

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1966



1967

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EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

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

Under Secretary: I. R. Berry

Director, Geological Survey: J. H. Lord

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1967

DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1966

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DIVISION IV

Annual Report of the Geological Survey Branch
of the Mines Department for the Year 1966

The Under Secretary for Mines

I submit herewith, for the information of the Honourable Minister for Mines, my report on the activities of the Geological Survey of Western Australia for the year 1966, together with some of the reports on investigations made for departmental purposes.

ORGANIZATION

Despite the shortage of geologists in Australia, the Geological Survey was fortunate in filling all vacancies, except for that of a geophysicist, in the early part of the year. However, later resignations have created vacancies, which are proving difficult to fill with competent officers.

The recommendations made last year for additional staff in the Sedimentary (Oil) Division, to keep abreast of the expanded company activity and general exploration for oil, are still under consideration and only one position for an additional senior geologist has been approved. It is hoped to make an appointment to this position early in the new year.

Because of the unprecedented activity in metalliferous mineral exploration, particularly for nickel and base metals, and the continued expansion in the oil search activities, the services provided by the Geological Survey were in great demand, particularly the reference library, the provision of information on known mineral occurrences, on localities, verbal discussions on the progress and results of geological mapping, and general advice on mineral potential.

STAFF

PROFESSIONAL

Appointments :

Name	Position	Effective Date
J. L. Baxter, B.Sc. (Hons.)	Geologist, Grade 2	5/1/66
J. J. G. Doepel, B.Sc. (Hons.)	Geologist, Grade 2	5/1/66
A. E. Cockbain, B.Sc. (Hons.), Ph.D.	Palaeontologist	6/1/66
J. H. Currie, B.Sc.	Geologist, Grade 2	18/1/66
R. Peers, B.Sc. (Hons.)	Geologist, Grade 2	21/2/66
P. C. Muhling, B.Sc. (Hons.)	Geologist, Grade 2	14/3/66
L. N. Wall, M.Sc., D.I.C.	Geologist, Grade 2	21/9/66

Resignations :

E. E. Swarbrick	Geologist, Grade 2	21/1/66
I. Gemuts	Geologist, Grade 2	25/2/66
J. H. Currie	Geologist, Grade 2	11/8/66
R. Milbourne	Geologist, Grade 2	31/8/66

Promotions :

K. H. Morgan	Geologist, Grade 1	1/10/65
L. E. de la Hunt	Supervising Geologist	10/1/66
J. G. Blockley	Geologist, Grade 1	14/1/66
J. L. Daniels	Senior Geologist	8/3/66
M. J. B. Kriewaldt	Geologist, Grade 1	24/6/66

CLERICAL AND GENERAL

Appointments :

R. A. H. Stevenson	Clerk	6/1/66
B. Kozak	Library Assistant (Temp.)	21/2/66
B. Aleksandrow	Laboratory Assistant	18/4/66
S. M. Fawcett, M.A.	Library Assistant	9/5/66
V. D. Thornber	General Assistant	27/6/66

Resignations :

V. M. Marshall	Library Assistant	4/2/66
S. C. Crew	Clerk	18/2/66
P. M. Bryant	Laboratory Assistant	18/2/66
B. Kozak	Library Assistant (Temp.)	9/5/66
R. A. Taylor	Geological Assistant	20/5/66

Transfer :

D. H. Johnston	Clerk to Education Department	30/4/66
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The total establishment for the Geological Survey is now 40 professional, 6 clerical, and 10 general officers.

ACCOMMODATION

The Branch continues to occupy five separate small buildings in three adjoining streets. At present there is no definite proposal to alleviate this position. The records section is working in cramped and poor accommodation, while the library is suffering from the lack of storage space and reading space for visitors.

Plans are being prepared for the expansion of the core library at Dianella.

The expansion of the Government Records Repository has limited the space for the Geological Survey's vehicle park and general store. Eventually it will be necessary to move this store and vehicle park, and, as there is no adjacent land available, another site will have to be found.

OPERATIONS

HYDROLOGY AND ENGINEERING GEOLOGY DIVISION

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

Hydrology

Exploratory drilling was completed in the Yule River area for the Port Hedland town water supply, where sufficient water for the immediate needs of the township was proved.

