junction between limestone and Precambrian rocks. To the east, another creek cuts across the limestone outcrop. In both creeks the limestone is sufficiently weathered to disaggregate readily and a well-preserved fauna of Foraminifera and Bryozoa has been obtained. Sample F6675, collected from the eastern creek (Widgiemooltha Run 16 photo 5721, Quadrant C, x co-ord. 3.60 y co-ord. 0.55) has yielded the following foraminifers:

| Species | Other Records | | |
|---|---|---|---|
| | Tep | Tew | Tet |
| *Lamarckina turgida* Dorreen .... .... .... | | (x) | (x) |
| *Elphidium* ex. gr. *ingressans* Dorreen .... .... | (x) | (x) | |
| *Discorbis finlayi* Dorreen .... .... .... .... | x | x | |
| *Reusella* cf. *finlayi* Dorreen .... .... .... | | | x |
| *Stomatorbina torrei* (Cushman & Bermudez) .... | x | x | x |
| *Gyroidinoides* cf. *zelandica* (Finlay) .... .... | | x | (x) |
| *Cibicides perforatus* (Karrer) .... .... .... | | x | ? |
| *C. vortex* Dorreen .... .... .... .... .... | | x | x |
| *Anomalinoides* sp. .... .... .... .... .... | | x | |
| *Asterigerina* sp. .... .... .... .... .... | | | (x) |
| *Sherbornina atkinsoni* Chapman .... .... .... | x | | |
| *Crespinina kingscotensis* Wade .... .... .... | x | | |
| *Globigerina* cf. *praeturritillina* Blow & Banner | | x | |
| *Operculina* sp. .... .... .... .... .... | x | | |
| *Bolivinella* sp. .... .... .... .... .... | x | | x |

Tep Plantagenet Group (Quilty *in* Hodgson and others, 1962 ; Cockbain, 1967).
Tew Wilson Bluff Limestone (Crespin, 1956 ; G.S.W.A. collections).
Tet Toolinna Limestone (Crespin, 1956 ; G.S.W.A. collections).
(x) Record of genus only.

Other records of these foraminifers in southern Western Australia are as indicated above.

## AGE

The fauna is similar to that of the Plantagenet Group, Wilson Bluff Limestone, and Toolinna Limestone. All three formations are usually considered Upper Eocene in age with the Wilson Bluff Limestone extending down in the Middle Eocene. Significant species for correlation purposes are *Sherbonina atkinsoni* and *Crespinina kingscotensis* both of which occur in Ludbrook's (1963) Tortachilla microfaunule.

The closest faunal similarities are with the Booanya Rock fauna recorded by Crespin (1956) from rocks now assigned to the Toolinna Limestone (Lowry, 1968). *Globigerina* cf. *praeturritillina* is poorly preserved and has a very coarsely ornamented spiral side, but closely resembles *G. praeturritillina* identified by Dr. N. H. Ludbrook from the Wilson Bluff Limestone at Wilson Bluff (G.S.W.A. sample 14266B). This species is characteristic of the Upper Eocene according to Blow and Banner (1962) although Jenkins (1967) shows it extending into the Oligocene in New Zealand. The balance of evidence suggests that the Norseman Limestone is of Upper Eocene age.

## ENVIRONMENT

Abundant *Elphidium* and the presence of robust and ornamented species such as *Lamarskina turgida* suggest shallow-water nearshore conditions. The single, aberrant, specimen of *Globigerina* does not conflict with this interpretation. Sponge spicules are very rare and in view of the proximity of spongolite outcrops this is somewhat surprising. Presumably conditions were such that sponges did not live in the nearshore environment.

Lithology and fauna suggest that the Norseman Limestone correlates most closely with the Toolinna Limestone. From this evidence, and from Morgan's (1966) map of the salt-lakes drainage system, it is probable that the Eundynie Group was deposited in an arm of the Upper Eocene sea which connected with the open water conditions of the Eucla Basin.

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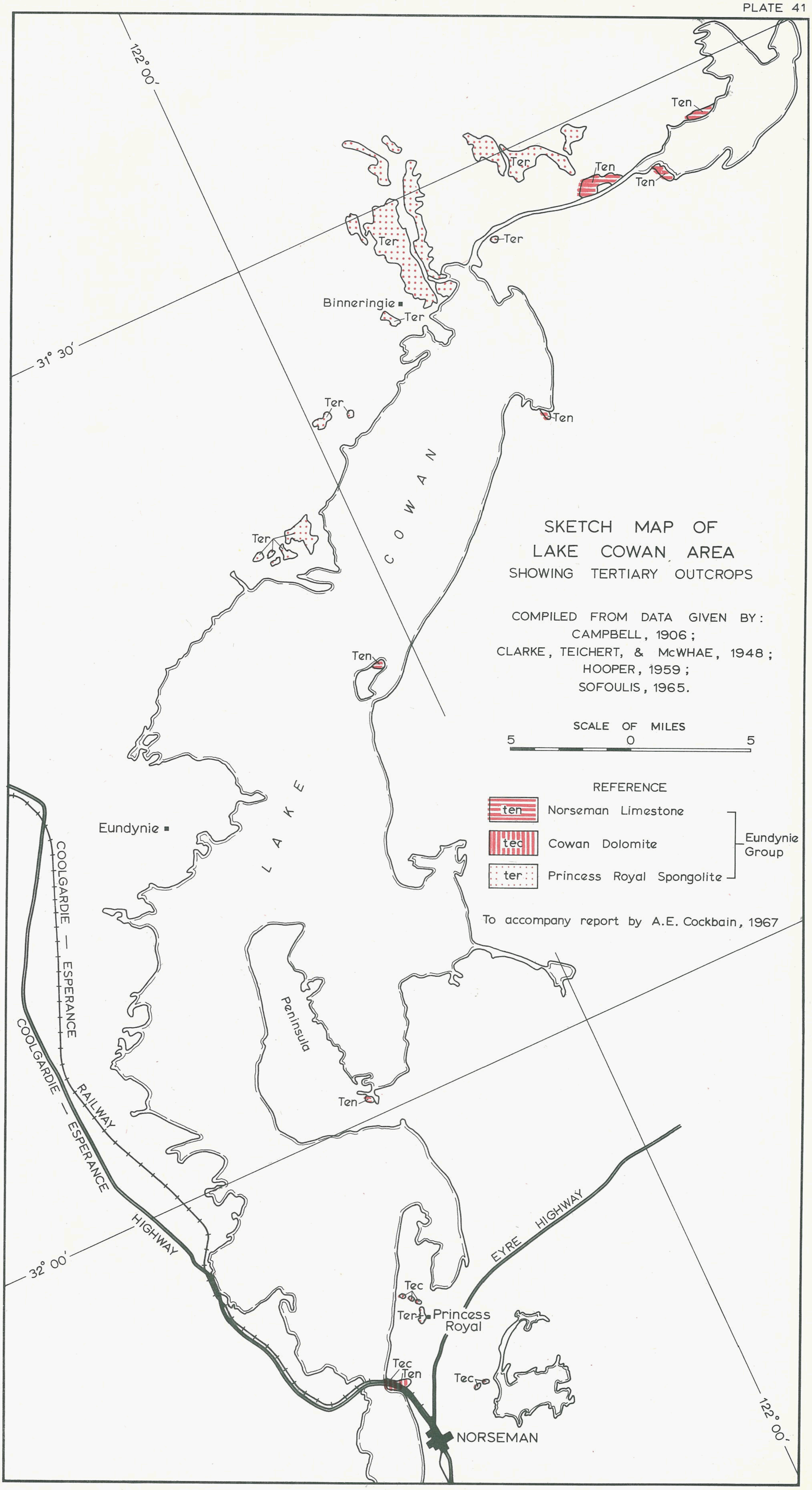


122° 00'
31° 30'
32° 00'
Ten
Ter
Binneringie
LAKE COWAN
Eundynie
Peninsula
COOLGARDIE — ESPERANCE RAILWAY
COOLGARDIE — ESPERANCE HIGHWAY
EYRE HIGHWAY
Tec
Princess Royal
NORSEMAN
SKETCH MAP OF
LAKE COWAN AREA
SHOWING TERTIARY OUTCROPS
COMPILED FROM DATA GIVEN BY:
CAMPBELL, 1906;
CLARKE, TEICHERT, & McWHAE, 1948;
HOOPER, 1959;
SOFOULIS, 1965.
SCALE OF MILES
5 0 5
REFERENCE
ten Norseman Limestone
tec Cowan Dolomite
ter Princess Royal Spongolite
Eundynie Group
To accompany report by A.E. Cockbain, 1967

# THE STRATIGRAPHY OF THE PLANTAGENET GROUP, WESTERN AUSTRALIA

by A. E. Cockbain

ABSTRACT

The Plantagenet Group in the Denmark-Esperance region consists of two new formations, the lower Werillup Formation of dark-coloured siltstone, sandstone, and lignite (including the thin Nanarup Limestone Member) and the upper Pallinup Siltstone of light-coloured siltstone and spongolite. Foraminifera from the Werillup Formation and nautiloids from the Pallinup Siltstone suggest an Upper Eocene age and hence correlation with the Eundynie Group and part of the Eucla Group.

## INTRODUCTION

The Plantagenet Beds were defined by Jutson and Simpson (1916, p.24) as a series of marine beds forming " . . . a low plateau to the north and northeast of Albany" and containing "abundant sponge spicules". The beds are now known to extend from Nornalup Inlet in the west to some 100 miles east of Esperance where they pass laterally into the Toolinna Limestone (Lowry, 1968). This region along the south coast of Western Australia will be referred to as the "Denmark-Esperance region" in this paper.

A type section for the Plantagenet Beds has never been designated and the only detailed description of the strata was given by Clarke and Phillips (1955). The purpose of this paper is to revise the stratigraphy of the Plantagenet Beds, define and describe two constituent formations, the Werillup Formation and the Pallinup Siltstone, and change the name of the unit to Plantagenet Group.

## PREVIOUS WORK

The original published description of the Plantagenet Group by Jutson and Simpson (1916) is, from internal evidence, a summary of their paper read before the Royal Society of Western Australia in October 1915 but not published until 1917. Prior to these papers the most important work was by Brown (1873, the relevant part of which is quoted by Maitland, 1899) and Maitland (1899, 1907) who described the Plantagenet Group between Albany and Cape Riche. A very full account of all the then-known outcrops of the Plantagenet Group was given by Clarke and Phillips (1955) who also summarised previous work on these beds. Subsequent stratigraphical work has been published by Sofoulis (1958) for the Ravensthorpe area, and Kay and others (1963) for the Bremer Bay area.

Palaeontologically, the Plantagenet Group has attracted considerable attention, especially because of the rich sponge fauna it contains. The most important works are by Chapman and Crespin (1926, 1934), molluscs and sponges; de Daubenfels (1953), sponges; Teichert (1944), Glenister and others (1956), Glenister and Glover (1958), Cockbain (1968), nautiloids; McTavish (1966), Cockbain (1967), foraminifers; Quilty *in* Hodgson and others (1962), foraminifers and echinoids; Cookson (1954), Balme and Churchill (1958), palynomorphus. Prior to 1953 the Plantagenet Group was assigned to the Miocene; however the presence of *Aturia clarkei* suggested an Upper Eocene age to Glaessner (1953). Later work (McTavish, 1966; Cockbain, 1967, 1968) has tended to substantiate this age.

## GENERAL STRATIGRAPHY

The Plantagenet Group was laid down on an uneven surface of Precambrian granite, gneiss, schist, and quartzite. Observations along the Pallinup River valley show that there is at least 200 feet of relief on this surface; evidence from boreholes would no doubt increase this figure. The beds are horizontal and are very rarely faulted. The abundance of sponge remains in the Plantagenet Group has been emphasised, and although spongolite is an important constituent, a variety of rock types occur, including sandstone, siltstone, limestone, conglomerate, clay and lignite.

Two major lithological units can be recognised in the Plantagenet Group: an upper unit of light coloured sandy siltstone and spongolite, and a lower unit of dark coloured siltstone, sandstone, carbonaceous clay, and lignite.

The stratigraphical nomenclature can be formalised as follows:

Plantagenet Group
- Pallinup Siltstone; white brown, red siltstone and spongolite, maximum thickness 200 feet.
- Werillup Formation; dark grey siltstone, maximum thickness 160 feet.

Descriptions of these formations are given below. The location of sections mentioned in the text is shown in Plate 42 and the measured sections are drawn in Plate 43.

## WERILLUP FORMATION

The name Werillup Formation is proposed for the dark-coloured sandstone and siltstone with occasional lignite occurring in the Denmark-Esperance region. The formation is named after a trigonometrical station some 4 miles west of Princess Royal Harbour, Albany. The lignite in the Fitzgerald River area was referred to as the "Fitzgerald Brown Coal Series" by Blatchford (1930) and whilst this name has priority over "Werillup Formation", it was not adequately defined and it is suggested that the term be allowed to lapse.

*Type section:* The type section is between 56 and 193 feet in Werillup 3 borehole situated 30 chains southwest of Albany prison. The formation rests on weathered granite and is overlain by Quaternary sand in the type section. Cuttings from this bore are stored in the core library of the Geological Survey.

*Lithology:* The Werillup Formation consists of grey and black clay, siltstone, sandstone, lignite, and carbonaceous siltstone. Bryozoan limestone at Nanarup quarry is here placed in the Nanarup Limestone Member.

*Stratigraphical relationships:* At its type section the Werillup Formation is underlain by Precambrian granite, the upper 67 feet of which is weathered to a white and grey clay. In all localities where the base of the formation is present it rests on Precambrian rocks.

*Distribution and thickness:* The formation is 132 feet thick at the type section and reaches a maximum known thickness of 160 feet in the Albany Aerodrome Bore. The Werillup Formation has a patchy distribution. Lignites have been recorded from Nornalup Inlet, Denmark, Fitzgerald River, and Esperance. Dark grey siltstone and sandstone with occasional carbonaceous siltstone also occurs in boreholes near Neridup, northeast of Esperance.

*Palaeontology:* The lignites contain microplankton, spores, and pollen which have been recorded by Cookson (1954) and Balme and Churchill (1959). Siltstone from the Neridup boreholes have yielded an abundant fauna of foraminifers, including the genus *Asterocyclina* (Cockbain, 1967), and bryozoans.

*Age and correlation:* The foraminifer fauna is of Upper Eocene age (Cockbain, 1967) and correlates with Ludbrook's (1963) "Tortachilla microfaunule". Formerly two microfloral assemblages based on the presence or absence of *Proteacidites pachypolus* were considered to occur in the lignites (Balme and Churchill, 1959). This species is now known to range from Upper Palaeocene to Upper Eocene (Harris, 1965), and Ingram (1967) believes these microfloras to be of Upper Eocene age. At the present time there is no evidence to suggest that the Werillup Formation (and hence the Plantagenet Group) is older than Upper Eocene.

The foraminifer fauna suggests correlation of the formation with the Norseman Limestone (Eundynie Group), Toolinna Limestone, and upper part of the Wilson Bluff Limestone (Eucla Group). In South Australia, the closest correlative formation is the Tortachilla Limestone. Eocene clays and lignites are also known from South Australia in the Pidinga Formation, Knight Group, and in lateral equivalents of the North Maslin Sand.

*Condition of deposition:* The Werillup Formation contains both marine and non-marine strata. There is no consistency in the stratigraphical sequence of marine and non-marine beds. The sporadic distribution of the formation and the presence of lignite and non-marine clays indicates that the beds were laid down in isolated hollows in the underlying Precambrian surface. Peat swamps were flooded by the sea and in some cases an area became landlocked and swamp conditions developed after an initial marine phase. The transgressing sea laid down silt, sand, and clay. A prolific shallow water fauna of foraminifers and bryozoans lived in the sea which, on the evidence of the tropical genus *Asterocyclina,* was warm along this coast in Upper Eocene times (Cockbain, 1967).

## NANARUP LIMESTONE MEMBER OF THE WERILLUP FORMATION

The name "Nannarup Limestone" *(sic)* was used, without definition, by McTavish (1966) following unpublished work by Quilty (*in* Hodgson and others, 1962). The unit is here defined as the Nanarup Limestone Member of the Werillup Formation to refer to the brown and white bryozoan limestone occurring in Nanarup lime quarry.

*Type section:* The type section is taken as the beds of limestone exposed in Nanarup lime quarry, (Mt. Barker run 8, photo serial no. 2944, quadrant D, x co-ord 1.31, y co-ord 0.73; Jan. 1965 photography). The base and top of the member are not exposed.

*Lithology:* The Nanarup Limestone Member comprises brown and white friable bryozoan limestone.

*Stratigraphical relationships:* Contacts with other formations are nowhere exposed. The member is placed in the Werillup Formation because of its fauna (see below) and its low altitude (approximately 30 feet above sea level); the Werillup Formation is well developed at the base of the Tertiary sequence in the Albany area.

*Distribution and thickness:* The member is known only from its type section where it is 15 feet thick.

*Palaeontology:* The limestone has yielded a good fauna of foraminifers, echinoids, bryozoans, brachiopods, and molluscs which have yet to be determined in full. The benthonic foraminifers and echinoids are recorded by Quilty (*in* Hodgson and others, 1962) whilst some remarks on planktonic foraminifers are given by McTavish (1966).

*Age and correlation:* An Upper Eocene age has been assigned to the fauna by McTavish (1966) and the foraminifers belong to the "Tortachilla microfaunule". The close similarity between the fauna of the Nanarup Limestone Member and that from the Werillup Formation in the Neridup boreholes is the main basis for assigning the member to the Werillup Formation.

*Conditions of deposition:* The fauna of the Nanarup Limestone Member suggests that the member was deposited in a shallow marine environment. Possibly local conditions caused a temporary lull in detrital deposition, enabling a shelly carbonate rock to form.

## PALLINUP SILTSTONE

The name Pallinup Siltstone is proposed for the light coloured, frequently banded siltstone and spongolite commonly occurring throughout the Denmark-Esperance region. These are the rocks which are usually considered typical of the "Plantagenet Beds". The formation is named after the Pallinup River. Maitland (1907) referred to the Pallinup Siltstone in the Albany-Cape Riche area as the "Cape Riche beds" and the "Warriup beds", but the names were not defined, have not been used subsequently and should be allowed to lapse.

### *Type section*

The type section is exposed in a cliff on the north side of Beaufort Inlet about one mile upstream from the mouth of the Pallinup River (Bremer Bay run 11, photo serial no. 5581, quadrant A, x co-ord 1.95, y co-ord 0.5; January 1958 photography). The section extends from river level up to the top of the cliff.

### *Lithology*

The Pallinup Siltstone typically consists of white, brown or red siltstone, and spongolite. Well-developed burrowings are present at several levels in the type section. The basal beds tend to be somewhat sandy, as in the type section, and in the upper part the rocks may be laminated and sponge-bearing. In the Fitzgerald River and Ravensthorpe area, spongolite makes up a large portion of the formation and should probably be named as a member of the Pallinup Siltstone. East of Esperance, the Pallinup Siltstone is a siltstone with moulds of molluscs and bryozoans abundant in places; all carbonate appears to have been leached out of the rocks.

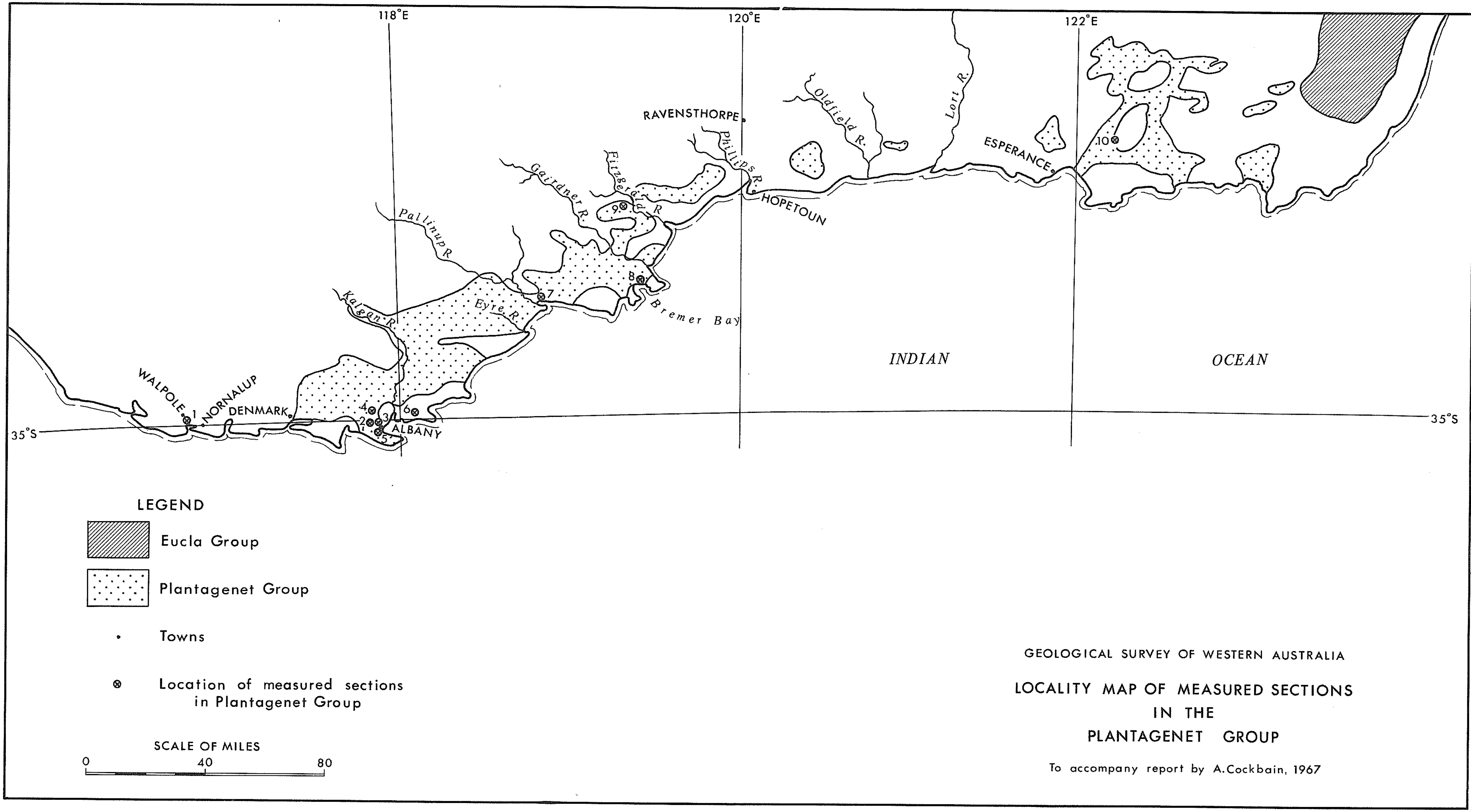
### *Stratigraphical relationships*

The base of the Pallinup Siltstone is not exposed at its type section. In the Neridup boreholes the Werillup Formation is conformably overlain by yellow-brown silty sandstone of the Pallinup Siltstone. The Albany Aerodrome bore, although not logged in detail, shows brown clay and siltstone of the Pallinup Siltstone (well exposed in Stoke's Brick Yard and near Cuthbert) overlying sand and clay with fossil wood which is assigned to the Werillup Formation. In the Fitzgerald River area the Pallinup Siltstone must overlie the Werillup Formation although the contact has not been seen. Elsewhere the Pallinup Siltstone rests directly on Precambrian rocks. There is a thin pebble bed at the base in some exposures in the Fitzgerald River area. Near the mouth of the Eyre River a thin shelly silty sandstone lies on tope of Precambrian gneiss. At Hummocks Beach, Bremer Bay, siltstone is underlain by 15 feet of boulder conglomerate (Kay and others, 1963) resting on a sloping surface of Precambrian rock.

### *Distribution and thickness*

The formation is 153 feet thick at the type section. The maximum known thickness of 200 feet occurs in the Albany Aerodrome bore, although greater thickness will probably be measured in the Bremer Bay to Ravensthorpe area.

The Pallinup Siltstone outcrops from north of Walpole, where a good fauna of molluscs and sponges have been found recently (G. W. Kendrick, pers. comm., Feb. 1967) to about 100 miles east of Esperance where the formation passes laterally into the Toolinna Limestone of the Eucla Basin. The formation extends at least as far north as the southern edge of the Stirling Range, there being good exposures of sponge-bearing white, brown and red siltstone in the Kalgan Valley east of Kendenup. There are records of plant remains and sponge-bearing siltstone to the north of the Stirling Range which probably indicate a northerly extension of the Pallinup Siltstone.




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

LOCALITY MAP OF MEASURED SECTIONS IN THE PLANTAGENET GROUP

To accompany report by A. Cockbain, 1967

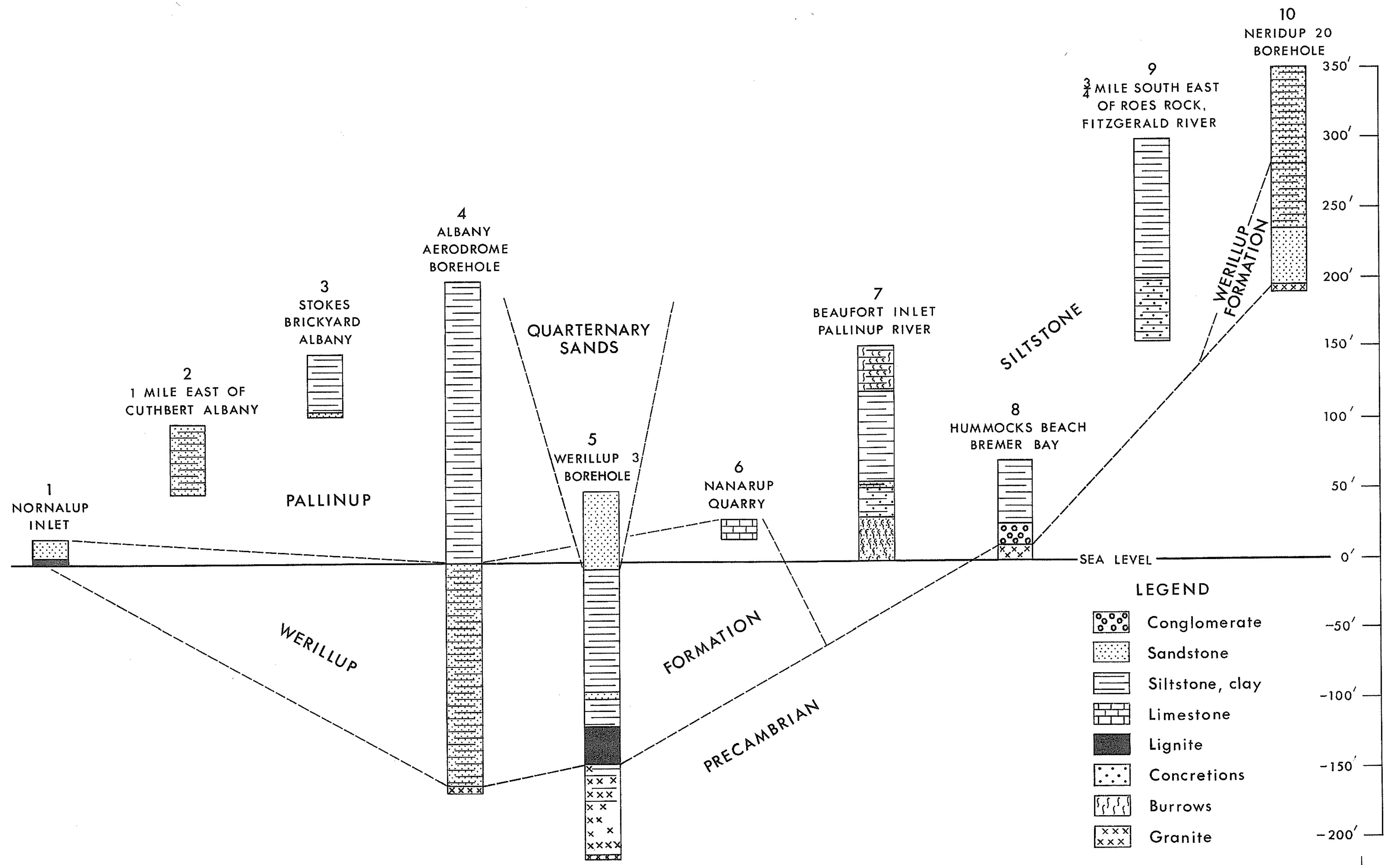
PLATE 42

9866

PLATE 43

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MEASURED VERTICAL SECTIONS IN THE PLANTAGENET GROUP OF DENMARK-ESPERANCE REGION

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*Palaeontology*

Most of the fossils listed by Chapman and Crespin (1934) as coming from the Plantagenet "Beds" in fact come from the Pallinup Siltstone. Preservation is frequently poor, and many of the fossils occur as internal and external moulds. Molluscs, sponges, and bryozoans are the most abundant fossils; nautiloids are rare, but stratigraphically useful. Foraminifers are also rare in the Pallinup Siltstone, but are known from the Jerdacuttup River north of Hopetoun (G.S.W.A. palaeontology collection) and the Bremer River (Glenister and Glover, 1958).

*Age and correlation*

The nautiloids *Aturia clarkei, Teichertia prora,* and *Cimomia felix* (see Teichert, 1944; Glenister and others, 1956; Glenister and Glover, 1958; Cockbain, 1968) have been recorded from the Pallinup Siltstone. All three genera occur in Upper Eocene or Middle and Upper Eocene strata elsewhere in Australia and together suggest an Upper Eocene age for the formation.

Lithologically the Pallinup Siltstone correlates with the Princess Royal Spongolite (Eundynie Group) and from its stratigraphical position it is laterally equivalent to the Toolinna Limestone and upper part of the Wilson Bluff Limestone. Spongolites are not known in the Eastern States, but the Pallinup Siltstone is of the same age as the Blanche Point Marls and Buccleuch Group of South Australia.

*Conditions of deposition:* The Pallinup Siltstone was laid down in a shallow transgressive sea because the formation overlaps the Werillup Formation and comes to rest on the Precambrian. Sand, sometimes pebbly, was the first deposit of this sea, with boulders occuring around areas of steeply sloping Precambrian basement. As the sea deepened, silt was laid down. Where terrigenous material was negligible and sponges throve, the sediment was extremely rich in sponge spicules. Eastwards, shelly material became abundant as the margins of the region of carbonate deposition in the Eucla Basin were approached.

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# STRATIGRAPHICAL PALYNOLOGY OF CRETACEOUS ROCKS FROM BORES IN THE EUCLA BASIN, WESTERN AUSTRALIA

by B. S. Ingram


## ABSTRACT

The Madura Shale in Madura No. 1, Eyre No. 1, and Gambanga No. 1 boreholes is subdivided into three microfloral assemblage zones of Neocomian—Aptian—Albian—Cenomanian, and Senonian age, and correlated with Cretaceous formations in the Perth Basin. All strata are marine except for non-marine Neocomian—Aptian beds (containing the first record of *Crybelosporites stylosus* in Western Australia) at the base of Madura 1 and Gambanga No. 1.


## INTRODUCTION

The existence of Cretaceous strata in the Eucla Basin has been known since 1910 when R. Etheridge, Jr., in a letter to A. G. Maitland, recorded *Aucella hughendenensis* and *Maccoyella corbiensis* from the Loongana (or No. 3) bore, although the identifications were not published until 5 years later (Maitland, 1915). The Lower Cretaceous age suggested by these pelecypods was long accepted as the age of all sediments below the Tertiary rocks of the Eucla Basin (see, for example, McWhae and others, 1958, p. 118).

Ludbrook (1958, 1960) showed that a much wider range of Cretaceous strata was present using evidence from arenaceous foraminifers and also suggested correlation on lithological grounds with Perth Basin formation. She commented, however (1958, p.111), that ". . . palynological study of the core in this bore (Madura 1) should be undertaken to confirm the correlations . . . ". The present work was carried out with this comment in mind.

Cretaceous strata do not crop out in the Western Australian part of the Eucla Basin and all information comes from boreholes. Pertinent boreholes are Madura 1, Loongana (or No. 3), both drilled by the Western Australian Public Works Department in 1902 and 1907 respectively, and Eyre No. 1 and Gambanga No. 1, drilled as oil exploration wells by Exoil Pty. Ltd. in 1959 to 1960.

Fairbridge (1953) proposed two formations, the Madura Shale and Loongana Conglomerate, for the Cretaceous strata in the Eucla Basin. The latter was defined as the sand and conglomerate in Loongana bore, between 1,260 and 1,314 feet. The Madura Shale was inadequately defined by Fairbridge (1953) and was placed in the Tertiary (p.X/9) and, on a later page, in the Cretaceous (p.XI/9). Subsequently McWhae and others (1958, p. 118) selected the type section in Madura 1 bore as ". . . between 927 feet and 2,041 feet (the total depth of the bore)". In fact the total depth is 2,101 feet, but since the lithology below 2,041 feet is similar to that above, all strata between 927 and 1,101 feet are here assigned to the Madura Shale.

The samples studied for this paper come from the Madura Shale in Madura 1, Eyre No. 1, and Gambanga No. 1 boreholes. The position of these bores is shown on the accompanying map (Plate 44). Portions of all available cores were treated by routine palynological methods and the important palynomorphs identified in each assemblage are recorded in Table 1. The material available for study from Madura 1 represents only a fraction of the original, as the bore was cored throughout, but it appears that only representative samples of each major rock type were kept. Frequently it is only possible to locate a sample within a 300-foot interval of the bore.

## PALYNOLOGICAL ASSEMBLAGE ZONES

Three Cretaceous palynological assemblage zones can be recognized in these bores. The assemblages correspond closely to those from the Gingin Chalk and associated greensand, the Osborne Formation, and the South Perth formation in the Perth Basin. The exact position of these assemblage zones within the European Stages is uncertain (see Ingram, 1967). The following table summarises these assemblage zones and correlates them with the age units suggested by N. H. Ludbrook.

| Ludbrook, 1958 | Ludbrook, 1960 | Palynological units | |
|---|---|---|---|
| Santonian | post-Cenomanian | Senonian | |
| ?Cenomanian-Albian | ? Cenomanian<br>Albian<br>? Albian | Albian-Cenomanian | |
| Aptian | .............. | Marine | Neocomian-<br>Aptian |
| | | Non-marine | |

**The correlation of these units in the three bores** is shown on Plate 45. The palynological assemblage zones are defined on microplankton, and spores and pollen grains. A chart showing the distribution of some of the genera and species identified is given as Table 1. The main features of each assemblage zone are discussed below.

### *Senonian*

All samples of Senonian age are marine and hence contain few spores and pollen grains. However some samples contain several species of *Proteacidites*, indicative of a late Upper Cretaceous or younger age. Microplankton present include several species previously recorded only from Upper Cretaceous strata in the Perth and Carnarvon Basins, for example:

- *Dinogymnium westralium* (Cookson and Eisenack).
- *Deflandrea tripartita* (Cookson and Eisenack).
- *Odontochitina cribropoda* (Deflandre and Cookson).
- *Nelsoniella aceras* (Cookson and Eisenack).
- *N. tuberculata* (Cookson and Eisenack).

### *Albian-Cenomanian*

The microfloras in the Albanian-Cenomanian assemblage zone are very similar to those from the Osborne Formation in the Perth Basin. For example, species of the microplankton *Diconodinium* and *Gonyaulacysta*, spores and pollen grains such as *Gleicheniidites* (at least three species), *Laevigatosporites*, and *Hoegisporis* (a restricted Albian-Cenomanian form) occur and all are common also in the Osborne Formation.

Microplankton species present which are only known from Albian-Cenomanian strata include:

- *Odontochitina striatoperforata* (Cookson and Eisenack).
- *Gonyaulacysta edwardsi* (Cookson and Eisenack).
- *Diconodinium dispersum* (Cookson and Eisenack).
- *D. glabrum* (Eisenack and Cookson).

### *Neocomian-Aptian*

Lower Cretaceous assemblages are present below about 1,960 feet in Madura 1 and in Cores 8 and 9 (1,200 to 1,229 feet) in Gambanga No. 1. The section in Madura 1 can be divided into marine (1,960 to 2,049 feet) and non-marine (below 2,049 feet). The Lower Cretaceous in Gambanga No. 1 is non-marine, correlating with or possibly even older than, the non-marine section in Madura 1.

The two diagnostic microplankton in the marine section are *Dingodinium cerviculum* (Cookson and Eisenack and *Muderongia mcwhaei* (Cookson and Eisenack), both of which appear to be restricted to Upper Neocomian-Aptian strata in Australia (Evans, 1966).

Spores and pollen grains are more diverse in this unit including mainly Lower Cretaceous forms although some extend into the Jurassic. Species include:

*Cicatricosisporites australiensis* (Cookson).

*Coronatispora telata* (Balme).

*Crybelosporites stylosus* Dettmann.

*Dictyophyllidites crenatus* Dettmann.

*Dictyotosporites complex* Cookson and Dettmann.

*Lycopodiumsporites circolumensis* Cookson and Dettmann.

Many other species, including species of long ranging genera such as *Tsugaepollenites, Ischyosporites, Contignisporites* and *Aequitriradites,* are also present.

## STRATIGRAPHICAL COMMENTS ON SOME OF THE SPECIES

*Microplankton*

The microplankton genera are arranged in alphabetical order.

### *DICONODINIUM* Eisenack and Cookson

A genus commonly abundant in the Osborne Formation and common in a few samples from the Albian-Cenomanian assemblage zone. Two of the species recorded here (*D. dispersum* (Cookson and Eisenack) and *D. glabrum* (Eisenack and Cookson) appear to be restricted to Albian-Cenomanian strata in Western Australia (Eisenack, 1964).

### *DINGODINIUM* Cookson and Eisenack

*Dingodinium cerviculum* Cookson and Eisenack

A common, widespread dinoflagellate which is considered to be restricted to late Neocomian-Aptian throughout Australia (Evans, 1966) and also in Germany (Alberti, 1961). In the Perth Basin it occurs only at the top of the South Perth Formation, where the formation is marine (Edgell, 1964).

### *DINOGYMNIUM* Evitt, Clarke and Verdier

Fossil dinoflagellates previously referred to *Gymnodinium* Stein are now placed in this genus.

*Dinogymnium westralium* (Cookson and Eisenack)

This species, and a few specimens of an indeterminate species of *Dinogymnium,* were recorded in samples from the upper assemblage zone unit. Evitt, Clarke, and Verdier (1967, p. 5) comment: "this genus is highly characteristic of Upper Cretaceous marine strata", and consider the few records outside of Upper Cretaceous can be attributed to reworking.

In Western Australia *D. westralium* has been recorded previously from the Korojon Calcarenite and the Molecap Greensand (Deflandre and Cookson, 1955; Cookson and Eisenack, 1958).

### *DEFLANDREA* Eisenack

A common genus with over 40 species. According to Manum and Cookson (1964, p. 31) it "has its main distribution in Upper Cretaceous and younger beds". Core 6 in Gambanga No. 1 has a particularly rich assemblage of *Deflandrea* species, several of which appear to be undescribed. *D. tripartita* Cookson and Eisenack, which occurs in some samples of the upper assemblage zone, has been recorded only from the Upper Cretaceous of Western Australia (Cookson and Eisenack, 1960) and Victoria (Cookson and Eisenack, 1961).

### *GONYAULACYSTA* Deflandre

*Gonyaulacysta edwardsi* (Cookson and Eisenack)

This species is said by Sarjeant (1966, p. 130) to range from Aptian to Turonian in Australia but has only been seen by the author in the Osborne Formation in the Perth Basin. It occurred only in the middle assemblage zone in this study.

Core 20 in Eyre No. 1 contains an abundance of large specimens of this genus (including *G. edwardsi*) which would be well worth taxonomic study.

### *MUDERONGIA* Cookson and Eisenack

*Muderongia mcwhaei* Cookson and Eisenack

Has a restricted range from Upper Neocomian to Aptian (Evans, 1966).

### *NELSONIELLA* Cookson and Eisenack

The only three species of this genus described by Cookson and Eisenack, 1960, are all from Western Australian Upper Cretaceous strata. The two recorded in this study (*N. aceras* and *N. tuberculata*) came from the upper assemblage zone.

### *ODONTOCHITINA* Deflandre

*Odontochitina cribropoda* Deflandre and Cookson

A distinctive species, again with a recorded occurrence restricted to the Upper Cretaceous in Western Australia and also in the Nelson Bore, Victoria (Cookson and Eisenack, 1960, p. 7).

*Odontochitina striatoperforata* Cookson and Eisenack

This species has only been recorded from Albian-Cenomanian strata in Australia (Cookson and Eisenack, 1962). It is very similar to *O. costata* described by Alberti (1961) from the Cenomanian-Turonian of Germany.

*Spores*

Only one species is considered worthy of comment.

### *CRYBELOSPORITES* Dettmann

*Crybelosporites stylosus* Dettmann

This species is considered by Dettmann (1963) to be restricted to the lower Neocomian in south-eastern Australia. Evans (1966, p. 10) notes it "is not a common fossil" and "more records of the species" occurrence are needed to indicate whether it is a reliable Cretaceous marker. The presence of *C. stylosus* in Madura 1 and Gambanga No. 1 is the first record of the species in Western Australia. It has not been seen in the numerous Neocomian samples which the author has examined from the Perth Basin.

## CONCLUSIONS

Palynological study of some Cretaceous sections in the Eucla Basin has shown that three microfloral assemblage zones can be determined, with a marked similarity to Perth Basin assemblages. This basically supports the stratigraphy as envisaged by Ludbrook (1958, 1960) although some of her boundaries are changed and Lower Cretaceous strata are recognized in Gambanga No. 1. This is based largely on the presence of *Crybelosporites stylosus* Dettmann, recorded for the first time in Western Australia.