Drilling continued in the Arrowsmith River area to determine the extent of the water province that is being used for the Morawa town water supply.

Drilling on the Mandurah hydrological investigation and on the Albany town water supply project continued, while successful drilling programmes for town water supplies were completed near Jurien Bay and Coomberdale.

On the long term programme of deep drilling in the Perth Basin, a line of holes across the basin near Gingin was completed and a new line was commenced near Busselton.

The regional investigation of the Esperance area continued, together with experimental work on the application of geophysics to the search for groundwater. The groundwater resources of a portion of the Kimberley was assessed in association with regional mapping, and a groundwater reconnaissance survey of the Pilbara area was made.

For the Metropolitan Water Board the investigation of the Gnaragara Lake area was continued on a restricted scale, and a preliminary investigation was made on three small catchments in the Darling Range to ascertain if they were suitable for detailed catchment management studies.

Field surveys on Government projects were made also of the West Mugadong district, Goodlands district, Miami area, Exmouth, Dwellingup, Jerdacuttup, Bindi Bindi, Latham, and Una townships, and for Pippingarra native reserve and Condingup, Waroona, Wannamal, and Mogumber schools. In all, 26 field inspections were made for other Government Departments and 75 for private landholders.

Engineering Geology

A comprehensive programme of site exploration was continued at the Kennedy Range dam site, which included detailed and regional mapping and the planning and supervision of percussion and Gemco auger drilling programmes.

Investigations were carried out on a proposed dam storage for the water supply for Wyndham at Moochalabra Creek, which included detailed mapping, supervision of diamond drilling, and the location of supplies of impervious core material, filter sand, and rockfill.

An erosion problem at the Bandicoot Bar Diversion Dam was appraised and remedial works, now completed, were suggested. The geology of the Ord River dam site was revised and geological contract documents and plans were completed.

A reconnaissance survey was made of eight possible dam sites in the Pilbara region.

SEDIMENTARY (OIL) DIVISION

P. E. Playford (Supervising Geologist), G. H. Low, and D. C. Lowry.

The progress of oil exploration, which continued to accelerate in Western Australia, was followed closely during the year, and the work programmes of oil exploration companies were reviewed.

P. E. Playford accompanied the Honourable Minister for Mines and the Assistant Under Secretary on a three-months visit to the United States, Canada, Europe, and North Africa to study petroleum exploration, production, and legislation in those countries.

In the Perth Basin, mapping was continued on parts of the Perth, Pinjarra, and Geraldton 1:250,000 Sheets. Regional mapping in the Eucla Basin has been completed as far as the South Australian border.

A drilling programme for ilmenite in the Pleistocene beach sands of the Yoganup area in the southern Perth Basin was planned and supervised.

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

Field work was continued on the Kurnalpi 1:250,000 Sheet, where valuable stratigraphic information has been gained on the Archaean. Advice was supplied to pastoralists on hydrology and to prospectors on mineral occurrences and local geology. A nickel prospect was discovered at Lake Rebecca, in the course of systematic geological mapping on the Kurnalpi Sheet.

Blackstone Area

Mapping commenced in the Blackstone area in the extreme eastern portion of the State. Field work on the Scott 1:250,000 Sheet was completed and the Cooper Sheet has been started. The work has also provided a better understanding of the distribution of the nickeliferous laterites, and the younger deposits that are the main source of water in the area.

General

An area along the Darling Scarp on the Pinjarra 1:250,000 Sheet was mapped. Visits were made to the Esperance and Cue—Mount Magnet regions to co-ordinate the results of geological mapping of other divisions into the general pattern of the Precambrian of the State.

The compilation of maps from field work completed in previous field seasons, continued.

Samples were collected for a joint programme of rock age determinations with members of the Australian National University.

The programme of geological mapping at 1:250,000 scale to the end of 1966 is shown on Figure 1.

MINERAL RESOURCES DIVISION

L. E. de la Hunty (Supervising Geologist), J. Sofoulis (Senior Geologist), J. G. Blockley, P. C. Muhling, J. Baxter, and R. S. Chaturvedi (Colombo Plan Fellow, temporarily attached from University of W.A.).

Kimberley Division

Appraisals were made of the mineral deposits of the Yampi, Lennard River, and Charnley Sheet areas, in conjunction with the regional mapping programme of that area conducted jointly with the Bureau of Mineral Resources. Reports were compiled on the bauxite potential of the northern part of the Kimberley Division, and on copper and mica deposits in the western part.

North-West Division

Field work was completed on the comprehensive survey of the blue asbestos deposits of the Hamersley Range area, and compilation of a bulletin was commenced. Several field excursions were arranged for visiting geologists to inspect the iron deposits with black shales, fossils, and pseudo-fossils localities and natural sections of the Precambrian succession in the Hamersley Range area.

The Robertson 1:250,000 Geological Sheet was compiled.

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

Miscellaneous inspections were made in connection with gold, copper, water, and a reported meteorite crater.

South-West Division

A diamond drilling programme was carried out at the Geraldine lead mine, near Galena, and field inspections were made on deposits of ilmenite and bauxite.

COMMON SERVICES DIVISION

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

During the year, 29 file reports were written dealing with collections of between one and 37 rocks. The reports were for all Divisions of the Survey, other Government departments, and members of the public. A total of 1,528 thin-

sections and 23 polished sections were prepared by the technical staff. An important part of the work of this section is to advise and assist geologists of all Divisions, particularly those engaged on regional mapping, in their own petrological treatment of their rocks. The appointment of an assistant petrologist has reduced considerably the backlog of petrological work.

Dr. Trendall assumed responsibility for the supervision of the special study of blue asbestos in the Hamersley Range area initiated in 1964. He spent six weeks in the field in the Hamersley area in connection with this work, and later 11 weeks were devoted to a tour of Precambrian iron formations in the Lake Superior area of the United States, the Labrador trough in Canada, and the Cape Province and Transvaal asbestos-producing areas of South Africa. The comparative knowledge thus gained of the iron formations of the Hamersley Group will ensure a definite assessment of the economic potential of blue asbestos in Western Australia during 1967. An informally circulated list of work on Western Australian iron formations is materially contributing to the international co-ordination of iron formation studies.

During the year Dr. Trendall was invited to join the Australian National Committee for the Upper Mantle Project, an international programme of geological and geophysical research. The Committee is organizing on a national basis an intensive study of the structure and development of the ancient rocks of the southwestern part of this State.

Chemical and mineralogical support for many petrological studies from the Government Chemical Laboratories must again be gratefully acknowledged.

Palaeontology (A. E. Cockbain and B. S. Ingram)

During the year, 68 file reports were written, many of which involved the palynology of Mesozoic samples sent in by the Hydrology Division. Palynological samples from bores in the Arrowsmith River and Gingin Brook areas have yielded useful stratigraphical and palaeontological information. Other work has included studies of the Permian and Cretaceous of the Kennedy Range—Gascoyne Junction area, the Tertiary of North West Cape, the Permian of the Irwin River region, and the Tertiary of the Albany—Esperance area.

In addition to these small-scale studies, the palaeontology laboratory is engaged on two major projects: (1) a palynological zonation of the Upper Jurassic—Lower Cretaceous sediments of the Yarragadee Formation in the northern Perth Basin and (2) systematic and stratigraphical palaeontology of Foraminifera and Bryozoa from the Eucla Basin.

The palaeontology laboratory is now able to handle most requests involving palynology and micropalaeontology, and whilst some macro-invertebrate groups are identified in the laboratory, other material is sent away to experts. We are especially grateful to Mr. B. E. Balme (University of Western Australia) and Mr. G. W. Kendrick (Western Australian Museum) for much helpful advice. With this expansion of the laboratory, it has been necessary to start a punched card index to the fossil samples catalogued under G.S.W.A. "F" numbers.

Geophysics (D. L. Rowston)

Geophysical work during the year encompassed well-logging and routine laboratory services, and a variety of field investigations.

Although the number of well-logging operations decreased to 35 the total footage logged increased substantially to 38,000 feet. Salinity determinations were made on about 600 samples. An experimental survey to test the applicability of geophysical methods to groundwater search was made in the Esperance area. Resistivity, electromagnetic, magnetic, and self-potential methods were used on several localities, where special problems of groundwater concentration and salinity were recognised. A number of bores, sited to test geophysical anomalies and to provide information for their interpretation, are being drilled.