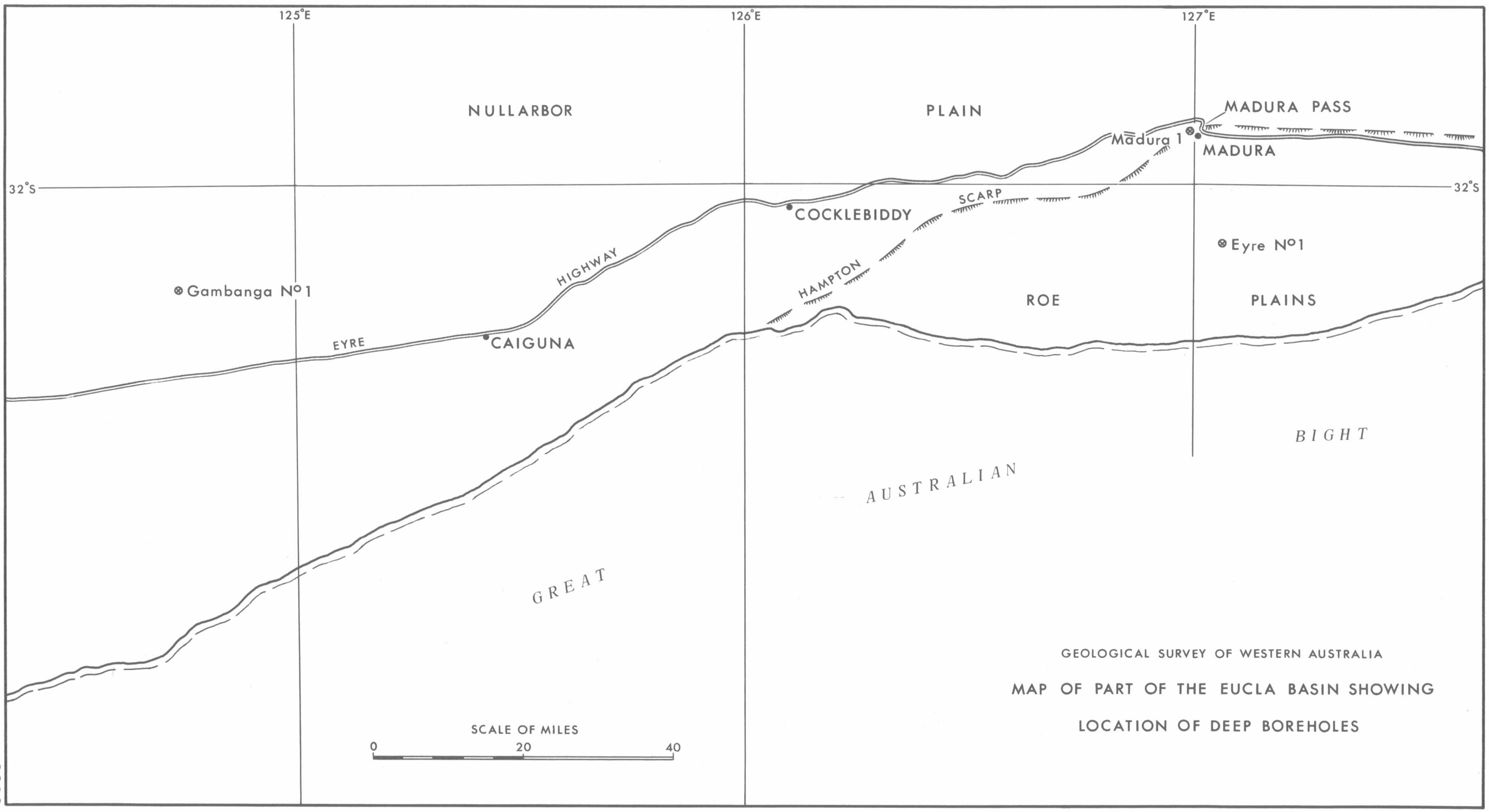
(5)—41571

**MICROPLANKTON**

| Bore | Sample Depth (feet) | Registered No. | Odontochitina cribropoda Deflandre & Cookson | O. porifera Cookson | Deflandrea tripartita Cookson & Eisenack | D. serratula Cookson & Eisenack | D. balmei Cookson & Eisenack | D. sp. cf. D. acuminata Cookson & Eisenack | D. spp. | Dinogymnium westralium (Cookson & Eisenack) | D. sp. indet. | Diconodinium pelliferum (Cookson & Eisenack) | Palambages (?algae) | Nelsoniella aceras Cookson & Eisenack | N. Tuberculata Cookson & Eisenack | Xenikoon australis Cookson & Eisenack | Palaeohystrichophora infusorioides Deflandre | Gonyaulacysta edwardsi (Cookson & Eisenack) | G. sp. cf. G. apionsis (Cookson & Eisenack) | G. spp. | Odontochitina striatoperforata Cookson & Eisenack | Microdinium ornatum Cookson & Eisenack | Ascodinium parvum (Cookson & Eisenack) | A. acrophorum Cookson & Eisenack | Diconodinium dispersum (Cookson & Eisenack) | D. glabrum Eisenack and Cookson | D. multispinum (Deflandre & Cookson) | Fromea amphora Cookson & Eisenack | Muderongia sp. cf. M. tetracantha (Gocht) | Diplofusa sp. cf. D. gearlensis Cookson & Eisenack | Veryhachium spp. | Dingodinium cerviculum Cookson & Eisenack | ? Canninginopsis sp. | Chlamydophorella nyei Cookson & Eisenack | Pterodinium cornutum Cookson & Eisenack | Muderongia mcwhaei Cookson & Eisenack | Gen et sp. indet. Forma A Eisenack & Cookson | Gonyaulacysta muderongensis (Cookson & Eisenack) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MADURA 1 | 963–968 | F6701 | × | | × | | | | × | × | × | × | × | | | | | | | | | | | | | | | | | | × | | | | | | | |
| MADURA 1 | 968–988 | F6702 | × | | | | | | | × | | | | × | × | | | | | | | | | | | | | | | | | | | | | | | |
| MADURA 1 | 1104–1470 | F6703 | | | | | | | | | | | | | | | | × | | | × | × | × | | | | | | | | × | | | | | | | |
| MADURA 1 | 1471–1486 | F6704 | | | | | | | | | | | | | | | | | × | | | | | | × | | | | | | | | | | | | | |
| MADURA 1 | 1486–1523 | F6705 | | | | | | | | | | | | | | | | | | | | | × | | × | × | | × | | | × | | | | | | | |
| MADURA 1 | 1523–1775 | F6706 | | | | | | | | | | | | | | | | | | | | | | | | | | | × | | | | | | | | | |
| MADURA 1 | 1775–1839 | F6707 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| MADURA 1 | 1839–1978(A) | F6708 | | | | | | | | | | | | | | | | × | × | | × | | | | | × | × | | × | | × | | | | | | | |
| MADURA 1 | 1839–1978(B) | F6709 | | | | | | | | | | | | | | | | | | × | | | | | | | | | × | | | × | × | × | | | | |
| MADURA 1 | 1960–1978 | F6710 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | × | | × | × | | | |
| MADURA 1 | 1978–1979 | F6711 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | × | | | | | | |
| MADURA 1 | 1979–1991 | F6712 | | | | | | | | | | | | | | | | | | | | | | | | | | ? | | | × | × | | | | × | × | × |
| MADURA 1 | 2015–2049 | F6713 | | | | | | | | | | | | | | | | | | | | | | | | | | × | × | | | × | | | | × | | |
| MADURA 1 | 2049–2101 | F6714 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | ? | |
| GAMBANGA No. 1 | 910–920 | F6715 | × | × | | | × | × | × | × | | | × | × | | | × | | | | | | ? | | | | | | | | | | | | | | | |
| GAMBANGA No. 1 | 1055–1065 | F6716 | | | | | × | | | | | | | | | | | | | | | | × | | × | × | × | × | | | × | | | | | | | |
| GAMBANGA No. 1 | 1200–1209 | F6717 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| GAMBANGA No. 1 | 1209–1229 | F6718 | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| EYRE No. 1 | 1220–1230 | F6719 | | | × | × | | | | | | | | × | | × | × | | | | | | | | | | | | | | | | | | | | | |
| EYRE No. 1 | 1400–1420 | F6720 | | | | | | | | | | | | | | | | × | | × | × | | | × | | | | | | × | | | | × | | | | |

**SPORES AND POLLEN GRAINS**

| Bore | Sample Depth (feet) | Registered No. | Proteacidites spp. | Gleicheniidites spp. | G. circinidites (Cookson) | Laevigatosporites sp. | Hoegisporis sp. | Microcachyridites antarcticus Cookson | Plicatella sp. | Cicatricosisporites sp. cf. C. hughesi Dettman | Inaperturopollenites limbatus Balme | Ceratosporites equalis Cookson & Dettmann | Tsugaepollenites spp. | Lycopodiumsporites circolumensis Cookson & Dettmann | Cicatricosisporites australiensis (Cookson) | Crybelosporites stylosus Dettmann | Coronatispora telata (Balme) | Dictyotosporites complex Cookson & Dettmann | Dictyophyllidites crenatus Dettmann | Aequitriradites sp. | Ischyosporites sp. | AGE UNITS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| MADURA 1 | 963–968 | F6701 | × | × | | × | | | | | | | | | | | | | | | | Senonian |
| MADURA 1 | 968–988 | F6702 | × | × | | × | | | | | | | | | | | | | | | | Senonian |
| MADURA 1 | 1104–1470 | F6703 | | × | × | × | | | | | | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1471–1486 | F6704 | | × | | × | × | × | | | | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1486–1523 | F6705 | | × | × | × | × | × | × | × | | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1523–1775 | F6706 | | | | | | × | | × | | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1775–1839 | F6707 | | × | × | | | × | | | | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1839–1978(A) | F6708 | | | × | | | × | | | × | | | | | | | | | | | Albian—Cenomanian |
| MADURA 1 | 1839–1978(B) | F6709 | | | | | | × | | | | × | | | | | | | | | | Neocomian—Aptian |
| MADURA 1 | 1960–1978 | F6710 | | | × | | | × | | | | | × | × | | | | | | | | Neocomian—Aptian |
| MADURA 1 | 1978–1979 | F6711 | | | × | | | × | | | × | × | | | | | | | | | | Neocomian—Aptian |
| MADURA 1 | 1979–1991 | F6712 | | | × | | | × | | × | | | × | × | | | | | | | | Neocomian—Aptian |
| MADURA 1 | 2015–2049 | F6713 | | | × | | | × | | × | | | | × | | | | | | | | Neocomian—Aptian |
| MADURA 1 | 2049–2101 | F6714 | | | | | | × | | | | | × | × | × | × | × | × | × | | | Neocomian—Aptian |
| GAMBANGA No. 1 | 910–920 | F6715 | | × | | | | | | | | | | | | | | | | | | Senonian |
| GAMBANGA No. 1 | 1055–1065 | F6716 | | × | | | | × | | | × | | | | | | | | | | | Albian—Cenomanian |
| GAMBANGA No. 1 | 1200–1209 | F6717 | | | | | | × | | | | | | × | | × | | | | × | × | Neocomian—Aptian |
| GAMBANGA No. 1 | 1209–1229 | F6718 | | | | | | × | | | | | | | | × | | | × | × | × | Neocomian—Aptian |
| EYRE No. 1 | 1220–1230 | F6719 | × | × | | | | | | | | | | | | | | | | | | Senonian |
| EYRE No. 1 | 1400–1420 | F6720 | | | | | | | | | | | | | | | | | | | | Albian—Cenomanian |

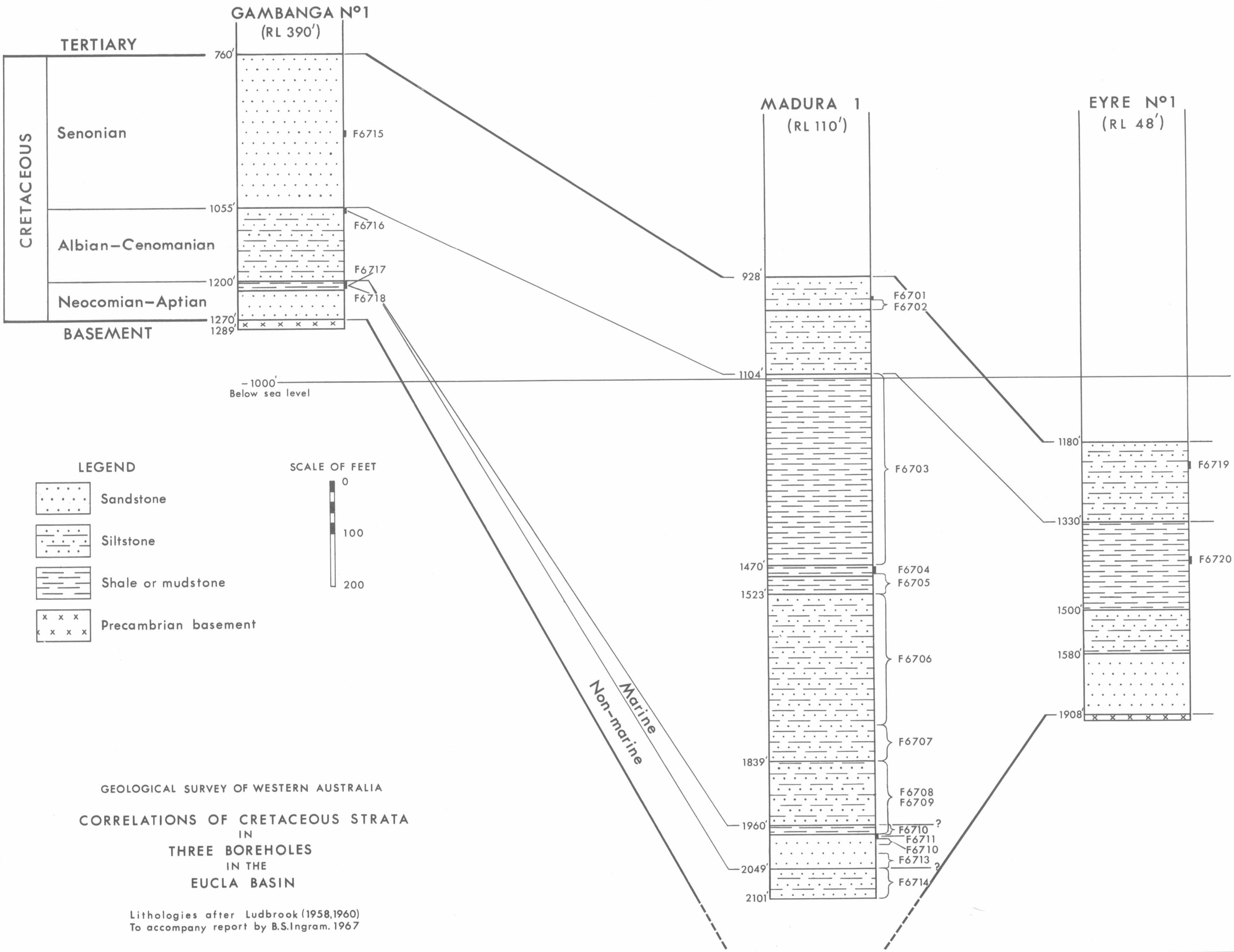



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MAP OF PART OF THE EUCLA BASIN SHOWING LOCATION OF DEEP BOREHOLES

6866

PLATE 44




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

CORRELATIONS OF CRETACEOUS STRATA IN THREE BOREHOLES IN THE EUCLA BASIN

Lithologies after Ludbrook (1958,1960)
To accompany report by B.S.Ingram. 1967

0666

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# A METEORITE FRAGMENT FROM DOOLGUNNA STATION, MEEKATHARRA DISTRICT, WESTERN AUSTRALIA

by W. N. MacLeod

ABSTRACT

A fragment of a chondritic meteorite has been recovered from a claypan near the southern boundary of Doolgunna Station in the Meekatharra District. The fragment weighs 20 grams and is the only piece found during an intensive search of the area.

The claypan, from which the fragment was recovered, bears some resemblance to a large meteorite explosion crater with a flat floor at a lower level than the surrounding country and an almost completely encircling sand dune. However, it is not considered to be a crater and it would appear likely that the meteorite has been carried into the claypan by aborigines.

## LOCALITY OF THE FIND

The claypan in which the meteorite was found is situated a few miles beyond the southern boundary of Doolgunna Station at latitude 25° 56′ S and longitude 119° 18′ E. This point is approximately 75 miles northeast of Meekatharra, the nearest town (see Plate 46).

From the southern part of the State the most convenient access is via the Great Northern Highway as far as the Doolgunna turn-off near Milepost 558. From Doolgunna homestead, which is 6 miles from the highway, the Diamond Well Station road is followed south for 22 miles. The claypan lies 2 miles west from this point and a vehicle with 4-wheel drive is required to negotiate the heavy drift sand over this final 2-mile approach. The circular peripheral dune completely hides the depression which cannot be seen until the summit of the dune is mounted.

The fragment was recovered on November 3rd, 1967 when I visited the depression in the company of Mr. Deane Davies of Doolgunna Station. Several weeks previously Mr. Davies had come across the depression by chance and had been impressed with the unusual circular form and distinctive vegetation pattern. I had observed the depression on aerial photographs and had noted the resemblance of the feature to a meteorite crater. However, such depressions are common on sand plains and develop over zones of higher water table as a result of progressive calcification of the soils and deflation by wind. Another depression, similar in form to the one in which the meteorite was found, lies about 3 miles to the north.

The floor of the depression is almost circular in plan with a maximum diameter of 1,600 feet. It supports a thick stand of desert oaks and is a pleasant shady oasis in contrast to the barren surrounding sand plain. The floor of the depression, which is almost perfectly flat, is between 6 and 10 feet lower than the general sand plain level and is made up of powdery calcareous soil and clay in which gilgai structures are common. The encircling dune forms an almost perfect amphitheatre except for a narrow breach on the northern side. The dune is composed of reddish brown and yellow quartz sand with a minor content of ironstone fragments and occasional kankar nodules. The dune is highest near the southern perimeter of the depression where it rises about 30 feet above the floor and 20 feet above the outside plain. It is asymmetrical in section with the steeper slope of between 10 to 15° on the outside and a gentler slope of about 5° on the inside down to the level floor of the depression.

There are no outcrops of any type of rock within or around the depression with the exception of kankar sheets and nodules near the breach in the dune at the northern end and in some zones around the gently sloping inner wall of the dune. The nearest exposures of hard rocks occur at Juderina Spring, about 5 miles west of the depression. Archaean granite and gneiss cut by basic dykes and quartz reefs crop out near the spring and probably underlie much of the extensive sand plain in which the depression is situated.

Despite the absence of any nearby outcrops, an assortment of stones was found in the depression in the grove of trees near the southern side. These included fragments of basic dyke rocks, amphibolites, quartz, and siliceous ironstone. These were lying loose on the surface scattered over a zone about 100 yards wide. Most of the fragments had been chipped and shaped and some had clearly been used as grinding stones. The place would appear to have been a tribal stonemason's "workshop", and it can be reasonably assumed that most of these stones have been carried into the site by natives. Small piles of stones from the excreta of emus are also common in the depression.

The meteorite fragment was recovered from the assortment of loose stones lying on the surface in the southern part of the depression. Under these circumstances it seems most likely that the fragment has been carried there by natives together with the other terrestrial stones, and the point of fall could be many miles distant.

The depression was revisited on November 27th and 28th and a very thorough search made of the area within and around the depression for more meteoritic material. None was found and a similar search of the northern depression, 3 miles distant, and the intervening sand plain proved equally fruitless. Magnetometer traverses were run across the southern depression in the hope of detecting anomalous zones which could correspond to buried meteorite material, and to check the possibility that the depression may actually be an ancient meteorite crater now infilled with sand and clay. No anomalies were detected and the variations could be attributed to normal magnetic gradients in the rocks beneath the sand plain. Pits were sunk in the floor of the depression and on the inner flank of the dune without disclosing any further rock or metorite fragments and conforming that the stones found on the surface had not been washed out of the underlying soil.

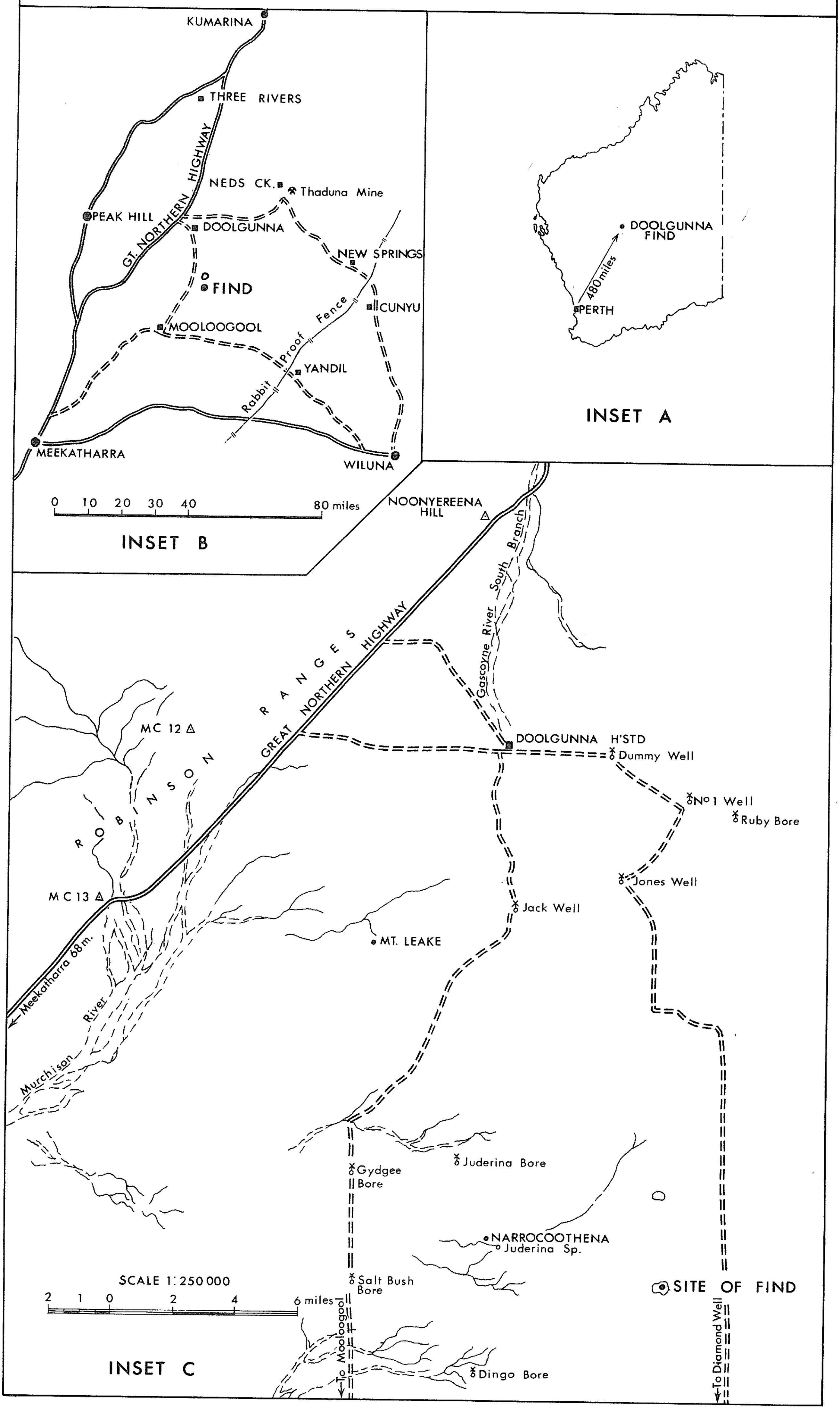
## DESCRIPTION OF THE METEORITE

The meteorite fragment is rhomboidal in shape and originally measured between 1.5 and 2 cm in diameter. When recovered the fragment weighed 20 grams but thin and polished sections have been cut for microscopic examination leaving a residual piece of 14 grams. The specific gravity is 3.37.

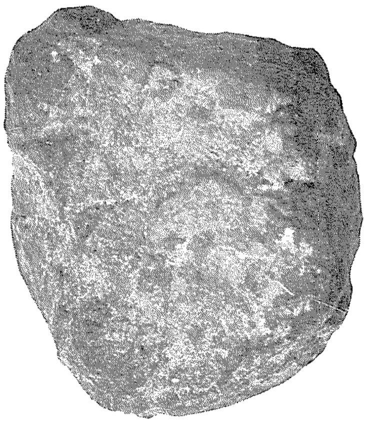
The surface is dark reddish brown with a thin coating of iron oxides which have probably developed during terrestrial weathering. Although the surface is pitted and rough there is little indication of fusion; flow lines are not apparent and there are no obvious signs of ablationary grooving or pitting. Shallow cracks extend across the full width of some faces. Both the angularity of the fragment and its rough hackly surface suggest that it may be one of many small stones produced by the disintegration of a larger body on entry into the atmosphere. There are many recorded instances of large stony meteorites breaking into thousands of small fragments during passage through the atmosphere. Accordingly a wider search for more fragments within this district would seem to be justified. Plate 47 A to C shows the external appearance of the meteorite fragment.

The meteorite has the following approximate mineralogical composition: olivine, 50 per cent.; orthopyroxene (hypersthene), 30 per cent.; nickel-iron and iron oxides, 20 per cent. There is a minor content of small clear plagioclase grains. The ferromagnesian silicate minerals are aggregated into chondrules in a mesostasis composed of small grains of olivine and orthopyroxene and the nickel-iron alloy. The composition and texture of the stone places it in the most common category of meteorites, the olivine-hypersthene chondrites.

# LOCALITY PLAN OF THE DOOLGUNNA METEORITE FIND



A



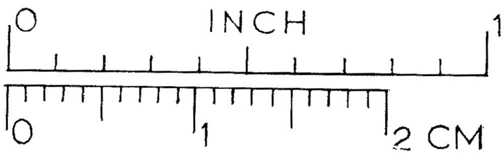
F 1195

B

F 1196

C

F 1197

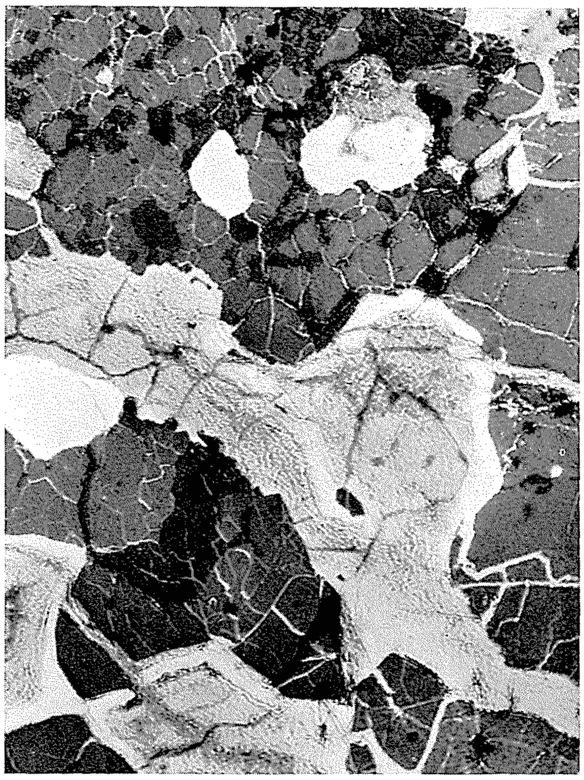



Photographs of the meteorite showing the hackly surface and irregular cracks.