A radiometric survey was made along an ancient strandline near Busselton to supplement a geological study of beach sand deposits and reserves of ilmenite, monazite, and zircon.

As a result of the increased activity in base metals exploration, numerous enquiries on geophysical prospecting methods and techniques were received. Minor surveys were made to demonstrate and test the efficacy of various methods in particular environments.

Technical Information Section (R. R. Connolly and M. E. Redman)

Technical editing of reports, maps and plans for publication, and the supervision of publications, continues to be the major function of this section. Twenty one Records were produced.

Requests for information by the staff, mining companies, consultants, and general public continue to increase but not at the same rate as in the previous year.

The operations of the library were hampered in the early part of the year by staff resignation. The library loans to staff increased to 1,683, while loans to the public and other libraries totalled 257. Requisitions raised on the Drafting Branch for drawing, copying, and photographing services totalled 601.

At the core library considerable time has been spent reducing the size of sludge samples but despite this reduction of bulk, little storage space remains for current material.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

The Bureau of Mineral Resources carried out both geophysical and geological work in this State during 1966. The projects included:

1. Regional geological mapping of the Yampi, Charnley, and Lennard River 1:250,000 Sheets in the Kimberley Division, jointly with the Geological Survey of Western Australia.
2. Continuation of sampling of Precambrian rocks in the Kimberley area for age determination.
3. Aeromagnetic survey (DC3 aircraft) of the Leonora and Laverton 1:250,000 Sheets.

PROGRAMME FOR 1967

HYDROLOGY AND ENGINEERING DIVISION

Hydrology

1. Continuation of the hydrological survey of the Perth Basin including deep drilling.
2. Hydrogeological investigation and exploratory drilling for groundwater in the following areas:
 - (a) Mandurah—Pinjarra
 - (b) Gnangara Lake
 - (c) Arrowsmith River area
 - (d) Albany
 - (e) Esperance Plains
 - (f) Port Hedland
 - (g) Midlands light lands
 - (h) Eucla Basin
 - (i) Others, as required.
3. Kimberley: hydrological assistance to pastoralists
 - (a) bore site selection as required
 - (b) regional hydrogeological mapping in conjunction with the Bureau of Mineral Resources.
4. Miscellaneous minor investigations as requested by other departments and the public.

Engineering

1. Kennedy Range Dam Site—supervising of drilling of abutments.
2. Standard Gauge Railway—investigations as requested and detailed mapping of cuttings.
3. Investigations of a dam site either on Fitzroy River or in Pilbara.
4. South Dandalup Dam Site—supervision of drilling.

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. Compilation of the geological survey of the Eucla Basin.
4. Miscellaneous investigations as required.

REGIONAL GEOLOGY DIVISION

1. Continuation of mapping in the Eastern Goldfields on the Kurnalpi and Menzies Sheets.
2. Continuation of the regional mapping of the Kimberley Division in conjunction with the Bureau of Mineral Resources.
3. Continuation of mapping in the Eastern Division on the Cooper, Talbot, and Bentley Sheets.

MINERAL RESOURCES DIVISION

1. Completing the regional investigation of the blue asbestos deposits of the Hamersley Range.
2. Continuation of the mineral survey of the Yalgoo and Murchison Goldfields.
3. Miscellaneous investigations as required.

PUBLICATIONS AND RECORDS

Listed below are the six publications issued during the year.

Printing of the two important bulletins on the Hamersley Range Iron Ore and the Devonian Reefs of the Canning Basin has not been completed although submitted over a year ago.

Issued during 1966

Annual Report 1965.

Geological Map of Mt. Bruce 1:250,000 Sheet (SF/50-11 International Grid) with Explanatory Notes.

Geological Map of Roebourne 1:250,000 Sheet (SF/50-3 International Grid) with Explanatory Notes.

Geological Map of Roy Hill 1:250,000 Sheet (SF/50-12 International Grid) with Explanatory Notes.

Geological Map of Newman 1:250,000 Sheet (SF/50-16 International Grid) with Explanatory Notes.

Geological Map of Western Australia 1:2,500,000 with Explanatory Notes.

In Press

Bulletin 117, The Geology and Iron Deposits of the Hamersley Range Area, Western Australia.

Bulletin 118, Devonian Reef Complexes of the Canning Basin, Western Australia.

Mineral Resources of Western Australia.

Geological Map of Widgiemooltha 1:250,000 Sheet (SH/51-14 International Grid) with Explanatory Notes.

Geological Map of the Pyramid 1:250,000 Sheet (SH/50-7 International Grid) with Explanatory Notes.

In Preparation

Geological maps (1:250,000) with Explanatory Notes, the field work for each having been completed: Turee Creek, Yarraloola, Wylloo, Kalgoorlie, Edmund, Robertson, Scott, and sheets

covering the Western Australian portion of the Eucla Basin.

Records Produced

- | | |
|---------|--|
| 1966/1 | Second progress report on the Brockman Iron Formation in the Wittenoom-Yampire area, by A. F. Trendall. |
| 1966/2 | The geology of the Ord River Dam and associated works, by F. R. Gordon (RESTRICTED). |
| 1966/3 | Stability of the Kellerberrin rock cuts, Standard Gauge Railway, Northam to Merredin, by F. R. |
| 1966/4 | An outline of the hydrogeology of Nicholson, Gordon Downs, Flora Valley, Sturt Creek, Ord River, Turner River, and Spring Creek Stations (Vestey's Stations), East Kimberleys, W.A., by A. D. Allen. |
| 1966/5 | Geological reconnaissance at Duracks Folly, Kununurra to Ord main dam site road, by F. R. Gordon (RESTRICTED). |
| 1966/6 | Not issued. |
| 1966/7 | Mt. Krauss diversion dam site, by F. R. Gordon (RESTRICTED). |
| 1966/8 | Geological reconnaissance at Mooloolaba Creek dam site by F. R. Gordon (RESTRICTED). |
| 1966/9 | Barramundi Range dam site, by F. R. Gordon (RESTRICTED). |
| 1966/10 | Geophysical investigations for beach sand deposits in the Yoganup area, by D. L. Rowston. |
| 1966/11 | Details of clay, loam, kyanite, and shale samples taken during a geological survey of Perth and environs, 1950-51, by L. E. de la Hunty. |
| 1966/12 | Details of limestone, bog limestone, and limesand samples taken during a geological survey of Perth and environs, 1950-51, by L. E. de la Hunty. |
| 1966/13 | Details of silica sand, diatomite, quartz, and glauconite samples taken during a geological survey of Perth and environs, 1950-51, by L. E. de la Hunty. |
| 1966/14 | Drilling for mineral beach sands in the Yoganup area, South-West Division, Western Australia, by G. H. Low (RESTRICTED). |
| 1966/15 | Exploratory drilling for underground water, Gingin Brook area, Perth Basin, by C. C. Sanders. |
| 1966/16 | The hydrogeology of the Kimberley Plateau, by A. D. Allen. |
| 1966/17 | Geological reconnaissance at Macdonald Gorge dam site, by F. R. Gordon. |
| 1966/18 | Review of a quarrying operation at Merredin Standard Gauge Rail Project, by F. R. Gordon. |
| 1966/19 | South Dandalup upper dam site, results of auger and diamond drilling, by J. D. Wyatt (RESTRICTED). |
| 1966/20 | Geological investigation of Mooloolaba dam site, by J. D. Wyatt. |
| 1966/21 | Wells drilled for petroleum exploration in Western Australia by P. E. Playford. |

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1st February, 1967.