D

Thin-section of the meteorite. Light-coloured areas are chondrules of olivine and orthopyroxene and dark areas correspond to nickel-iron and iron oxides. The large chondrule left of centre is composed entirely of olivine grains in random orientation and the chondrule in the extreme upper left is composed of bladed orthopyroxene (Magnification—8 diameters); F 1198.

E



Polished section of the meteorite viewed in reflected light. Nickel-iron forms the isolated white blebs. Iron oxides in broad veins and fine veinlets (light grey) cut the dark grey groundmass of silicate minerals. (Magnification—202 diameters); F 1199.

The chondrules generally range in diameter between 0.5 mm and 1.5 mm with the largest of the order of 2.5 mm and grading down to small monomineralic blebs of 0.2 mm. The majority of chondrules are made up of euhedral to subhedral olivine grains; a few are composed entirely of bladed, radiating crystals of hypersthene, whilst some contain both minerals, although in these cases the olivine is predominant and the orthopyroxene occupies a central position in the chondrule. The groundmass of the stone is made up of small grains (0.01 to 0.1 mm) of olivine and hypersthene with scattered and isolated subrounded grains of nickel-iron and occasional grains of clear plagioclase. The olivine crystals show a development of iron oxide and iron staining along cleavages but otherwise are unaltered.

A striking feature of the stone which is most apparent on examination of a polished section is the intricate net-veining of the entire stone by anastomosing veins and veinlets of iron oxides. These are probably a mixture of goethite and maghemite. From the complex penetrative relationships with all other constituents it is inferred that the iron oxides were the last minerals to form. Their distribution suggests a forcible injection into a shattered and cracked medium and it is a matter of surmise whether the shattering was developed during terrestrial or spatial impact. The iron oxides form continuous broad veins traversing and enclosing the chondrules and groundmass silicates, and penetrating along intergranular boundaries as a continuous network of fine veins.

The stone is sufficiently magnetic to be picked up by a small hand magnet. As the nickel-iron content amounts to little more than 5 per cent. of the volume it is thought that some of the magnetism is accountable to the presence of maghemite in the veins.

Typical textural and compositional features of the meteorite are illustrated in Plate 47 D and E.

# PRECAMBRIAN ROCKS ENCOUNTERED DURING DRILLING IN THE MAIN PHANEROZOIC SEDIMENTARY BASINS OF WESTERN AUSTRALIA

by R. Peers and A. F. Trendall


## ABSTRACT

The structural development of Western Australia during Phanerozoic times has produced the "basin and swell' structure typical of many shield continents; an inevitable consequence is that much Precambrian geology of potential interest is hidden. Thirty-three geologically recorded boreholes in the main Phanerozoic sedimentary basins of Western Australia have reached Precambrian rocks; 30 of these have been drilled since 1957 in the course of oil exploration. This paper is a compilation and summary of all information on the nature of the Precambrian rocks thus encountered, and includes a brief discussion of the signifiance of the information for Precambrian geology. In general, this is slight, but some possibilities for future work are noted, and one probable Precambrian sequence from the Officer Basin is well represented by preserved core, and is of interest for paleogeographic interpretation.


## INTRODUCTION

In most stable ("shield") regions of the present continents Phanerozoic sedimentary basins are separated by broad areas of Precambrian rocks. In Africa this has been aptly called "basin and swell" structures (Holmes, 1965, p. 1053-6); the western part of Australia has a closely similar structure. An important problem associated with it, as yet unresolved anywhere, is that of the genetic relationship between the Phanerozoic basins and the structure of the underlying Precambrian rocks: when and how, during the Precambrian, were the structures initiated which led to the sinking of the Phanerozoic basins in their present positions. Evidence for the solution of this problem must come mainly from detailed studies of the structural history of the Precambrian areas, but any continental-scale reconstruction of such history will involve postulated correlations across, and beneath, the Phanerozoic basins. Any direct evidence concerning the Precambrian rocks below these basins is therefore valuable.

During the last 60 years, 33 geologically documented boreholes have penetrated Precambrian rocks beneath the major Phanerozoic basins of Western Australia; 30 of these were drilled during petroleum exploration since 1957. Although descriptions of the rocks encountered in many of these holes are publicly available, some are not, and none have been collected and listed in a convenient form. The purposes of this paper are:

(1) to list all boreholes in the main Phanerozoic basins of Western Australia which penetrated to Precambrian rocks, and to show their locations on a single map;
(2) to provide brief descriptions of the Precambrian rocks encountered;
(3) to indicate where further information or material is available;
(4) to discuss briefly the signifiance of the described material for Precambrian geology.

Very many boreholes drilled for water relatively close to basin edges are not included in this compilation, since no material has been recovered, recorded, or preserved from them. Boreholes in the Collie basin (Low, 1958) are also excluded, since this is small enough for Precambrian geology to be more reliably predictable from mapping around its perimeter.

One borehole, Fraser River No. 1 well of WAPET, is omitted because it is controversial. The dolerite and gabbro intersected at this locality (lat. 17° 25′ 04″ S, long. 123° 09′ 39″ E) between 10,056 and 10,132 feet were considered at the time of drilling to be intrusive, on the evidence of thermal metamorphism of the overlying Carboniferous sedimentary rocks and of cross-cutting glassy doleritic veins in the 1,000 feet above the main igneous body (J. E. Glover, *in* Campbell, 1956). Closely similar dolerite in Barlee No. 1, some 40 miles southwest and stratigraphically similar, later gave a K-Ar age of 196 m.y. (Harding, 1967, quoted in Veevers, 1967), compatible with its intrusive relationship, but dolerite from Fraser River No. 1 itself has yielded an age of 830 m.y. (White, 1962). As a result of the direct conflict of these two separate types of evidence no confident age can yet be assigned to the gabbro in which drilling in Fraser River No. 1 well ceased.

Many of the rock descriptions are modified from consultants' reports; attributions are noted with each. Those lacking attributions are by Miss Peers, while Dr. Trendall wrote the discursive and introductory sections, and initiated and supervised the compilation.


## ACKNOWLEDGEMENTS

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Limited (WAPET) for permission to include unpublished information in this report. Thanks are due to Dr. J. E. Glover for useful discussion, and we acknowledge the invaluable help of Mr. M. H. Johnstone, of WAPET, without whose advice and co-operation this compilation could not have been accomplished.

## SUMMARY OF AVAILABLE INFORMATION

The positions of the 33 boreholes with which this report is concerned are shown in Plate 48, together with the positions and accepted limits of the five main basins—Perth, Carnarvon, Canning, Officer, and Eucla, in clockwise rotation from the south-west. In Table 1 the name and exact co-ordinates of each hole are listed, together with the name of the exploration company or organisation, the depth of the hole, depth to the Precambrian, and other appropriate information.

## DESCRIPTIONS OF THE PRECAMBRIAN ROCKS

### *PERTH BASIN*

#### *Allanooka No. 2*

*GARNET GNEISS* (core 3: 3,278-3,283 feet)

*Hand specimen:* Grey and coarse-grained, with a faintly developed foliation; contains quartz, kaolinised feldspar, and pink garnet.

*Thin-section:* The predominant minerals are quartz and slightly kaolinised microcline which includes blebs and stringers of plagioclase. Grains of one mineral have been completely altered to masses of minute flakes of a colourless, highly birefringent mineral. The original mineral may have been cordierite or plagioclase but the presence of pale yellow pleochroic haloes indicates that it was almost certainly cordierite. Garnet is the characterising mineral but other minerals include brown biotite, chlorite, calcite, pyrite, zircon, sphene, leucoxene, and apatite. The texture is allotriomorphic granular with a faint foliation due to a tendency toward preferred orientation of flaky minerals and elongation of quartz and feldspar. (Description modified after J. E. Glover *in* reference below) .

*Further information:* see Burdett (1965).

#### *Arrowsmith No. 1*

*GRANITE* (cuttings only: 11,290-11,294 feet)

Minerals identified from a grain mount of cuttings include microcline, quartz, sericitised plagioclase, reddish-brown biotite, and zircon.

*Further information:* see Elie (1965a).

#### *Beharra No. 1*

*GNEISS* (cuttings only: 6,735-6,740 feet)

Minerals identified from a grain mount of cuttings include microcline, quartz, sericitised plagioclase, and reddish-brown biotite.

*Further information:* see Cooper and Sweeney (1967).

#### *Bookara No. 1*

*GARNET-CORDIERITE GNEISS* (core 1: 914 feet-914 feet 10 inches)

*Hand specimen:* A grey, medium-grained, gneissic rock with a weak foliation.

*Thin-section:* The predominant minerals are quartz with numerous two-phase inclusions, plagioclase, garnet, and cordierite. The plagioclase is andesine which is altered particularly along margins to sericite and chlorite and forms minor myrmekite when in contact with potassium-feldspar. The cordierite shows abundant twinning and its alteration which is strongest along grain margins, proceeds inwards along irregular channels throughout the crystals. The alteration products consist of pinite and an isotropic mineral. Small amounts of potassium feldspar with plagioclase inclusions, and flakes of reddish-brown biotite occur. Other minerals include pyrite, ilmenite altering to leucoxene, apatite, and zircon. Texturally this rock may be described as allotriomorphic granular with minor myrmekite developed between andesine and the potassium feldspar. (Description modified after J. E. Glover *in* reference below).

*Further information:* see Jones (1965).

#### *Bookara No. 3*

*BIOTITE GARNET GRANITE* (core 3: 1,762 feet)

*Hand specimen:* The rock is a medium-grained pink and grey granite composed of quartz, feldspar, red garnet, and biotite.

*Thin-section:* The texture is allotriomorphic granular. The predominant feldspar is an unaltered microcline which perthitically includes spindles of plagioclase. Grains of plagioclase elsewhere in the rock are now represented by a mixture of alteration products including chlorite, albite, sericite and calcite. Almandine garnet forms irregular grains up to 5 mm in diameter which are sieved by quartz inclusions. Abundant irregular grains of quartz with numerous two-phase inclusions occur. Biotite flakes are common and are pleochroic with X = pale brown, Y = orange, and Z = dark orange. Other minerals include zircon, leucoxenized sphene, and pyrite.

Further information: see Bowering (1967).

#### *B.M.R. No. 10A (Beagle Ridge)*

*GARNET GNEISS* (core 14: 4,852-4,862 feet)

*Hand specimen:* This is a medium-grained gneiss with well-developed foliation.

*Thin-section:* Plagioclase, quartz, microcline, and garnet are the predominant minerals. The plagioclase is andesine and is extensively altered to sericite and chlorite. Abundant two-phase inclusions occur in the quartz grains, and stringers of plagioclase are included in the unaltered microcline. The garnet, which is pink, forms subhedral grains which are extensively altered to chlorite. Some garnets are virtually pseudomorphed by chlorite. Other minerals include flakes of a red-brown biotite altering to chlorite, muscovite, zircon, kaolinite, and pyrite. The texture is allotriomorphic granular, with a preferred orientation of the flaky minerals and an elongation of quartz and feldspar grains.

*Further information:* see MacTavish (1965).

#### *Cadda No. 1*

*GNEISS* (cuttings only: 9,160-9,165 feet

Minerals identified from grain mount of cuttings include microcline, quartz, mildly sericitised plagioclase, muscovite, red garnet, and red-brown biotite.

*Further information:* see Elie (1956b).

#### *Dongara No. 6*

*GRANITIC GNEISS* (sidewall core, 5,100 feet)

*Hand specimen:* An off-white, very friable rock composed of quartz grains in a matrix made up of argillaceous material and small flakes of a soft white mineral.

*Thin-section:* The rock consists mainly of quartz grains, a micaceous mineral and abundant argillaceous material. The quartz grains range in diameter from 0.05-2 mm and commonly form interlocking aggregates which have a crude preferred orientation of elongation. The micaceous mineral may be altered biotite. Most of the remainder of the rock consists of brown argillaceous material. Other minerals in the rock include calcite, zircon, brown tourmaline, and minor pyrite and limonite.

Positive identification of this rock is difficult because of its alteration. The fabric resembles that of granitic gneiss, and the mineralogy is consistent with that of a weathered granitic gneiss. (Description modified after J. E. Glover *in* reference below.)

*Further information:* see Lehmann (1968).

### *Geraldton Municipal Bore*

*GRANITE* (cuttings only: 1,408-1,453 feet)

Minerals identified from a grain mount of cuttings include sodic plagioclase, quartz, microcline, brown biotite, zircon, and an opaque mineral.

*Further information:* Geological Survey of Western Australia file No. 500/1897, Boring for Water in the Geraldton District.

### *Jurien No. 1*

*GRANITIC GNEISS* (core 16: 3,365-3,366 feet)

*Hand specimen:* The rock is light-grey, medium-grained and well foliated.

*Thin-section:* The predominant minerals are microcline, quartz, plagioclase, and mica. Microcline is mostly clear and unaltered, but contains blebs and stringers of plagioclase and quartz. The plagioclase grains are zoned with an inner highly altered core of oligoclase and an outer clear rim of albite. The alteration products include sericite and carbonate. Three varieties of mica are present, a pale greenish brown, moderately pleochroic mica, minor brown biotite, and muscovite. Sillimanitic needles and rods occur oriented parallel to the plane of foliation of the mica, and are most abundant in the micaceous bands. Other minerals include pyrite, zircon, and tourmaline as rare accessories. The texture is allotriomorphic granular with preferred orientation of mica and sillimanite to give a marked foliation. (Description modified after J. E. Glover *in* reference below).

*Further information:* see Pudovskis (1964b).

### *Sue No. 1*

*GARNET QUARTZ-PLAGIOCLASE-HORNBLENDE-GRANULITE* (core 35: 10,018-10,028 feet)

*Hand specimen:* The rock is dark-grey and is made up of anhedral porphyroblasts of pink garnet up to one centimetre in diameter in a medium-grained groundmass of hornblende, feldspar, and quartz with some pyrite.

*Thin-section:* The rock has a granulitic fabric and is composed of pale yellow-green to olive-green hornblende and partly altered albite. The albite has altered to a cloudy grey aggregate of chlorite, sericite, and probably some clay minerals. Hornblende is altered locally to penninite and epidote. Quartz is an important constituent and other minerals include apatite, opaque iron oxide, pyrite, and zircon. The rock is cut by a narrow vein of prehnite containing cloudy aggregates of a very fine-grained mineral, probably sphene.

*GNEISSIC BIOTITE GRANITE* (core 36: 10,096 feet)

*Hand specimen:* The rock is medium to coarse-grained and composed of feldspar, quartz, and biotite.

*Thin-section:* The fabric of the rock ranges from hypidiomorphic granular to allotriomorphic granular. The most abundant minerals are clear microcline, kaolinised and sericitised calcic oligoclase, and quartz. Red-brown biotite is common and alters in places to pale-green chlorite. Other minerals include a little muscovite and calcite, a few grains of opaque iron oxide, apatite, and zircon. (Descriptions modified after J. E. Glover *in* reference below).

*Further information:* see Williams and Nicholls (1966).

### *Woolmulla No. 1*

*SHEARED MUSCOVITE APLO-GRANITE* (core 12: 9,212-9,218 feet)

*Hand specimen:* This specimen is a slightly mineralised sheared leucocratic muscovite granite cut by a narrow pegmatite vein.

*Thin-section:* The rock is medium-grained holocrystalline, and has a poorly developed foliation. It has an even-grained granitic texture in which all constituents, other than pyrite, occur as interlocking anhedra. It consists, in order of abundance, of completely sericitised feldspar, water-clear microcline, quartz often showing undulose extinction due to strain, muscovite flakes, irregular patches of secondary calcite, pyrite euhedra, and very rare grains of apatite. The pegmatite vein is composed of quartz, feldspar, and minor pyrite. (Description modified after R. T. Prider *in* reference below).

*Further information:* see Pudovskis (1964a).

## *CARNARVON BASIN*

### *Yanrey No. 1*

*QUARTZ-MUSCOVITE SCHIST* (core 8: 1,395-1,413 feet)

*Hand specimen:* This rock is a pale grey, medium-grained schistose rock with a very strong foliation.

*Thin-section:* The bulk of the rock is composed of muscovite, quartz, plagioclase, and microcline. The plagioclase is unaltered except for a slight dusting of kaolinite whereas the microcline is intensely kaolinised and altered to chlorite. Quartz forms clear irregular grains. Muscovite is abundant, occurring as flakes and aggregates throughout the rock. It is the arrangement of the muscovite which gives the rock its schistosity. Chlorite also occurs in patches some of which appear to be pseudomorphous after garnet because they are bounded by a relict crystal outline. Minor accessory minerals include pyrite and apatite. The texture is allotriomorphic granular with a distinct schistosity due to the alignment of muscovite flakes.

*Further information:* None. Data and sample for above description kindly supplied by West Australian Petroleum Pty. Limited.

## *CANNING BASIN*

### *B.M.R. No. 3 (Prices Creek)*

*BIOTITE SCHIST* (core 7: 656 feet)

Biotite schist with numerous thin quartz lenses parallel to the schistosity. The schist itself contains little quartz and the biotite has been chloritised. The quartz lenses are of coarse-grained anhedral quartz with some inclusions of biotite. The quartz has been highly strained and fractured.

*BIOTITE-QUARTZ SCHIST* (core 8: 686 feet)

Fine-grained biotite-quartz schist, which is a lighter colour and contains more quartz (70%) than the other schists. It contains granular disseminated pyrite which in some places is parallel to the schistosity. Biotite is common and is concentrated parallel to the schistosity, which produces thin lined structure in hand specimen; these bands may represent original bedding.

*HORNFELS* (core 9: 686-690 feet)

This is a fine to medium-grained hornfels consisting of granoblastic grains of quartz, microcline, microperthite, albite, small flakes of biotite, some muscovite, granular pyrite, and magnetite. In some places the texture becomes finer and distinctly schistose, producing a quartz-feldspar-biotite schist, poor in opaque minerals.

*HORNFELS* (core 10: 693 feet)

Fine-grained quartz-biotite hornfels composed of equant grains of quartz and minor albite forming a mosaic with elongate flakes of green-brown biotite and pale-green muscovite oriented parallel to the foliation. Other minerals include microcline, magnetite, epidote, and pyrite, with glomeroblastic garnet. (Descriptions modified after R. D. Stevens *in* reference below.)

*Further information:* see Henderson (1963).

### *B.M.R. No. 4A (Wallal)*

*MYLONITIZED PORPHYRITIC BIOTITE GRANODIORITE* or *CRUSHED BIOTITE-QUARTZ-OLIGOCLASE GNEISS* (core 9: 2,224-2,228 feet)

*Hand specimen:* This is a grey sheared gneissic rock containing light grey lenses rich in feldspar.

*Thin-section:* The rock is composed mainly of altered sodic plagioclase (albite-oligoclase) and quartz, with accessory epidote, biotite, chlorite and pyrite, and rare leucoxene, zircon, and apatite. The plagioclase is sericitised and epidote is a subordinate product of its alteration. The grain-size of the feldspar is fairly even, and is about 0.1 mm; that of quartz is less even, but about the same order of average size. Biotite has been broken up into small shreds which are admixed with quartz and feldspar. (Description modified after W. B. Dallwitz *in* reference below.)

*Further information:* see Bastian (1963).

*Goldwyer No. 1*

*GRANITE* (core 20: 4,717-4,720 feet)

*Hand specimen:* A medium-grained pink and grey granite.

*Thin-section:* The fabric is allotriomorphic granular. Microcline, the predominant feldspar forms lightly kaolinised phenocrysts up to 3 mm long. The plagioclase is oligoclase occurring as smaller less common grains which are mildly altered to kaolinite and sericite. Quartz forms irregular grains which are quite unaltered. Other minerals include muscovite, a greenish-brown biotite, chlorite, secondary carbonate, and minor apatite, zircon, and magnetite.

*Further information:* see Elliott (1959).

*Hawkstone Peak No. 1*

*METAMORPHIC QUARZITE* (core 20: 3,895 feet)

*Hand specimen:* This rock is a pinkish-grey, medium-grained quartzite with fine fracture planes which appear to be constant in direction and which are now infilled by carbonate.

*Thin-section:* Most of the rock is composed of a tightly interlocking mosaic of quartz grains of average grain diameter about 0.2 mm. These tend to be slightly elongated in the direction of the foliation. Minor iron oxide occurs along fractures and grain margins and occasional thin veins of cryptocrystalline carbonate cut irregularly across the quartzite. Rare zircon grains occur. The fabric is allotriomorphic granular with a very weak foliation. (Description modified after G. R. Pearson *in* reference below.)

*Further information:* see Gardner (1963a).

*Langoora No 1*

*QUARTZ-CHLORITE-BIOTITE-CALC SCHIST* (core 11: 5,239-5,258 feet, top part of core)

*Hand specimen:* The rock is grey-green and has a rough foliation due to bands with concentrations of dark grey-green mica. Calcite makes up the bulk of the rock and lenses of quartz are present.

*Thin-section:* Granular calcite in grains elongate parallel to the general schistosity constitutes most of the rock. Anhedral quartz grains poikiloblastically enclose finely granular calcite. Quartz grains form aggregates parallel to the schistosity. Other minerals include biotite, pyrite and a black opaque

*CALCITE-MICA-CHLORITE-QUARTZ* SCHIST (core 11: 5,239-5,258 feet, middle part)

*Hand-specimen:* The rock is dark grey-green and foliated with narrow bands and lenses of calcite.

*Thin-section:* The rock is made up of lenticular bands of different mineralogical composition and texture. The thickest bands are composed of angular, granular, quartz, pale-green mica, chlorite, brown biotite, a black opaque mineral converted to hematite, and minor oligoclase, leucoxene, and apatite. The texture is lepidoblastic. Thinner, well-defined bands of quartzite and granular calcite are intercalated between the schist.

*QUARTZ-MICA-CALC SCHIST* (core 11: 5,239-5,258 feet, lower part)

*Hand specimen:* The rock is light grey-green with with a pronounced foliation due to parallelism of dark green mica and grey siliceous bands.

*Thin-section:* About 70% of the rock is made up of granular calcite. The mica is pale yellow-green and concentrated in bands. Other minerals include chalcedonic quartz, a black opaque mineral, and a little pyrite and sphene.

*QUARTZ-HORNBLENDE SCHIST* (core 11: 5,239-5,258 feet, bottom)

*Hand specimen:* The rock is dark grey-green, massive to poorly schistose, and cut by narrow carbonate veinlets.

*Thin-section:* Prismatic hornblende showing a strongly preferred orientation is the dominant mineral of the rock. Quartz grains are generally elongated parallel to the hornblende rods. Other minerals include brown biotite, black iron ore grains, rare apatite and pale brown sphene. The rock is cut by a narrow vein of carbonate and pyrite. (Descriptions modified after J. E. Glover *in* reference below).

*Further information:* see Gardner (1963b).

*May River No. 1*

*ACTINOLITE SCHIST* (core 7: 5,434-5,451 feet)

*Hand specimen:* This rock is dark-grey, fine-grained and has a strong foliation but weak schistosity. It is cut by secondary veinlets of calcite and quartz with which is associated minor sulphide mineralisation.

*Thin-section:* The predominant minerals are actinolite, quartz, calcite, and biotite. Actinolite forms irregular blades oriented parallel to the foliation and averaging 0.05 mm in length. It is pleochroic with X = very pale green, Y = pale green, and Z = pale bluish-green. The biotite also forms ragged blades which are scattered through the rock and are distinctly pleochroic in shades of brown. Plagioclase and clear quartz grains form a groundmass mosaic of average grain diameter 0.04 mm. Other minerals include epidote, sphene, calcite, and the opaque sulphide.

The secondary veinlet which cuts the hand specimen is composed of quartz, calcite, and epidote of average grain diameter 0.5 mm, with scattered irregular grains of the opaque sulphide mineral (pyrite?).

*Further information*: None. Data and sample for above description kindly supplied by West Australian Petroleum Pty. Limited.

*Meda No. 1*

*QUARTZITE* (core 25: 8,685-8,694 feet)

*Hand specimen:* This is a medium-grained pale grey quartzite with minor cross-cutting veinlets of calcite.

*Thin-section:* It is composed almost entirely of irregular grains of quartz of 0.5 mm average grain diameter. The quartz is quite unaltered but has marked strain extinction. A number of cross-cutting veinlets of calcite and chalcedony penetrate the rock. Accessory minerals include sphene and zircon. The texture is allotriomorphic granular.

*CHLORITE-CALC SCHIST* (core 26: 8,744-8,755 feet)

*Hand specimen:* This is a greyish green schistose rock cut by veinlets of carbonate.

*Thin-section:* It is made up of irregular grains of quartz of 0.1 mm average grain diameter, abundant pale green chlorite, minor muscovite, sodic plagioclase, and abundant calcite in patches and veinlets. Accessory minerals include zircon and tourmaline, and a leucoxenised opaque mineral (ilmenite?). The texture is schistose.

*Further information:* see Pudovskis (1962).

*Parda No. 1*

*SCHIST* (core 66: 5,868 feet)

*Hand specimen:* The rock is light-grey to white, and soft. It contains a little quartz and effervesces slightly in cold dilute HCl.

*Thin-section:* The rock is composed mainly of a mixture of clay minerals, muscovite, and quartz.

Calcite and a little limonite are present. Despite the strong alteration of the rock, it still possesses a pronounced lepidoblastic texture.

GNEISS (core 5: 6,017-6,024 feet)

*Hand specimen:* The rock has a gneissic texture and is made up of bands composed mainly of chlorite separated by bands of coarsely granular quartz and altered feldspar.

*Thin-section:* The rock consists mainly of lepidoblastic lenses of biotite which has been largely converted to chlorite, separated by granoblastic aggregates of quartz and feldspar. Muscovite is a common associate of the chlorite. Albite and microcline can be recognised in places, but much of the feldspar has been altered to a mixture of calcite and a colourless flaky mineral which may be sericite or a clay mineral. Small veins of the latter mineral traverse the rock. A little pyrite is present. (Descriptions modified after J. E. Glover *in* reference below.)

*Further information:* see Williams (1965).

*Samphire March No. 1*

GRANITE (core 12: 6,668 feet)

*Hand specimen:* This rock is a medium-grained pink, green, and black granite.

*Thin-section:* The predominant minerals are quartz, plagioclase, and microcline. The quartz forms irregular, clear grains with undulose extinction and narrow veinlets of carbonate along fracture planes. Plagioclase is zoned from andesine to albite and slightly altered to sericite and carbonate. The microcline grains include irregular patches of plagioclase and quartz. Flakes of biotite are strongly pleochroic with X = pale yellow, Y = olive green and Z = dark brown, are altering to chlorite and are associated with minor hornblende. Other minerals include ilmenite, sphene, zircon, and apatite. The texture is allotriomorphic granular.

*Further information:* see Johnstone (1961).

*Thangoo No. 1A*

PHYLLITE (core 9: 5,236-5,266 feet)

*Hand specimen:* This rock is dark grey with closely spaced, very thin, light-coloured beds. It has a slightly silky lustre and is cut by pyritic quartz-carbonate veinlets.

*Thin-section:* It consists mainly of fine-grained quartz and feldspar dusted with fine-grained graphite. Biotite is abundantly and uniformly distributed throughout the rock and is altered to pale green chlorite. The carbonate veinlets consist of a granular aggregate of carbonate, and quartz with minor amounts of pyrite and chlorite. (Description modified after Dallwitz, and after Prider, *in* reference below).

*Further information:* see Pudovskis (1960).

*67 Mile Bore (Derby-Lennard Road)*

METAMORPHOSED CALCAREOUS SILTSTONE (core from 2,613 feet)

*Hand specimen:* This is a fine-grained, pink and grey, well-balanced metamorphic rock.

*Thin-section:* Bands, composed almost entirely of fine-grained muscovite arranged parallel to the foliation, with minor quartz, calcite, and magnetite, alternate with bands in which quartz predominates. Minor biotite is associated with the muscovite, and scattered grains of bluish green tourmaline occur.

BIOTITE-CALCITE-QUARTZ ROCK (core from 2,772 feet)

*Hand specimen:* This rock is medium-grained with irregular bands of quartz and calcite alternating with bands of biotite.

*Thin-section:* The white bands are composed of an irregular mosaic of quartz and calcite with minor scattered flakes of muscovite. The dark bands are almost entirely composed of biotite flakes which are pleochroic with X = very pale green, Y = pale green, and Z = green. Minor grains of a sulphide mineral occur.

QUARTZ (core at 2,793 feet)

*Hand specimen:* This sample is composed entirely of white quartz.

*Thin-section:* The whole thin-section is composed of a single grain of quartz, presumably part of a vein.

CHLORITE-BIOTITE SCHIST (core from 3,012 feet)

*Hand specimen:* This is a black, schistose rock with scattered grains of sulphide.

*Thin-section:* It is composed of green and brown biotite and green chlorite which are arranged in flakes parallel to the foliation. Other minerals occurring in minor quantities include quartz, pyrite euhedra, and apatite crystals. The texture is lepidoblastic.

*Further information:* see Playford (1960).

## OFFICER BASIN

*Browne No. 1*

BROWNE EVAPORITES (435-1,269 feet, cuttings only)

*Further information:* see Jackson (1966).

*Browne No. 2*

BROWNE EVAPORITES (860-960 feet, cuttings only)

*Further information:* see Jackson (1966).

*Lennis No. 1*

LENNIS SANDSTONE (614-2,009 feet, cuttings only)

OFFICER VOLCANICS (2,009-2,016 feet, cuttings only)

*Further information:* see Jackson (1966).

*Yowalga No. 1*

LENNIS SANDSTONE (1,502-2,011 feet, cuttings only)

*Further information:* see Jackson (1966).

*Yowalga No. 2*

(See Discussion for further comment on the stratigraphic relationships of the rocks whose descriptions follow; these are a representative sample of the fifteen descriptions given in the reference appended.)

ALTERED BASALT (core 3: 2,423 feet)

*Hand specimen:* The rock is brown with small pink phenocrysts and numerous dark green amygdales.

*Thin-section:* The rock is amygdaloidal with phenocrysts of altered iron-stained plagioclase in a groundmass of feldspar laths, opaque iron oxide grains, and interstitial pale green serpentine. There are also a few phenocrysts of a mineral now completely transformed to hematite and serpentine; this mineral was probably ferromagnesian. The amygdales range up to 8 mm in diameter and are composed of serpentine, chlorite, and possibly nontronite. This is an altered, amygdaloidal, slightly porphyritic volcanic rock containing sodic plagioclase. It may represent a basalt which has undergone extensive deuteric alteration, possibly followed by weathering.

THOLEIITIC BASALT (core 4: 2,764 feet)

*Hand specimen:* This rock is fine-grained and dark grey.

*Thin-section:* The rock is made up mainly of plagioclase and clinopyroxene, and the fabric ranges between intergranular and subophitic. The plagioclase laths are zoned from bytownite to labradorite near the margins. Most of the coarser grains of pyroxene are augite. The smaller grains are pigeonite, which is altered to uralite and stained by hematite. Other minerals in the rock include hematite grains and interstitial patches of chlorite and a poorly crystallised mineral which may be K-feldspar, and which includes needles of apatite.

*Chemical analysis:* A sample of this rock analysed at the Government Chemical Laboratories gave the following result:

| | Weight per cent. |
|---|---|
| $SiO_2$ | 52.90 |
| $Al_2O_3$ | 15.63 |
| $Fe_2O_3$ | 2.80 |
| FeO | 6.79 |
| MgO | 6.62 |
| CaO | 9.13 |
| $Na_2O$ | 1.81 |
| $K_2O$ | 1.20 |
| $H_2O+$ | 1.18 |
| $H_2O-$ | 0.82 |
| $CO_2$ | 0.02 |
| $TiO_2$ | 0.89 |
| $P_2O_5$ | 0.06 |
| $FeS_2$ | 0.07 |
| $Cr_2O_3$ | 0.01 |
| $V_2O_5$ | 0.06 |
| NiO | 0.02 |
| CoO | 0.01 |
| MnO | 0.14 |
| TOTAL: | 100.16 |

Analyst: J. R. Gamble.

The composition is very typically tholeiitic (cf. Turner and Verhoogen, 1960: Table 15, p. 208).

*QUARTZ SANDSTONE* (core 5: 2,793 feet)

*Hand specimen:* This rock is red-brown with light grey-green patches, and contains rounded quartz grains and minute mica flakes. It effervesces locally in cold dilute HCl.

*Thin-section:* It is made up mainly of poorly sorted, subangular to rounded quartz grains ranging in diameter from 0.1 mm to 1.5 mm. Other clastic grains include dolomite and partly silicified dolomite rock, chalcedony, sandstone, plagioclase, microcline, quartzite, volcanic rock, and other fine-grained lithic fragments. Cement includes clay minerals, anhydrite, hematite, carbonate, muscovite, biotite, and chlorite. The rock is a clastic sediment deposited in an evaporitic environment under oxidising conditions.

*MICACEOUS SILTSTONE* (core 5: 2,797 feet)

*Hand specimen:* The rock is red-brown and is made up of alternating slightly cross-bedded bands up to 2 mm thick of silty argillaceous material.

*Thin-section:* The bands are composed mainly of angular silty quartz and clay-sized minerals. The bands of silty quartz also contain hematite grains and thin lenses, muscovite and brown biotite flakes, and rare microcline grains. The bands of clay-sized material also contain abundant, very fine silty quartz, muscovite, biotite, and grains and narrow lenses of hematite. The specimen is cut by several thin veins of anhydrite. This rock was deposited in a neutral to oxidising environment. The presence of anhydrite veins indicates evaporitic conditions in the sequence.

*CHALCEDONY-ANHYDRITE ROCK* (core 7: 2,931 feet)

*Hand specimen:* The rock is grey, and contains numerous irregularly shaped, pale brown to off-white patches up to a centimetre in diameter. The specimen does not effervesce in cold dilute HCl.

*Thin-section:* The rock is composed mainly of anhydrite (the grey areas of the hand specimen) and chalcedony (the pale brown to off-white patches). The anhydrite grains are subhedral to euhedral and range from 0.015 to 0.1 mm in length. The chalcedony forms pale brown flaring masses. Quartz is also present and both chalcedony and quartz enclose isolated grains of anhydrite and dolomite . There are numerous argillaceous and dolomitic patches and schlieren in the rock. They contain irregularly shaped aggregates of minute pyrite crystals. Isolated dolomite rhombs, pyrite crystals, and pale green chlorite grains occur throughout the rest of the rock. This rock is evidently the product of an evaporitic environment.

*Chemical analysis:* A sample of this rock was analysed at the Government Chemical Laboratories with the following result:

| | Weight per cent. |
|---|---|
| $SiO_2$ | 32.39 |
| $Al_2O_3$ | 4.10 |
| $Fe_2O_3$ | 0.97 |
| FeO | 1.21 |
| MgO | 2.24 |
| CaO | 22.65 |
| $Na_2O$ | 0.23 |
| $K_2O$ | 1.01 |
| $H_2O+$ | 1.38 |
| $H_2O-$ | 0.56 |
| $CO_2$ | 4.09 |
| $TiO_2$ | 0.16 |
| $P_2O_5$ | 0.20 |
| $SO_3$ | 28.12 |
| $FeS_2$ | 0.65 |
| $V_2O_5$ | 0.02 |
| NiO | 0.01 |
| CoO | 0.01 |
| MnO | 0.19 |
| C | 0.16 |
| TOTAL | 100.35 |

Analyst: J. R. Gamble.

*Further information:* see Jackson (1966).

*DOLOMITIC SILICIFIED SANDSTONE* (core 8: 3,237 feet)

*Hand specimen:* The rock is grey, fine to medium-grained, and thoroughly indurated.

*Thin-section:* It is made up mainly of an interlocking mosaic of quartz grains which range in diameter mainly between 0.2 mm and 0.3 mm. Ghost outlines of rounded to sub-rounded clastic cores are visible in a few grains. The rock is a fairly well-sorted sandstone which has been partly cemented by authigenic quartz, dolomite, and a rare mineral which is probably an authigenic sulphate. Also present are a few rounded grains of green tourmaline, chert, microline, and plagioclase.

*SILTY SHALE* (core 8: 3,239 feet)

*Hand specimen:* The rock is red-brown and finely laminated with thin alternating silty and argillaceous beds.

*Thin-section:* It is composed of thin alternating bands of angular silty quartz and clay-sized material. Most of the bands are less than one millimetre thick, and all are impregnated with hematite. Muscovite and green biotite are found throughout the rock, and the flakes are almost invariably parallel to the bedding. (All Yowalga No. 2 descriptions modified after J. E. Glover *in* reference below.)

*Further information:* see Jackson (1966).

## *EUCLA BASIN*

### *Eucla No. 1*

*GRANITE* (cuttings only: 720-725 feet)

Minerals identified from a grain mount of cuttings include microline, quartz, sericitised plagioclase, biotite, chlorite, and hematite.

*Further information:* see Stach (1964).

### *Eyre No. 1*

*GNEISSOSE GRANITE* (core 23: 1,715 feet 4 inches to 1,715 feet 9 inches)

*Hand specimen:* The rock is light grey, medium-grained and foliated with numerous well-aligned microline phenocrysts up to 2 cm long.

*Thin-section:* Microline, quartz, and oligoclase are the predominant minerals. Microline forms both phenocrysts and irregular grains in the groundmass, and commonly includes oriented spindles of plagioclase. The oligoclase is lightly sericitised and commonly forms a graphic intergrowth with quartz. Numerous acicular crystals (rutile?) are included in the oligoclase and are oriented in three directions oblique to the twin planes. Quartz occurs as irregular grains with a marked strain extinction and numerous two-phase inclusions. A reddish-brown biotite is common and is partly altered to chlorite. Other minerals include calcite, apatite, zircon, and an opaque iron oxide. The texture is allotriomorphic granular.

*Further information:* see Shiels (1960a).

### *Gambanga No 1*

*PYROXENE-BEARING GRANITE* (core 10: 1,279 feet)

*Hand specimen:* This is a grey, medium-grained gneissic rock with a distinct foliation due to the alignment of the platy minerals.

*Thin-section:* The predominant minerals are quartz, plagioclase, and orthoclase, and the texture is allotriomorphic granular. The plagioclase is fresh, unaltered oligoclase forming irregular grains which are not well twinned. Quartz occurs as irregular grains and as a myrmekitic intergrowth with plagioclase along the grain boundaries. Numerous two-phase inclusions occur in the quartz. The predominant feldspar is orthoclase, which forms mildly kaolinised and sericitised grains with numerour fine spindle-shaped inclusions of plagioclase. Orange-brown biotite is abundant occurring as scattered flakes. An orthopyroxene forms ragged grains which are extensively altered to chlorite and a dark green hornblende. Accessory minerals include zircon, apatite, and magnetite.

*Further information:* see Shiels (1960b).

### *Transcontinental Railway Bore 4*

*BIOTITE GRANITE* (core: un-numbered, unknown depth, but below 940 feet)

*Hand specimen:* This is a very weathered and crumbly medium-grained, pink and grey granitic rock.

*Thin-section:* The texture is allotriomorphic granular, and the main consituents are quartz, microcline, plagioclase, and biotite. The microcline is completely fresh except for minor secondary calcite developed along fracture planes, and a slight dusting of kaolinite. The predominant plagioclase grains are so completely altered to sericite, clay minerals, and chlorite as to preclude more specific identification. However, smaller plagioclase inclusions in microcline are quite unaltered and were identified as oligoclase. The quartz is extensively fractured and exhibits a marked strain extinction. Calcite is developed along the fracture planes. Minerals which are the products of alteration (probably both deuteric and weathering) include pale green chlorite, olive green biotite, muscovite, and calcite. Euhedral magnetite grains have been altered to hematite.

*Further information:* see Maitland (1915).

## DISCUSSION

A glance at a geological map of almost any large region is enough to show the difficulty of geological extrapolation away from mapped areas, particularly of older rocks. The geology of the sub-Phanerozoic surfaces of Western Australian basins may be guessed at by continuing structural trends, outcrop areas, unconformities, metamorphic gradients, and so forth. However, there are no reliable rules to be applied, capable of forecasting such known phenomena as the abrupt cut-off of linear geological trends which are continuous for hundreds of miles. Another almost insuperable difficulty is that, to be of use for extrapolation on the scale required, any trend must be so broad and general as to be highly subjective, while an objective and uninterpreted map of the Precambrian of Western Australia would be more confusing than helpful.

Some attempt must nevertheless be made to select some broad features of the Precambrian geology which may be expected to persist under the Phanerozoic basins, and on whose actual extrapolation the data listed above may thus give some clue. The Precambrian information on Plate 48 represents the minimum possible framework for discussion here. It is diagrammatised from the map of Horwitz (1966), with age data from Compston and Arriens (1968). All ages are rounded to the nearest 100 m.y., and many important features, which on this conceptual scale are details, are omitted entirely. Therefore this selective sketch map is not intended to replace reference to the sources referred to (which list further authorities) for those seeking a review of the Precambrian geology of Western Australia, nor should the rounded dates on this map be quoted without reference to Compston and Arriens' paper.

The salient features marked on the plate are as follows:

(1) The largely gneissic and granitic Yilgarn Block in the southwest; the western part seems to be distinctly older than the eastern part, but no geological boundaries are yet relatable to this division.

(2) Marginal metamorphic or magmatic overprints of the Yilgarn Block. These include: to the southeast the Fraser Range granulites; to the south the slightly younger Albany Granite; on the west the off-lying Leeuwin—Naturaliste and Greenough blocks, and a narrow strip of uncertain significance close to Perth.

(3) The stable Pilbara Block, farther north, which seems to be roughly coeval with the western part of the Yilgarn Block.

(4) The Mt. Bruce Supergroup, which dips gently off the southern and eastern margins of the Pilbara Block. The uppermost part (the Wyloo Group) is altered and intruded by granites in the western part, around the western termination of the overlying Bangemall Group.

(5) The Bangemall Group sediments, which lie unconformably upon folded Mt. Bruce Supergroup to the north, and on the Yilgarn Block to the south.

(6) The Kimberley Block, which comprises mainly a thick and only gently folded clastic sequence including the Kimberley Group. This sequence lies unconformably upon the Lamboo Complex.

(7) The Lamboo Complex, which consists of mixed metamorphosed older rocks and granites of ages just older than that of the sedimentary succession of the Kimberley Block. The two arms of the Lamboo Complex, the King Leopold Mobile Zone on the west and the Halls Creek Mobile Zone to the east, have histories of continuous movements before and after sedimentation and granite intrusion.

(8) Between the eastern side of the Halls Creek Mobile Zone and the Warburton—Blackstone area, in the north-south strip of country adjacent to the Northern Territory and South Australia borders, the Precambrian geology is complex, and insufficiently well known for useful generalised trends to be suggested. It includes younger Precambrian correlatives of the Adelaide System, with glacigene sediments, and acid volcanics in the Warburton—Blackstone area with an age of about 1,100 m.y. (Compston and Nesbitt, 1967).

In the Perth Basin the data compiled contain no surprises. Taken as a group the nine holes clustered south of the Greenough Block yielded much the rocks that would be expected from a random sample of the block itself (see Jones and Noldart, 1961, for a summary). Similarly the granulite and granite from Sue No. 1 are entirely similar to many rocks of the Leeuwin—Naturaliste Block (R. C. Horwitz *in* Lowry, 1965).

The schist from Yanrey No. 1, in the Carnarvon Basin, is less easily matched with the immediately adjacent Precambrian. There are two possible interpretations. It is possible that the metamorphism of the Wyloo Group around the western extremity of the Bangemall Group outcrop (Daniels, pers. comm.) continues to increase in grade westwards; the lithology of the Yanrey rock is entirely consistent with its identity as part of the Wyloo Group which reached garnet grade and suffered later retrograde metamorphism. But it is also possible that the discontinuity in Precambrian lithology which evidently runs north-south between the Greenough and Leeuwin—Naturaliste blocks continues northwards through the eastern side of the Carnarvon Basin and separates the Yanrey site from the adjacent Precambrian.

In the Canning Basin the six holes closest to the northeastern edge all yielded rocks which have close counterparts within the adjacent Lamboo Complex. It is the remaining five holes, between and including B.M.R. No. 4A and Thangoo No. 1A, that seem to offer the greatest promise of useful information. The rocks encountered in these holes may, as a group, be matched petrographically either with the Pilbara Block, the Lamboo Complex, or the granites and metamorphic rocks between Lake Disappointment and the Paterson Range, marked on Plate 48 by a question mark about 200 miles south of the group.

Yowalga No. 2, in the Officer Basin passed through the following succession between 1,335 and 3,246 feet (Jackson, 1966):

| | Thickness in feet |
|---|---|
| Lennis Sandstone .... .... | 1,055 |
| Officer Volcanics .... .... | 385 |
| Babbagoola Formation .... | 471 |

The Lennis Sandstone consists of arkosic and feldspathic sandstones; no examples are described here. Two descriptions of the basalts which comprise the Officer Volcanics are given above, as well as examples of sandstone, siltstone, shale, and an evaporite from the lithologically mixed Babbagoola Formation. No unequivocal evidence for the age of this succession is given by either palaeontological or isotope evidence, and the surface correlation of the Lennis Sandstone tentatively accepted by Jackson *via* a suggestion of Wells (1963) is not itself sufficient evidence for a reliable age. Daniels (personal communication) suggests that, on the simplest structural interpretation of the Warburton Range area, the Yowalga No. 2 succession may be expected to be younger than any of the Precambrian sequences exposed there; until further evidence is forthcoming there is more reason to accept than to reject a Precambrian age.

In the Eucla Basin the recovered rocks are similar to those associated with the overprinted metamorphic and magmatic activity along the southeastern edge of the Yilgarn Block.

In summary, none of the recovered material solves important Precambrian problems, but there is a real possibility that some of it may be a worthwhile object for future study. In particular, additional isotope analyses may well resolve present doubts concerning the Precambrian or younger age of the lowest rocks in Fraser River No. 1 (see Introduction) and also concerning the Officer Volcanics in Yowalga No. 2. Isotope analyses could also be fruitful in the series of holes across the northern Canning Basin, which span a time gap of over 1,000 m.y. (not indicated by Veevers, 1967, Fig. 4). A single K-Ar determination from Samphire Marsh No. 1 in this series, gave an age of 484 m.y. (White, 1962); this seems most likely to represent Ordovician weathering, the effect of which may be less apparent if the total rock Rb-Sr method were used. However, any future work on these lines should also take into account the possibility that some terminal "basement" rocks logged (and here accepted) as Precambrian may be large boulders in Phanerozoic sediments; this possibility exists at B.M.R. No. 4 (pers. Comm. M. H. Johnstone) and Goldwyer No. 1 (pers. comm. P. E. Playford). The problem of the Yanrey material is also potentially solvable from isotope analysis. We hope that by tabulating the available material in this compilation we have increased the likelihood of future work on it.