J. H. LORD,
Director,
Geological Survey.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

1:250,000 OR 4 MILE GEOLOGICAL MAPPING

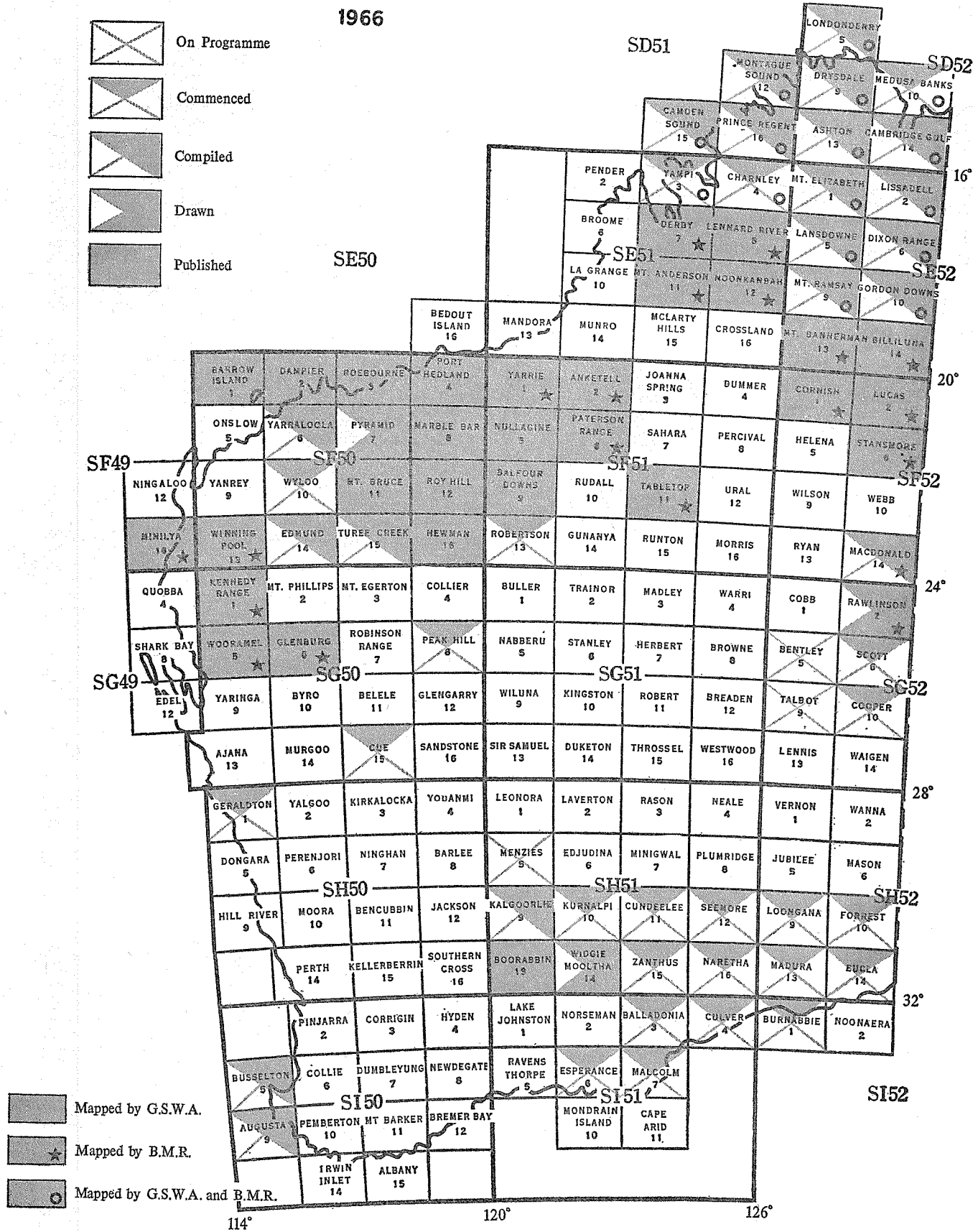


FIGURE 1

AN APPRAISAL OF THE GROUNDWATER CONDITIONS IN THE GOODLANDS AREA

by K. Berliat

INTRODUCTION

Centered about longitude 117°15' and latitude 30°05', the Goodlands area is covered by Lands Department lithograph 88/80. The area extends southward from the Emu Proof Fence, and is limited to the east and west by the systems of Lake Moore and Lake de Courcy. The total area is about 500 square miles.

It is a marginal agricultural area under active development, but there are also some long established farms, particularly in the south. The nearest railheads are Kalannie in the south and Dalwallinu and Wubin in the west.

Long term rainfall records are not available, but annual averages are stated to be in the order of 9 to 11 inches. In the last 2 years however, falls appear to have been considerably in excess of these figures.

TOPOGRAPHY, GEOLOGY

Topographically the surface is flat or broadly undulating, and consists of about equal parts of heavy, clayey country and sandplains. Internal drainage is towards the salt lakes in the east and west, but there are no incised channels, and only a few incipient, ill-defined gullies have been developed.