Table 1

WELLS DRILLED INTO PRECAMBRIAN ROCK OF SEDIMENTARY BASINS IN WESTERN AUSTRALIA TO THE END OF 1967

| Basin | Name | Type | Location | | Ground level elevation (feet) | Total depth (feet) | Depth to Precambrian (feet) | Drilled for | Year completed | Material recovered | Well completion report description |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Latitude (S) | Longitude (E) | | | | | | | |
| PERTH .... | Allanooka No. 2 .... | Oil test | 29° 06′ 00″ | 114° 59′ 36″ | 218 | 3,300 | 3,232 | Wapet | 1965 | Core | Yes |
| | Arrowsmith No. 1 .... | Oil test | 29° 36′ 38″ | 115° 06′ 55″ | 168 | 11,306 | 11,218 | F.P.C. | 1965 | Cuttings | No |
| | Beharra No. 1 .... .... | Oil test | 29° 29′ 10″ | 115° 00′ 45″ | 74 | 6,744 | 6,695 | F.P.C. | 1966 | Cuttings | No |
| | Bookara No. 1 .... .... | Strat. | 28° 59′ 28″ | 114° 45′ 50″ | 65 | 926 | 863 | Wapet | 1965 | Core | Yes |
| | Bookara No. 3 .... .... | Strat. | 29° 06′ 27″ | 114° 53′ 14″ | 107 | 1,764 | 1,560 | Wapet | 1967 | Core | No |
| | B.M.R. No. 10A (Beagle Ridge) | Strat. | 29° 49′ 38″ | 114° 58′ 30″ | 15 | 4,862 | 4,794 | B.M.R. | 1960 | Core | No |
| | Cadda No. 1 .... .... | Oil test | 30° 20′ 15″ | 115° 12′ 45″ | 256 | 9,000 | 9,169 | F.P.C. | 1965 | Core | No |
| | Dongara No. 6 .... .... | Oil test | 29° 11′ 41″ | 114° 56′ 16″ | 94 | 5,115 | 5,053 | Wapet | 1967 | Cuttings & SWC | Yes |
| | Geraldton Municipal .... | Water | 28° 46′ 40″ | 114° 36′ 30″ | unknown (approx. 122) | 1,453 | 1,435 | State Govt. | 1940 | Cuttings | No |
| | Jurien No. 1 .... .... | Oil test | 30° 08′ 40″ | 115° 02′ 54″ | 30 | 3,366 | 3,208 | Wapet | 1962 | Core | Yes |
| | Sue No. 1 .... .... | Strat. | 34° 03′ 54″ | 115° 19′ 04″ | 269 | 10,097 | 10,021 | Wapet | 1966 | Core | Yes |
| | Woolmulla No. 1 .... | Oil test | 30° 01′ 24″ | 115° 11′ 28″ | 382 | 9,224 | 9,097 | Wapet | 1963 | Core | Yes |
| CARNARVON | Yanrey No. 1 .... .... | Oil test | 22° 15′ 16″ | 114° 34′ 57″ | 45 | 1,413 | 1,383 | Wapet | 1957 | Core | No |
| CANNING .... | B.M.R. No. 3 (Prices Creek) | Strat. | 18° 38′ 00″ | 125° 54′ 00″ | 518 | 694 | 654 | B.M.R. | 1956 | Core | Yes |
| | B.M.R. No. 4A (Wallal) | Strat. | 19° 44′ 12″ | 120° 44′ 28″ | 27 | 2,228 | 2,224 | B.M.R. | 1958 | Core | Yes |
| | Goldwyer No. 1 .... .... | Oil test | 18° 22′ 47″ | 122° 22′ 58″ | 259 | 4,720 | 4,660 | Wapet | 1958 | Core | No |
| | Hawkstone Peak No. 1 | Oil test | 17° 14′ 45″ | 124° 24′ 26″ | 161 | 3,897 | 3,855 | Wapet | 1962 | Core | Yes |
| | Langoora No. 1 .... .... | Oil test | 17° 18′ 07″ | 124° 06′ 48″ | 69 | 5,299 | 5,240 | Wapet | 1962 | Core | Yes |
| | May River No. 1 .... | Strat. | 17° 14′ 50″ | 124° 05′ 01″ | 56 | 5,505 | 5,387 | Wapet | 1967 | Core | No |
| | Meda No. 1 .... .... | Oil test | 17° 24′ 00″ | 124° 11′ 30″ | 88 | 8,809 | 8,663 | Wapet | 1958 | Core | No |
| | Parda No. 1 .... .... | Oil test | 18° 56′ 08″ | 122° 00′ 34″ | 335 | 6,256 | 5,830 | Wapet | 1965 | Core | Yes |
| | Samphire Marsh No. 1 | Oil test | 19° 31′ 08″ | 121° 10′ 51″ | 16 | 6,664 | 6,610 | Wapet | 1958 | Core | No |
| | Thangoo No. 1A .... | Oil test | 18° 21′ 52″ | 122° 53′ 09″ | 559 | 5,429 | 5,100 | Wapet | 1960 | Core | Yes |
| | 67 Mile Bore (Derby-Lennard Road) | Water | 17° 57′ | 124° 49′ | .... | 3,012 | 2,528 | State Govt. | 1910 | Core | No |
| OFFICER .... | Browne No. 1 .... .... | Strat. | 25° 51′ 15″ | 125° 48′ 58″ | 1,489 | 1,269 | 435 | Hunt | 1965 | Cuttings | No |
| | Browne No. 2 .... .... | Strat. | 25° 56′ 00″ | 125° 57′ 45″ | 1,588 | 960 | 860 | Hunt | 1965 | Cuttings | No |
| | Lennis No. 1 .... .... | Strat. | 27° 17′ 00″ | 126° 21′ 00″ | 1,362 | 2,016 | 614 | Hunt | 1965 | Cuttings | No |
| | Yowalga No. 1 .... .... | Strat. | 26° 10′ 12″ | 125° 58′ 00″ | 1,554 | 2,011 | 1,502 | Hunt | 1965 | Cuttings | No |
| | Yowalga No. 2 .... .... | Oil test | 26° 10′ 12″ | 125° 58′ 00″ | 1,550 | 3,246 | 1,335 | Hunt | 1966 | Core | Yes |
| EUCLA .... | Eucla No. 1 .... .... | Strat. | 31° 52′ 15″ | 128° 13′ 21″ | 40 (app.) | 728 | 702 | A.O.D. | 1964 | Cuttings | No |
| | Eyre No. 1 .... .... | Strat. | 32° 07′ | 126° 58′ | 48 | 1,719 | 1,708 | Exoil | 1960 | Core | No |
| | Gambanga No. 1 .... | Strat. | 32° 16′ | 124° 50′ | 390 | 1,279 | 1,282 | Exoil | 1960 | Core | No |
| | Transcontinental Railway Bore 4 | Water | 30° 52′ | 128° 25′ | 520 (app.) | 996 | 940(?) | State Govt. | 1910/11 | Core | No |

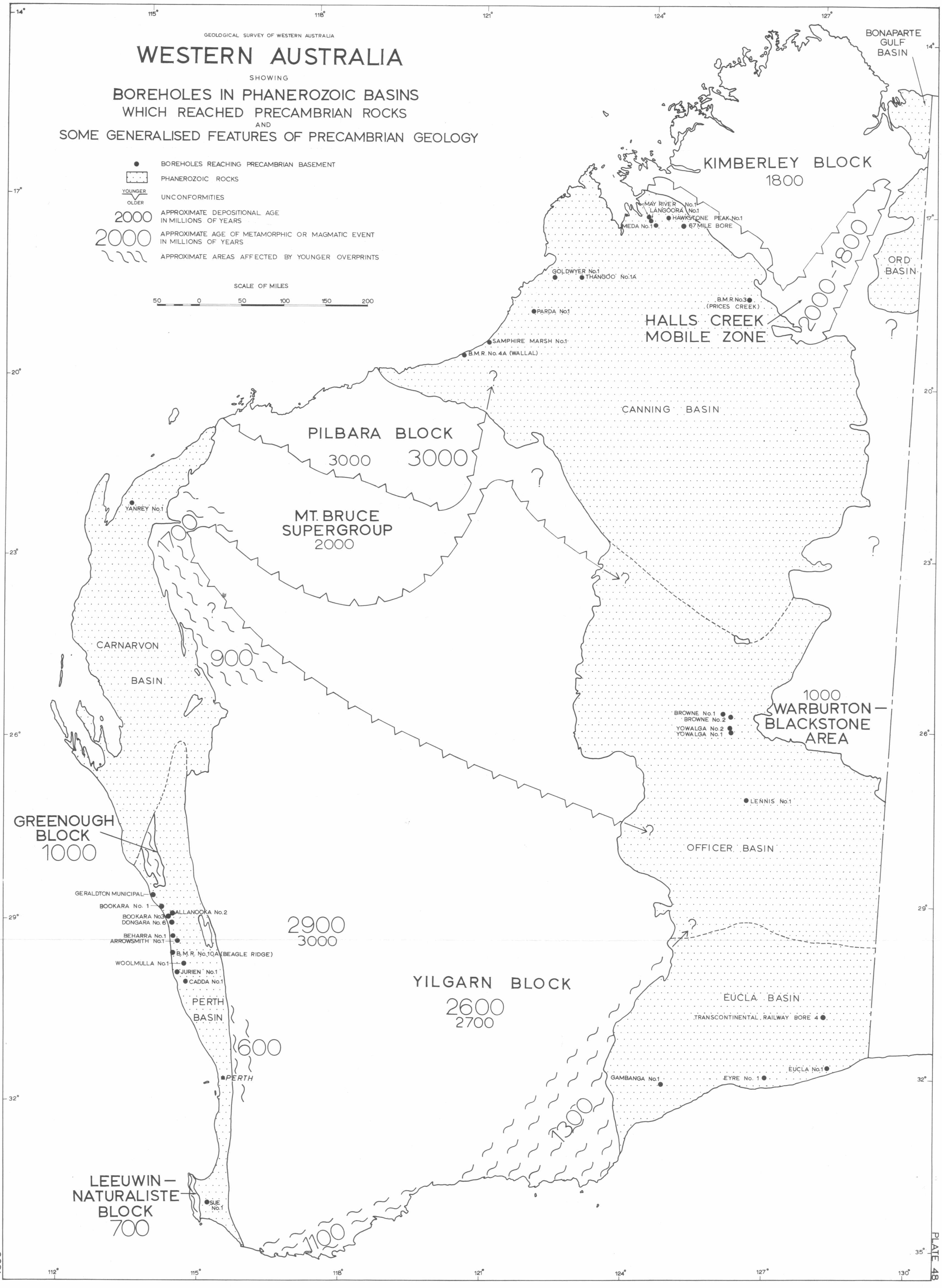


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PLATE 48

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# EXPERIMENTAL GEOPHYSICAL METHODS IN GROUNDWATER SEARCH NEAR ESPERANCE

by D. L. Rowston


## ABSTRACT

Experimental geophysical investigations in the Esperance Plains area during 1966 indicated that the magnetic resistivity, and electromagnetic methods can be usefully employed in the search for groundwater. The methods were used to determine the depth to granitic bedrock, the bedrock relief, and probable variations in the salinity of the groundwater in a number of relativity simple environments. Twenty-six percussion bores were drilled to test the initial geophysical interpretations and to evaluate the methods generally.

The magnetic anomalies are attributed mainly to the bedrock relief and can delineate major depressions and probable drainages; most of the productive test bores were sited in magnetic lows.

The results of the resistivity mapping and depth probes were not entirely satisfactory because of high electrode contact resistances and instrumental shortcomings. However, drilling substantiated that accurate depths to bedrock can be obtained and there is a possible correlation of the deeper layer resistivities with groundwater salinity. The resistivity mapping results were influenced by near-surface variations. The electromagnetic method was similiarly affected but in areas where the surface conditions were homogeneous, the magnitude of the imaginary component increased negatively with the increase in groundwater salinity.


## INTRODUCTION

The Geological Survey of Western Australia is engaged in the study of the regional geology and hydrology of the Esperance 1:250,000 Sheet between latitude 33° and 34° S and longitude 121° 30′ and 123° E. Part of this Sheet, the Esperance Plains (see Plate 49) has received special hydrological study because of rapid agricultural expansion and the urgent demand for underground water supplies. Bores are frequently preferred to dams because of costs and saline surface conditions.

Although many of the factors influencing groundwater accumulation and salinity are now better understood, several problems still remain. Experimental geophypsical surveys were made in selected areas during 1966 to determine whether or not some of these problems could be resolved. Percussion drilling was carried out concurrently on geophysical anomalies to assist interpretation and to evaluate the methods.

The Esperance Plains comprise about 3,000 square miles of gently undulating sandplain country to the north and east of the Esperance township. The Archaean granitic basement is overlain by marine and terrigenous sediments of Eocene age, and Recent eolian deposits. The granitic rocks crop out sporadically as monadnocks and form the only prominent physical features away from the coast. A thin veneer of sand and laterite and the general paucity of outcrop prevents any reliable estimate of the thickness of Eocene sediments or of their lithology, and to attempt to elucidate these unknowns was an objective of the geophysical work.

The annual rainfall is reliable but rapidly decreases from 27 in. on the coast to 18 in. at the north margin of the plains. Generally the decrease in rainfall is accompanied by an increase in the salinity of the groundwater as demonstrated by the isohyet and isohalsine contours on Plate 49. Any isohalsine contour indicates the predominant salinity only, and locally there are large departures from this value; the range of salinities that may be encountered in a small area are exemplified by the current drilling data. Thus another of the objectives was to define the least saline groundwater within a particular area.

With the exception of a few streams along the immediate coastal strip, drainage is internal and ephemeral; the drainages are poorly defined and frequently terminate in small saline swamps or lakes. Bores are commonly sited along these drainages on the assumption that the present day channels correspond to ancient drainages which have been infilled with permeable fluvial deposits.

The granitic hills constitute excellent sources of recharge and, provided there is a reasonable thickness of sediments, good quality water can sometimes be obtained from bores around their peripheries. However, many of the properties are devoid of granite outcrop or distinct drainage lines and successful bore siting is largely a matter of luck.

## GEOPHYSICAL METHODS AND TECHNIQUES

Magnetic, resistivity, electromagnetic, and self-potential methods were used during the surveys. The first two have been widely used in hydrological investigations but the others are not usually employed for this purpose. The general theory and application of these methods is well described in the standard texts such as Parasnis (1962) and need no reiteration. However some explanation of the reasons for using them in this environment and some of the assumptions made in the interpretation of the results is warranted.

### *MAGNETIC*

Magnetic anomalies may be attributed to either variations in the magnetic susceptibility of different rocks or, assuming a uniform susceptibility for the bedrock and non-magnetic sediments, related to the bedrock relief. Despite the lack of susceptibility information it was hoped that depressions and drainages in the Archaean basement would be indicated.

An ABEM torsion magnetometer Type MZ-4, accurate to about two gammas, was used to measure local variations in the vertical component of the earth's field. Diurnal corrections were applied in the usual manner but the limited extent of the work precluded corrections for regional effects.

### *RESISTIVITY*

Depth probe and resistivity mapping techniques were employed to determine the depth to bedrock, the general bedrock configuration, and probable sub-surface lithology; it was also possible that the mapping could define the salinity pattern. The inherent ambiguity of the interpretation of resistivity results is well known. For instance a zone of low apparent resistivity may be due to a sand containing saline water or a clay layer which is almost impervious; high resistivities could indicate shallow bedrock, fresh water sands, or dry material above the water table. The more geological information available the better the chance of resolving the ambiguities.

Interpretation of the Wenner array depth probes was made by curve matching using standard two-layer type curves with Hummels' extension to the multi-layer case. High contact resistances and erratic readings at the larger electrode intervals sometimes prevented a reliable estimate of the depth to bedrock. However, even in these instances, the resistivities of the layers above bedrock are useful. The unit electrode spacing used in the mapping technique was restricted to 50 feet by the accurate readability of the instrument; readings were often as low as 0.10 ohms.

The resistivity measurements were made with a Tellohm Resistivity Meter. Although salt water was used at all electrode points the contact resistances were commonly above 2,000 ohms.

### *ELECTROMAGNETIC*

The electromagnetic method was used to test whether subsurface conductivity variations could be related to changes in the lithology or in the salinity of the groundwater. Whilst giving much the same information as the resistivity mapping technique it has the advantage that no direct electrical contact with the ground is required.

An ABEM E.M. Gun equipment with frequencies of 440 and 1,760 cycles per second was used for the work. According to the manufacturers, coil separations of 100 and 150 feet gave depths of investigation ranging down to about 100 feet.

*SELF-POTENTIAL*

Potential measurements were made with a Sharpe VP-6 millivoltmeter because of the possibility that differences in concentration of salts in solution or of groundwater movement could generate small potentials. When readings over three areas failed to detect other than erratic potentials the method was abandoned.

## DRILLING

A Mines Department Ruston Bucyrus percussion rig was used to drill 26 bores as a follow up to the geophysical work. The bores were sited to test a combination of geophysical anomalies rather than those obtained by any one method. All holes were drilled to bedrock and regular sludge samples collected for logging, and water samples were taken for salinity determinations and chemical analyses. Lithological logs and completion reports were prepared by K. H. Morgan who also supervised the drilling.

The borehole information proved invaluable in modifying the original interpretations of the geophysical indications and in evaluating the methods.

## AREAS INVESTIGATED

The four main areas studied were parts of Neridup Locations 169, 14, and 159, and Esperance Location 1445 to the west of the highway; these locations are shown on Plate 49. All of the properties lie north of the 24 in. isohyet where surface water salinities are generally greater than 5,000 ppm TDS. The groundwater potential is largely unknown and many bore failures are reported. The localities were selected to give a variety of test conditions.

At Neridup Location 169 a flat tract of country of about 150 acres in the southwest corner of the property and adjoining a low granite dome was studied. Recharge from the granite made this a prospective area, provided there was a reasonable thickness of sediments. Although isolated clay pans were scattered throughout the area there were no obvious drainages or other features to aid bore siting.

A more detailed survey over about 75 acres was made at Neridup Location 14. The grid lies between a prominent granite hill near Condingup Peak and a low sand ridge to the west. The shallow depression so formed was considered to have excellent groundwater potential and the survey here was to test the ability of the geophysical methods to define salinity variations.

Twelve private bores had been put down at Neridup Location 159; many of these were dry, a few yielded very small supplies of saline (10,000 ppm) water and one produced about 50 gallons per hour of domestic quality water. A strip of ground along the southern slope of an elongate granite ridge from which adequate recharge could be expected was investigated.

The survey at Esperance Location 1445 covered about ¾ square mile and was made to determine the speed with which an area could be adequately investigated. Because of the apparent success of the magnetic method in delineating drainages, work was restricted to this method supported by minor electromagnetic traversing. There are no granite outcrops but two producing bores in one corner struck granite at depths of 25 feet and 60 feet.

## DISCUSSION OF RESULTS

For the purposes of this discussion typical geophysical results from Locations 14 and 159 have been selected to demonstrate the efficacy of the work.

At Location 169, although there was excellent agreement between the geophysical anomaly patterns from all methods and the follow up drilling, the thin layer of clayey sediments precluded groundwater concentrations. Drilling verified the indicated basement depressions but none of these contained other than seepage quantities of groundwater of about 14,000 ppm TDS.

An interesting magnetic low was obtained at Esperance Location 1445 but this anomaly has not been tested by drilling.

*NERIDUP LOCATION 14*

The topographic depression in the southeastern corner of Neridup Location 14 is controlled by Archaean basement rocks which flank the western and southeastern margins of the geophysical grid. The basement rocks are, in the main, concealed by a typical granitic weathering profile capped by pisolitic laterite. Test drilling revealed that the central trough contains up to 160 feet of terrigenous and marine sediments of Eocene to Recent ages. Although the sedimentary sequence is highly variable, the lithology generally includes a thick siltstone or cemented silty sand containing porous porcellanite and opaline silica, about 30 feet of fossiliferous silts and sands, 20 feet of grey sand, and decomposed granite and fresh bedrock. The sequence is overlain by a few feet of silty sand with some lateritic pisolite. The siltstone is the only bed that is laterally persistent; the underlying strata are commonly heterogeneous and the fossiliferous bed is sometimes absent.

At the conclusion of the geophysical work eight percussion holes were sited to test the geophysical interpretation and anomalies. With the exception of the two holes, 17 and 18, that were drilled to verify shallow granite on the ridge, all bores encountered groundwater. The wide range of groundwater salinity, from 1,800 to 9,800 ppm TDS, emphasises one of the major problems in selecting boresites. This variability within a small area is common over much of the Esperance Plains.

Water was struck generally at between 50 and 60 feet and a static level of 50 feet was observed in all but bore 25 where the rest level was at 45 feet. Estimated yields ranged from 200 to 2,000 gph with most around 1,000 gph. Groundwater supplies are available from most of the sedimentary rocks including the siltstone which has a significant secondary porosity due to the porcellanite bands. Contrary to the usual pattern there is no pronounced increase in salinity with depth in any of the bores.

The main geophysical results from this investigation together with the relevant information from the test bores are shown on Plate 50.

*Magnetic*

The magnetic vertical force contours relative to the arbitrary base station 1N/100 are shown on Plate 50 together with the appropriate drilling and depth probe data.

The simple magnetic pattern was interpreted initially as due to a bedrock depression elongated in a northeasterly direction across the grid. Steep gradients indicated shallow granite beneath the sand ridge in the west and northwest, and the gradual increase in intensity from the minimum (-300 gammas) towards the southeast again suggested a probable thinning of the sediments.

The percussion drilling subsequently verified this interpretation but showed that the deepest part of the depression was displaced to the east of the magnetic low. The shallowing of the bedrock towards the southeast is not as gradual as inferred from the contours although the depth differences between bores 25 and 14 are accompanied by a minor steepening of the gradient. The magnetic results thus give a broad and qualitative picture of the bedrock relief.

*Resistivity*

The results of the resistivity mapping are shown as contours on Plate 50, which also includes the layer resistivities determined from the depth probes. The granitic bedrock resistivity which tends towards infinity has been omitted.

The depths to bedrock estimated from the satisfactory depth probes, and those found by drilling, show reasonable agreement although it was not possible to site the bores to specifically test these results. At bores 16, 17, and 18 where depth probes were made, the estimated and drilling depths to bedrock agree very well.

The reliability of some of the resistivity mapping results is open to question because of the high electrode resistances. In particular the anomalies centred about 7N/600 and 11N/800 which occur over dry lateritic soils are considered due mainly to surface inhomogeneities.

There is an obvious correspondence between the mapping and depth probe second layer resistivities. The latter correlate with about 30 feet of silty sand and clay which directly underlie the soil and it is inferred that the mapping results are largely influenced by variations in composition, porosity, and amount of saturation of this layer. As water was not struck above 50 feet in any of the bores it is unlikely that a direct correlation between groundwater salinity and the resistivity mapping can be established. Even if this layer is saturated by capillarity from below, the salinity would be diluted by rainfall intake and not representative of the main aquifer salinity.

The resistivities of the third layer, where identified, show a broad correlation with the groundwater salinity but there is insufficient data to assess this relationship quantitatively. In general the lower resistivities correspond to relatively saline water; for instance the third layer values along line 17N are lower than those in the southeast corner of the grid where fresher water was encountered.

Despite the unsatisfactory results in the area the resistivity method has promise; an instrument with greater power and a lower range would overcome many of the difficulties and allow larger spacings to be used in the mapping technique. Accurate depth probe curves could define the layer boundaries and the depths to bedrock.

*Electromagnetic*

A rigorous interpretation of electromagnetic results is far more complex than that of the resistivity method and normally involves consideration of both real (in-phase) and imaginary (out-of-phase) components to correctly define variations in resistivity. However, at Location 14 the real component was seriously affected by changes in the coil separation and topography and was, without correction, unsuitable for presentation. The imaginary component contours are shown on Plate 50.

Positive anomalies are attributed to high resistivities and, conversely, negative ones to zones of relatively low resistivity. Thus the e.m. results should be, and are, very similiar to the resistivity mapping pattern. The most noticeable discrepancy is at bore 16 sited in a zone of high resistivity whereas the electromagnetic contours indicate a low resistivity and agree with the depth probe at this point. Several feet of laterite was logged at the top of bore 16 and the high mapping resistivity is probably erroneous due to poor electrode contacts.

There is reasonable agreement between the magnitudes of the imaginary component and the second layer resistivities but no apparent relationship with the salinity of the groundwater, except that the 9,800 ppm salinity of bore 26 coincides with a strong negative anomaly, and that of 25 (1,800 ppm) coincides with a zero contour. The salinities of bores 13, 14, 15, and 16 are completely at variance with a possible correlation; the lower salinities in 14 and 16 occur with strong negative anomalies.

This suggests that the e.m. anomalies, like the resistivity mapping variations, originate in the near surface layers, and that the depth penetration is limited. Even if the penetration was down to the theoretical 100 feet calculated for 1,760 cps and 6 ohm-m, it would be almost impossible to segregate the secondary field effects at depth from the strong surface anomalies. The method could be used for selecting sites with relatively low salinity prospects if the water table was very close to the surface.

*NERIDUP LOCATION 159*

Geophysical work at this locality was restricted to the magnetic and electromagnetic methods; unreliable resistivity results due to extremely high contact resistances and erratic potentials were obtained in early testing and these methods were discontinued.

The magnetic and electromagnetic imaginary component contours are given on Plates 51 and 52 respectively. At the conclusion of the geophysical work six bores were drilled to test the field interpretation and salinity distribution, and the relevant data is summarised on the contour plans.

Three of the boreholes yielded groundwater and the main purpose of this survey, to locate an adequate supply in an area where earlier boring had been comparatively unsuccessful, was accomplished. However the borehole information raised several problems concerning the interpretation of magnetic data and hydrology which have not been satisfactorily resolved.

*Magnetic*

The vertical force contours, plotted relative to the base station 2W/00, delineate part of an interesting magnetic low which is elongated east-west and roughly parallel to the granite outcrop just north of the grid (Plate 51). No attempt was made to trace the continuation of the anomaly to the east. The magnetic low was interpreted simply as a depression in the granitic bedrock and as such was predicted to channel groundwater with possible movement towards the east.

The first three bores, 19, 20, and 21, substantiated the interpretation but 22, drilled on a magnetic high attributed to shallow granite, continued to 155 feet before encountering bedrock.

From the geophysical viewpoint the contradiction of bore 22 complicates the interpretation. Whilst the intensity gradient to the north of the magnetic low can still be ascribed to the relief of the granite, the southern maximum is less readily explained. None of the tentative explanations can be supported by fact. An increase in the magnetic susceptibility of the bedrock, perhaps because of a basic dyke, would account for the magnetic high but the bottom hole sample from bore 22 did not contain fresh bedrock or any other indication of increased bedrock basicity. The anomaly could also be due to a channel cut through magnetic sediments and subsequently refilled with non-magnetic material but a careful examination and planning of the bore samples failed to reveal any trace of magnetite or ilmenite, and this theory was ruled out.

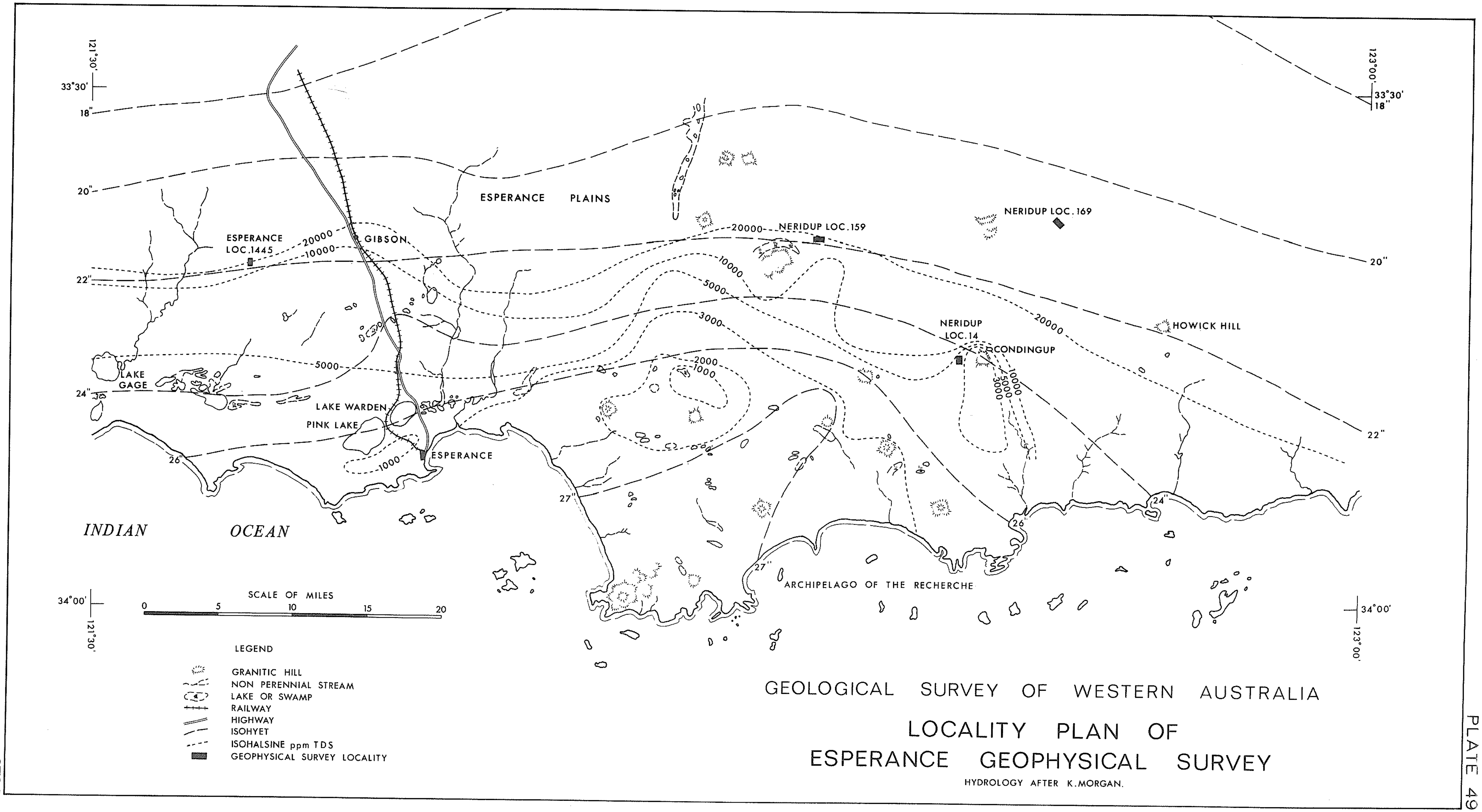
In the absence of a depression in the bedrock the reason why the groundwater should be restricted to the magnetic low is an enigma.

*Electromagnetic*

The electromagnetic contours on Plate 52 appear to be mainly related to variations in the underground water salinity and, to a lesser degree, to the surface distribution of dry sand, laterite, and silty sand.

With the exception of the pronounced negative anomaly in the southwest corner of the grid, the contours west of line 00 are zero or positive and denote high resistivities. Most of this part of the grid is covered with fine dry sand and, to the north, lateritic soils. The laterite extends to the east of Line 00 and north of the zero contour. The remainder of the eastern part corresponding to the negative e.m. zone is occupied by silty sand. This zone becomes increasingly negative towards the east and culminates with the strongest negative indications over a number of small clay pans. The negative anomaly in the southwest is also associated with a clayey surface layer.

Typically the surface material is only two or three feet deep and is underlain by about 30 to 40 feet of yellow silty sandstone, 30 feet of brown sandstone, about 40 feet of grey clayey fossiliferous sandstone or siltstone, and weathered granite. Water was struck from about 30 feet downwards in bores 20, 21, and 23; bore 22, which is shown as dry, contained seepage water of 3,900




GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

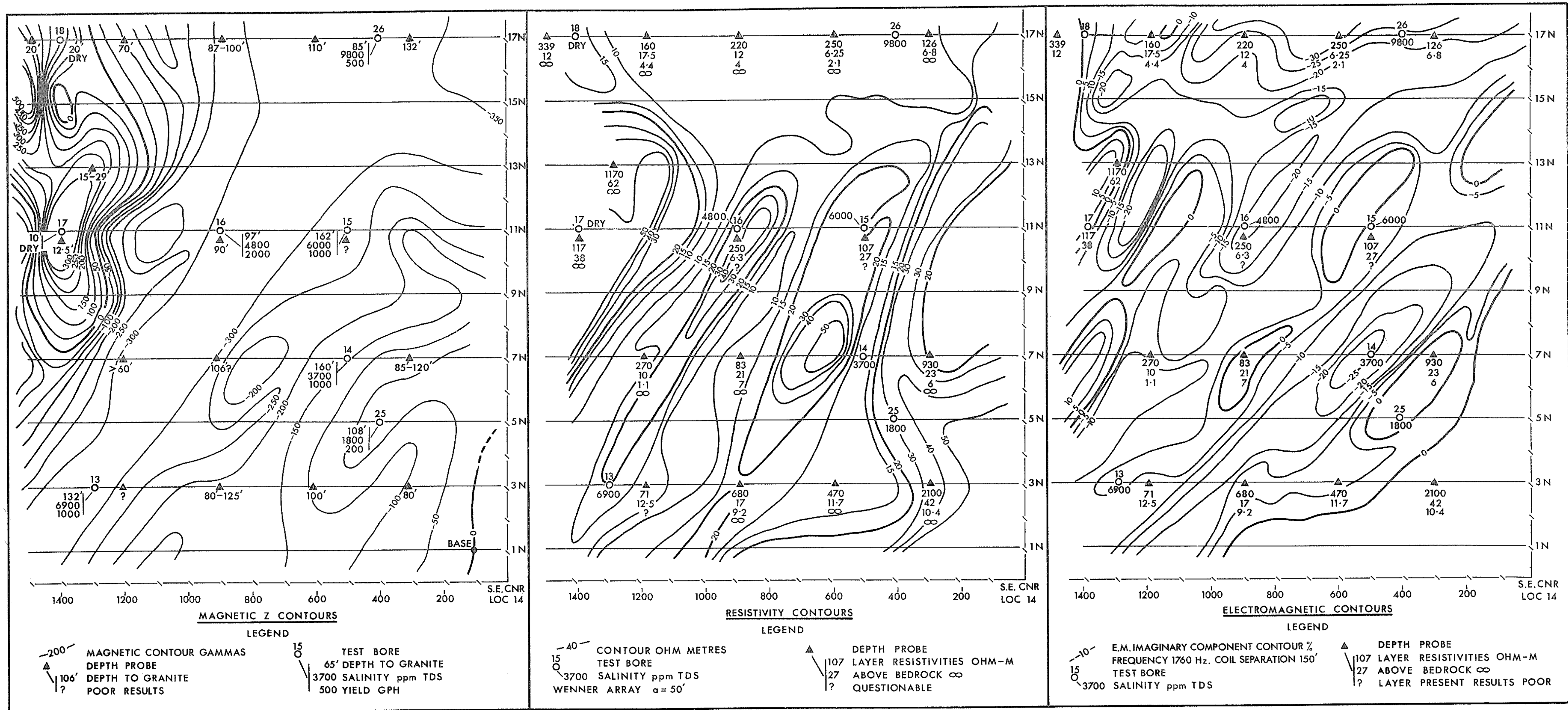
# LOCALITY PLAN OF ESPERANCE GEOPHYSICAL SURVEY

HYDROLOGY AFTER K. MORGAN.

PLATE 49

9782

PLATE 50



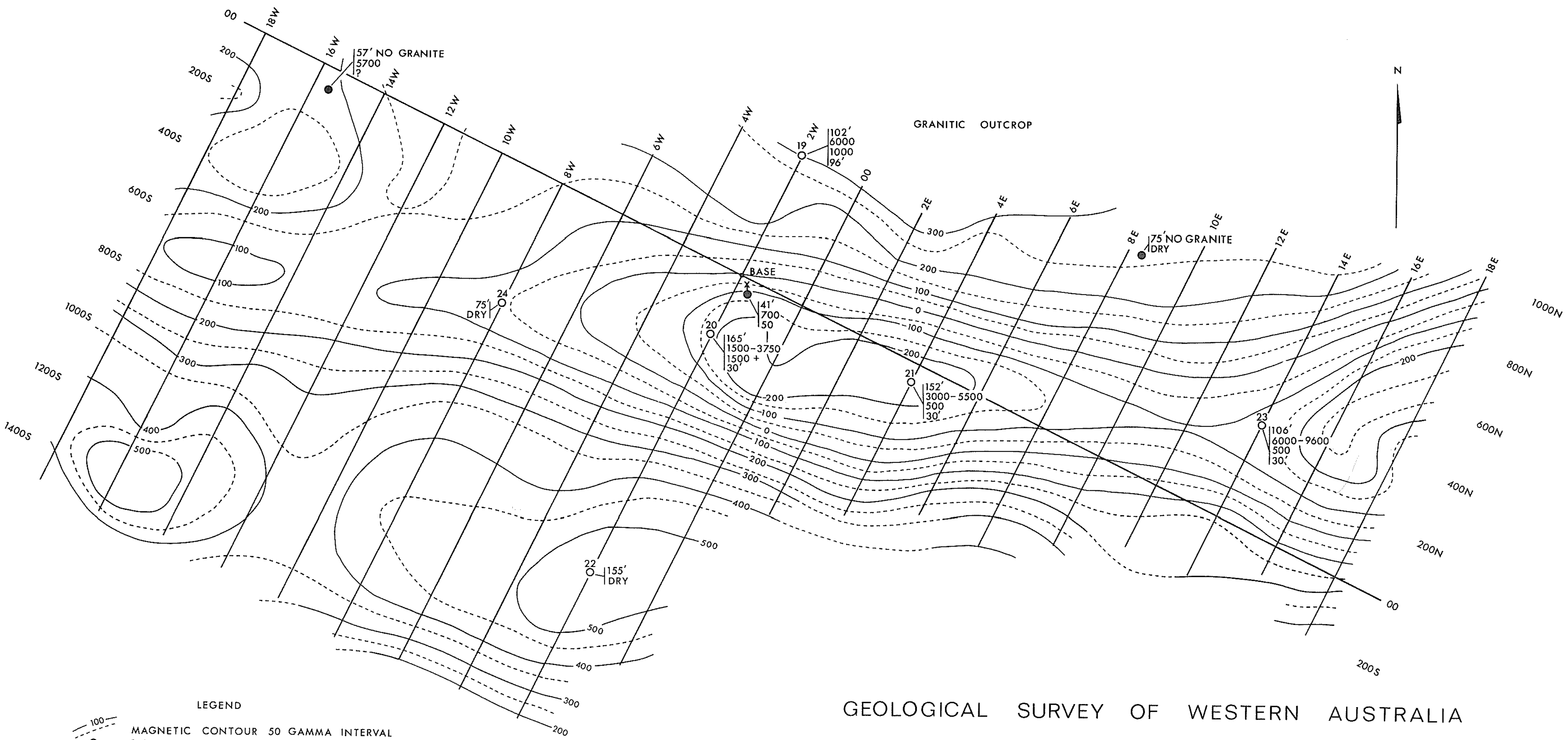

# GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

0 200 400 600 800 1000 FT.

TO ACCOMPANY REPORT BY D.L. ROWSTON. 1967

## PLAN OF PART OF NERIDUP LOC 14 SHOWING MAGNETIC, RESISTIVITY AND ELECTROMAGNETIC CONTOURS

4182




LEGEND

| | |
|---|---|
| 100 | MAGNETIC CONTOUR 50 GAMMA INTERVAL |
| ● | PRIVATE BORE |
| ○21 | TEST BORE NERIDUP No 21 |
| 152′ | DEPTH TO GRANITIC BEDROCK |
| 3750 | WATER SALINITY ppm TDS |
| 500 | ESTIMATED YIELD GALLONS PER HOUR |
| 77′ | WATER CUT |
| ¥ | MILL |

0 200 400 600 800 1000

SCALE OF FEET

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

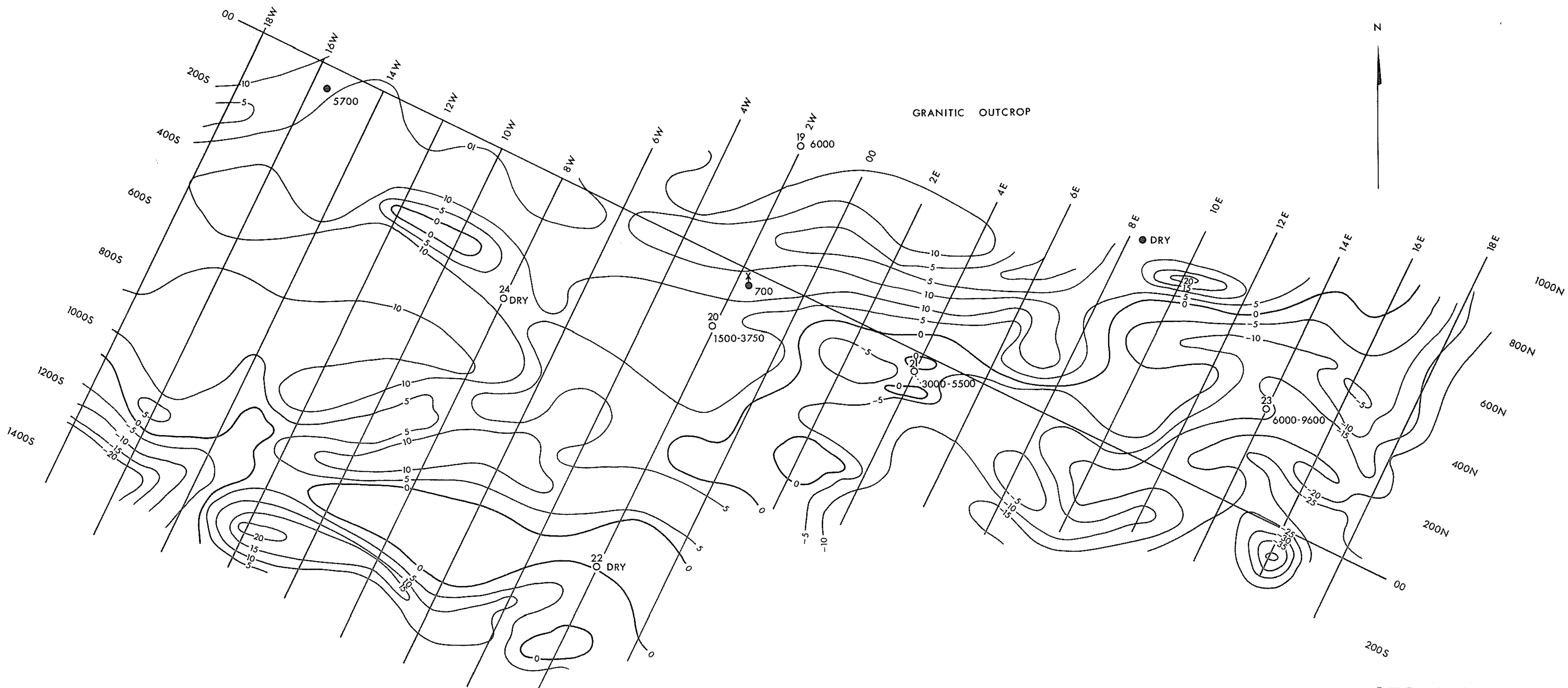
# PLAN OF PART OF NERIDUP LOC 159 SHOWING MAGNETIC Z CONTOURS

TO ACCOMPANY REPORT BY D. L. ROWSTON. 1967

9786

PLATE 51

PLATE 52




LEGEND

E.M. IMAGINARY COMPONENT CONTOUR % FREQUENCY 1760 Hz COIL SEPARATION 150 FT

PRIVATE BORE

TEST BORE

19 3000 SALINITIES ppm TDS

0 200 400 600 800 1000

SCALE OF FEET

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

# PLAN OF PART OF NERIDUP LOC 159 SHOWING ELECTROMAGNETIC CONTOURS

TO ACCOMPANY REPORT BY D.L. ROWSTON. 1967

9787

ppm quality between 22 to 28 feet. Yield from this surface layer amounts to only 50 gph as does the supply from the mill (reputed 700 ppm); the main yield of up to 1,500 gph comes from the lower aquifer and generally below 60 feet.

There is a strong correlation between the e.m. results and the salinity of this near surface groundwater, but it is not possible to establish a quantitative relationship because of the small number of water samples. It is sufficient to say that the more negative the e.m. results the more saline the groundwater. The effects of the water encountered in bore 19 and the private bore at about 16W/50S may be neglected because the depths at which water occurs are beyond the range of the equipment.

The salinity distribution is considered to be mainly controlled by localised surface recharge to the aquifers in the vicinity of bore 20. The outcrop catchment provides, in the main, sheet runoff over the impervious lateritic clay fringing the granite to the sandy soil at the foot of the slope. To the east of bore 20 the surface material is relatively clayey and most of the run-off is dissipated by surface drainage. Some replenishment is also supplied from the weathered granitic layer and this more saline water (6,000 ppm in bore 19), together with the marine environment, probably accounts for the higher salt content in the lower water horizon. The gradual increase in groundwater salinity to the east typifies the normal pattern down a drainage from the source of recharge.

The problem of the dry bores, 22 and 24, has yet to be resolved satisfactorily. These bores encountered the same strata as bore 20 and are only 600 feet away. There is no evidence to suggest a break in continuity of the horizontal beds and it is difficult to explain why these bores failed to yield other than seepage quantities of groundwater. Bore 21, 600 feet east of 20 and with the same lithology, yielded better than 500 gph.

## CONCLUSION AND RECOMMENDATIONS

The magnetic, resistivity, and electromagnetic methods were moderately successful in underground water investigations in the Esperance Plains. The self-potential method failed to give any worthwhile results.

The specific problems, which were to determine the depth to granitic bedrock, the general bedrock topography, and to define relatively the least saline groundwater, were resolved albeit with some reservations. None of the methods can detect water directly or indicate the probable yield; these can only be found by drilling.

Notably, all of the test bores that yielded useful supplies of underground water were sited in magnetic lows. The magnetic patterns generally were attributed to variations in the granitic bedrock relief and thus the lows are minima ascribed to bedrock depressions or drainages. Shallow granite is usually indicated by steep magnetic gradients. Of the 26 holes put down in the three areas only one, bore 22 at Location 159, completely contradicted the magnetic prediction. On the evidence of this bore the magnetic anomaly at Location 159 must be due in part to a change in the magnetic susceptibility of the granitic bedrock, and therefore not all anomalies can be considered due only to bedrock relief. In view of the lack of susceptibility data the method can only be used to give a qualitative picture of the bedrock configuration.

Applications of the resistivity techniques, depth probes, and mapping, were seriously affected by high contact resistances in both dry sand and lateritic soils. The addition of salt water does not entirely overcome the problem and general use of the method in the Esperance area is restricted by local conditions. In addition a high-power instrument capable of reading accurately down to 0.01 ohm is necessary for reliable results. The 50-foot electrode spacing used for the mapping was quite satisfactory in the shallow bedrock environment at Location 169 but larger spacings are required elsewhere to minimise local surface inhomogeneities and to measure main aquifer resistivities. Accepting these limitations, depth pobes can be used to provide estimates of the depths to bedrock. The layer resistivities show promise of direct correlation with the salinity of the underground water but further work is required to ratify this possibility.

The results of the electromagnetic work also show that the variations in conductivity may be related qualitatively to water salinity provided the water table is within about 30 feet of the surface and the surface lithology homogeneous. This method has the advantage over resistivity work that no direct electrical contact with the ground is required but it is also seriously affected by near surface variations which mask indications from depth. These near surface effects are inherent with a dipole primary field source and restrict the use of the E. M. Gun equipment to areas where the surface layers are fairly uniform, such as at Location 159. Other electromagnetic methods using large horizontal loops or long grounded cables for the primary field array would probably give better results. Although not tested at Esperance, the seismic refraction method could accurately determine the thickness of sediments and the basement relief.

If geophysical methods are used for further prospecting for underground water at Esperance the following practical approach is suggested.

A rapid magnetic survey should be made to broadly define depressions in the Archaean bedrock. These probable depressions should then be investigated by a pattern of depth probes to find the depths to bedrock and verify the interpretation of magnetic data. At the same time the resistivities of layers at or below about 50 feet could give some indication of the groundwater salinity distribution; on the assumption that the sediments are laterally homogeneous the lower resistivities would indicate the more saline localities.

Resistivity mapping, which requires at least four men for efficient operation, and the electromagnetic method, are not advocated unless surface conditions are suitable.

Although the hydrological aspects of the drilling results will be dealt with in more detail in a separate report, some mention of them is justified here. The belief that fresher supplies are obtained from near the areas of recharge is supported by the drilling data. However the influence of recharge can be quite local as exemplified by bores 16, 25, and 15 at Location 14 and bore 20 at Location 159. The salinity of the formation water does not always increase with the depth of a bore and thus larger supplies of the same quality water may sometimes be obtained by continuing drilling. On the evidence from Location 159 the surface aquifers is capable of yielding only about 50 gph whereas supplies up to about 1,500 gph can be pumped from the bottom aquifer.

Whilst most of the highest yielding aquifers are sandstone or fossiliferous marine beds, good supplies can be obtained from apparently impervious siltstones, particularly where they are intercalated with porcellanite and opaline silica bands. For example these beds at Location 14 are capable of yielding 500 gph and similar strata elsewhere should not be neglected or a bore abandoned because of hard drilling.

## REFERENCE

Parasnis, D. S., 1962, Principles of applied geophysics: London. Methuen.



(6)—41571

# WATER SALINITIES FROM RESISTIVITY WELL LOGS

by D. L. Rowston


## ABSTRACT

An empirical method of estimating formation water salinities from $R_{64}''$ long normal resistivity well logs has been developed and used effectively in the Perth Basin of Western Australia. Salinities can be determined with an accuracy of ± 15% or better for aquifers in the relatively unconsolidated Mesozoic and younger sediments. Estimates in older strata may be unreliable.


## INTRODUCTION

The Geological Survey of Western Australia has used a Widco well logger, Model XMVA-12, to obtain hydrogeological data from exploratory water bores drilled in the Perth Basin since the end of 1963. The logger is equipped to provide gamma ray, point resistivity (PR), normals resistivity ($R_{16}''$ and $R_{64}''$), potential (SP), caliper, and temperature measurements to depths of 2,500 feet.

The electrical and gamma ray logging has been particularly useful in rotary drilled holes. In addition to the normal identification of lithology and stratigraphic correlations, an empirical method has been developed whereby formation water salinities can be estimated fairly reliably from the $R_{64}''$ normals restivity logs. Although developed independently the method had been described previously by Jones and Burford (1951). In view of its successful application locally, the method is considered worthy of reiteration because of possible interest to other investigators who are unable to employ more sophisticated logging techniques. It is not suggested that it can be applied elsewhere categorically; in Western Australia the method has been refined over a period of four years and is reassessed continually as more data comes to hand.

The Geological Survey has been engaged in a systematic study of the hydrology of the Perth Basin for some years. A series of exploratory bores have been drilled across the Basin from the coast to the Darling Scarp at Busselton, Mandurah, Pinjar, and Gingin (Plate 53) with more localised patterns at Arrowsmith and, currently, at Watheroo. The bores are generally about 2,000 feet deep and penetrate relatively unconsolidated Cainozoic to Mesozoic sediments. Permian rocks have been encountered in a few bores. Artesian to subartesian aquifers occur in the Quaternary, Cretaceous, and upper Jurassic sediments whereas the Permian strata are generally too tight to yield large supplies. The water quality is highly variable and the hydrological pattern further complicated by shallow faulting, sea water encroachment, and local recharge conditions.

## WELL LOGGING

Well logging is now carried out as a matter of routine to augment water sample and lithological data obtained during the course of drilling. In rotary drilled holes, gamma ray, SP, PR, $R_{16}''$, and $R_{64}''$ logs are recorded; the first run is usually made at 1,000 feet and the final run at total depth.

Originally the potential log was to be used to determine formation water salinities according to the standard procedure detailed by Schlumberger (1962). But potential logs obtained in the relatively shallow and fresh water environment are frequently unusable because of drift, and the comparatively small potentials generated by the low resistivity contrast between formation water and drilling fluid. Attempts to enhance the magnitude of the potentials by increasing the mud salinity resulted in erratic and unrepetitive logs. The SP logs are still used qualitatively to indicate whether the formation water is more, or less, saline than the drilling fluid. Potentials negative with respect to the shale line denote water salinities higher than that of the mud and conversely positive potentials indicate less saline water.

With the failure of the SP method to estimate water salinity, recourse was made to the calibrated $R_{64}''$ normals resistivity log as the next most prospective function. Existing logs showed that excellent repetition with different runs in the same hole was possible, despite variations in mud resistivity and other hole parameters.

## OUTLINE OF METHOD

The estimation of formation water salinity from the $R_{64}''$ log is based on the fundamental relationship propounded by Archie (1942), namely:

$$Rt = \frac{F\,Rw}{S_w^n} \quad \ldots\ldots (1)$$

where RT = true formation resistivity.
F = formation resistivity factor.
Rw = resistivity of formation water.
$S_w^n$ = fraction of pore volume of sediment occupied by interstitial water.

The relationship can be simplified by assuming that the formation is 100 per cent. water saturated and contains no hydrocarbons. Under these conditions, $S_w^n = 1$ and

$$Rt = Ro = F\,Rw \quad \ldots \quad (2)$$

where Ro = formation resistivity when 100 per cent saturated with water of resistivity Rw.

These conditions are considered quite tenable for shallow sediments in the Perth basin.

With equation (2) accepted, values for Ro and F are required to resolve Rw and thus the formation water salinity.

(a) Ro is measured directly from the long normal $R_{64}''$ log, that is

$Ro = R_{64}''$

and equation (2) becomes

$$R_{64}'' = F\,Rw \quad \ldots \quad (3)$$

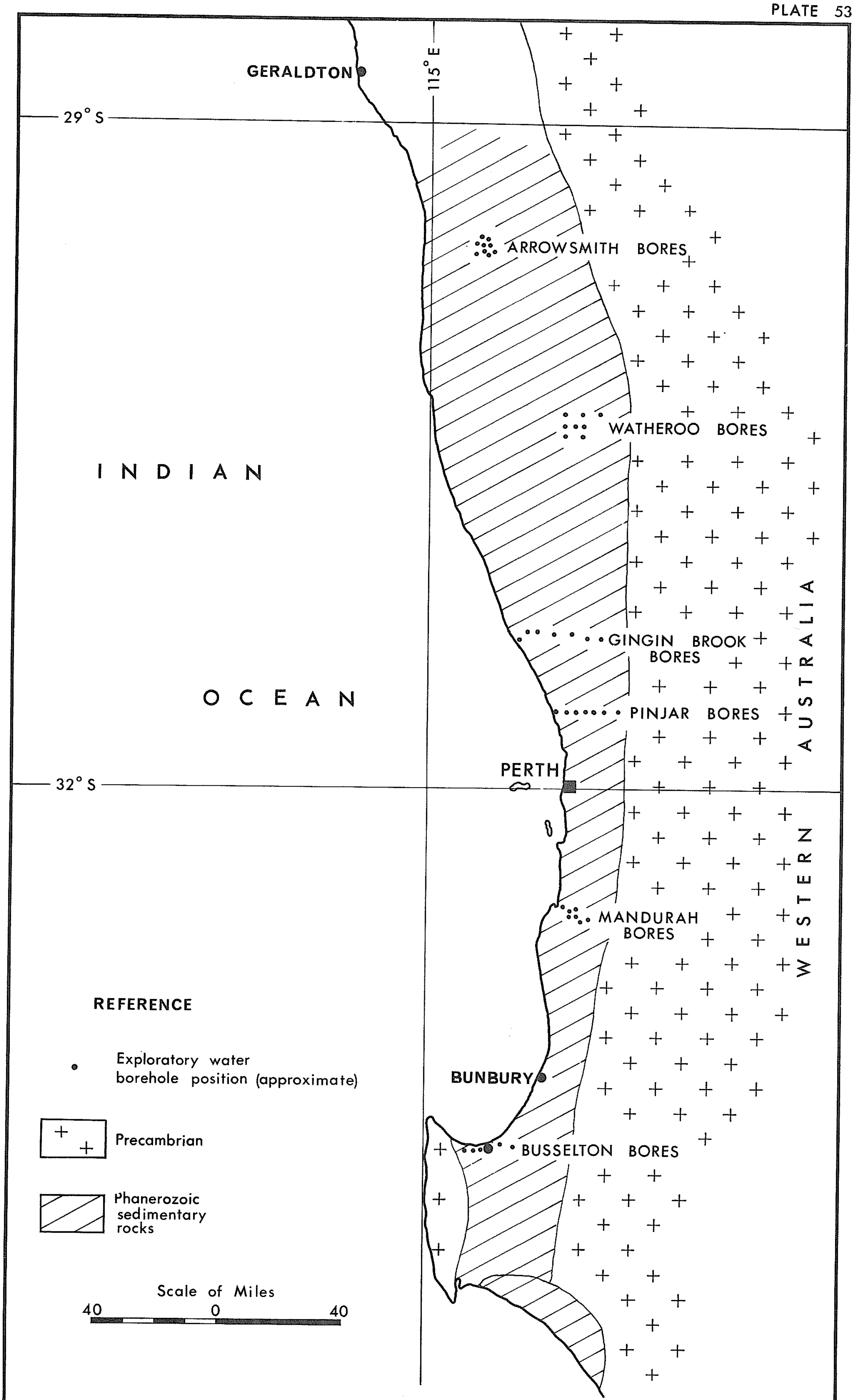
(b) F is obtained empirically from (3) by measuring Rw of a control water sample from the bore and using the $R_{64}''$ reading corresponding to the interval sampled. Temperature corrections, either Rw to the temperature of the formation of both Rw and $R_{64}''$ to 20°C are applied.

This value for F is then used with the $R_{64}''$ readings to determine Rw for other clean sands in the bore. Rw is entered on a resistivity versus salinity chart to the appropriate temperature curve and the salinity read off. The conversion chart used by the Geological Survey has been constructed from a great number of water sample analyses by the Government Chemical Laboratories and gives total dissolved salts (TDS) directly instead of the standard NaCl equivalent.

## PROBLEMS AND LIMITATIONS

On theoretical grounds there are numerous objections to the assumption that $R_{64}''$ is equivalent to Ro and to the application of F to other clean sands, even within a particular formation. These objections are debated thoroughly by Patten and Bennett (1963) and only a brief discussion of the more salient points is warranted here. The empirical nature of the method is emphasised and, despite theoretical considerations to the contrary, it can be used to determine salinities to within about ± 15 percent in Mesozoic and younger sediments in the Perth Basin.

The discussion is based on hydrogeological data from about 18 bores totalling some 27,000 feet where reliable calibrated resistivity logs were recorded.



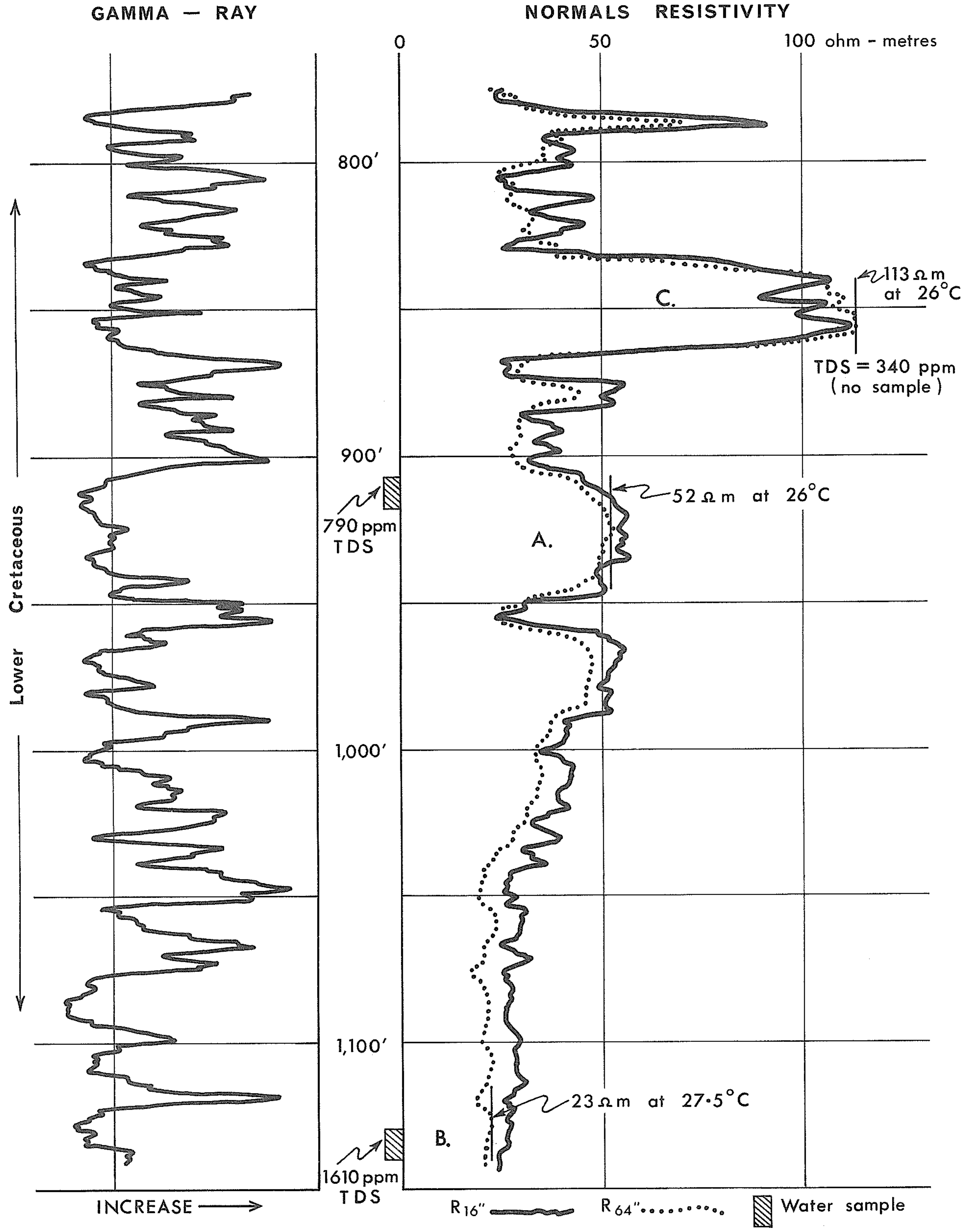

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

## PERTH BASIN EXPLORATORY WATER BORE LOCATIONS

To accompany report by D. L. Rowston, 1967

# PINJAR No. 1 - EXPLORATORY WATER BORE

$R_m$ = 1·97 Ω m at 20°C




**A.** $R_{64''}$ = 52 Ω m at 26°C
F = 6·4 (empirical)
$R_{64''} = F R_w$
$R_w$ = 8·1 Ω m at 26°C
TDS = 750 ppm

**B.** $R_{64''}$ = 23 Ω m at 27·5°C
F = 6·4
$R_w$ = 3·6 Ω m at 27·5°C
TDS = 1600 ppm

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## EXAMPLE OF CALCULATION OF WATER SALINITIES FROM RESISTIVITY WELL LOGS

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The objections to assuming $R_{64}'' = Ro$ are related primarily to the unknown influence of the mud filtrate in the flushed and invaded zones on the $R_{64}''$ curve. Long normal dogging runs made under different hole conditions indicate that variations such as mud resistivity (Rw) and borehole diameter have negligible effect; the $R_{64}''$ long generally repeats within 1 to 2 per cent. even in permeable sands. On the other hand the short normal ($R_{16}''$) curve can be strongly affected by changes in these parameters. The relative magnitudes of the two curves can be used qualitatively to gauge the permeability of a bed. Rm, and thus the filtrate resistivity Rmf, are usually lower than Rw with the result that, in permeable beds, the $R_{64}''$ is appreciably greater than $R_{16}''$. Where the $R_{16}''$ and $R_{64}''$ logs have similar magnitudes, penetration of the mud filtrate into the formation is inhibited by either a tight formation or high formation pressure. These are broad generalisations of a complex relationship which do not always apply and each case must be assessed individually.

Experience has shown that the $R_{64}''$ log indicates Ro reliably in most cases and besides, as the method is empirical, small discrepancies are compensated for when F is determined. In permeable strata where invasion is deep, salinities estimated from $R_{64}''$ are liable to be maximum values.

The determination of F and the validity of applying it elsewhere to estimate unknown salinities are the more serious problems.

The main prerequisite for finding F is a reliable water sample. The Geological Survey obtains samples by using Johnson and Halliburton formattion testers, or by plugging, casing and bailing the hole; salinities are found by conductivities and chemical analyses. The latter indicate that about 30 per cent. of the samples obtained have been contaminated by the drilling mud or the cement used in plugging the hole. Another 20 per cent. cannot be used because the interval sampled is silty and the corresponding $R_{64}''$ value is therefore unrealistic, or for other reasons.

An appraisal of the remaining reliable data shows that F ranges from 5.5 to 42 and can be related to the ages of the strata. The observed increase in F with increase in age agrees with the theoretical inverse dependence of F on porosity; the older and more compacted sediments are less porous and thus have higher factors. An investigation of the possible variation in F with depth, irrespective of age, failed to reveal any relationship.

Although the values of F tend to be gradational there are three distinct stratigraphic groups in the range. In the Cretaceous and younger sediments F ranges from 5.5 to 7.4 and has an average value of 6.4. The even frequency distribution precludes further subdivision even though finer stratigraphic distinctions can be made readily. Only eight reliable water samples have been obtained from rocks identified positively as Jurassic; F varies between 7.9 and 11.5 and has been given a tentative weighted value of 10.4. Five values of F, from 22 to 42 have been determined for the Permian and obviously the accuracy of the method under these circumstances is very low. As water from the Permian is saline and the yields generally small, this inaccuracy does not detract from the usefulness of the method.

Thus, F cannot be applied unconditionally and, for accurate results, the stratigraphy should be known. Palynological examination of core is used extensively by the Geological Survey for this purpose.

## EXAMPLE

A section of the gamma ray and normal resistivity logs from the Pinjar 1 bore (Plate 54) have been selected as typical and because two uncontaminated water samples are available for comparison with the estimated salinities.

The gamma ray log indicates an interval of interbedded sandstone and siltstone which has been identified by palynology as the Leederville Sandstone of lower Cretaceous age. Thus the average formation resistivity factor, $F = 6.4$, has been used to determine Rw at the appropriate temperature from the $R_{64}''$ log. The gamma ray log also shows that the sands A and B from which the samples were taken are relatively clean and of sufficient thickness to assume $R_{64}'' = Ro$. On the other hand sand C is somewhat silty and $R_{64}''$ is probably lower than the actual formation resistivity.

The estimated salinities for A and B compare very favourably with the water sample salinities found by chemical analyses. Although the salinity of water from C has not been verified this estimate is considered realistic because water of this quality is common elsewhere in the Leederville Sandstone. The estimated salinity here is a maximum value and the true salinity could be as low as 300 ppm.

Reliable salinities cannot be calculated from $R_{64}''$ in silty or shaly sections such as 1,010 to 1,053 feet where a transition zone occurs, or in thin sands similar to the one at 787 feet. Experience has shown that for the thinner, silty sands (B and C) the peak $R_{64}''$ values give better results, whereas in the thick aquifers (A) minor peaks can be ignored.

## CONCLUSIONS

The long normal resistivity log has been used successfully in rotary drilled water bores in the Mesozoic and younger sediments of the Perth Basin to determine water salinities within an accuracy of ± 15 per cent. In common with most other well logging interpretive procedures, the method is empirical and depends on the amount of control data available. It is unlikely that the accuracy can be improved to better than ± 10 per cent. but this is acceptable for most regional hydrological investigations and particularly where water sampling is unsatisfactory or incomplete.

The main requirements for effective application in similar environments are:

(a) a reliably calibrated long normal resistivity log;

(b) uncontaminated water samples, initially for finding F and for verification of results when the method has been established;

(c) stratigraphic control;

(d) formation temperature measurements;

(e) a gamma ray or other log to indicate the quality of the sands. The method is advocated only for clean sands which are preferably more than 20 feet thick.

Proving the efficacy and reliability of this or related methods for a particular area is generally a long term project. For this reason it is suggested that records of hole conditions, (mud weight, mud resistivity, mud cake) lithology and stratigraphy, porosity and permeability of cores etc. be kept from the inception of logging to study the theoretical aspects more fully.

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