Basement rock is predominantly Archaean granite, sporadically intruded by quartz dykes. Outcrops occur mostly in the form of granite 'rocks', and occur mainly in the eastern half of the area bordering Lake Moore. Almost everywhere else the basement is obscured by a mantle of decomposed material ranging in thickness from a few feet to about 200 feet.

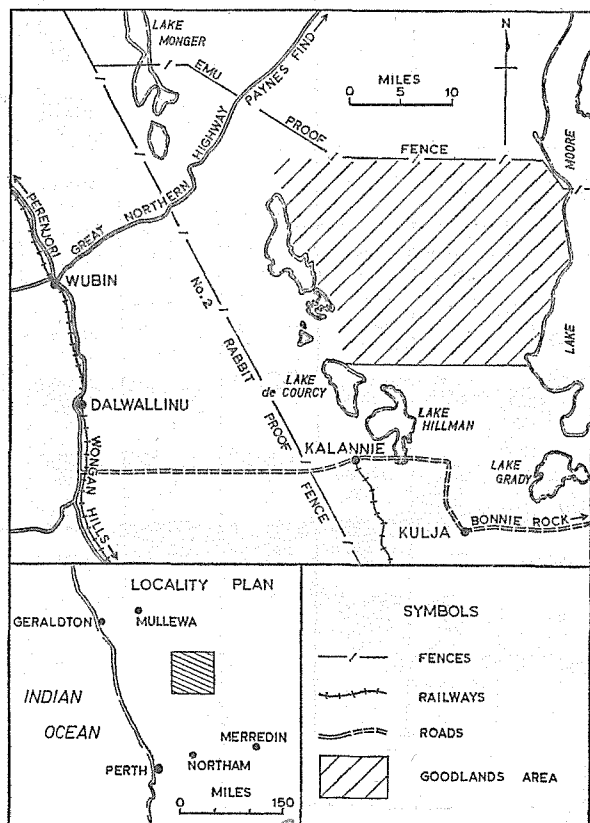


FIGURE 2 · LOCALITY PLAN — GOODLANDS AREA

HYDROLOGY

Three potential sources of groundwater have been recognized.

The superficial weathering profile

This is by far the most important aquifer, and, as it covers practically all of the area,

one might be inclined to think that groundwater should readily be available. There are however many factors controlling its occurrence, quality and yield, and to obtain a useful supply these factors must overlap. This is not the rule, but rather the exception. Disregarding all other things it must be kept in mind that precipitation is directly related to the quality and quantity of the groundwater, and in areas receiving falls of less than about 17 inches per annum the groundwater is naturally saline, and the location of usable supplies becomes a matter of difficulty. For such regions of low rainfall the best prospects are where there is concentrated local intake, a factor related to good catchments and therefore dependent upon a well differentiated topographical relief. In the Goodlands area favourable conditions of this nature occur only exceptionally around the margins of some of the major granite outcrops.

Another factor to be considered is the permeability of the weathering profile, which is subject to wide variations both horizontally and vertically. In this respect all the heavy red country has to be eliminated as a source of groundwater. Also, to avoid highly saline water, it is important that the permeable profiles be located in the higher portions of the topography.

The most critical single factor, however, is the thickness of the zone of decomposition, in other words the configuration of the bedrock surface at depth. With the possible exception of high salinity, shallow bedrock is by far the most frequent cause for the great number of unsuccessful bores in the district. It must be understood that the bedrock is not a level surface but has irregularities that are not related to the land surface. Drilling information in the district shows that the bedrock relief can change rapidly, and this is a major cause for the great differences in bore performance over short distances. Economic supplies of groundwater can only accumulate where there is sufficient area and volume for storage, i.e., in bedrock depressions filled with pervious material. Unfortunately it is rarely possible to determine such depressions from surface evidence, and therefore the selection of bore sites in granitic terrain will always be speculative to some degree. The Geological Survey is currently conducting experiments to determine the bedrock relief by geophysical means. If the tests are successful, and if a quick and inexpensive method can be worked out, it will be of very great assistance in areas such as Goodlands.

The solid granite

Solid granite has practically no porosity and the occurrence of water in this rock type depends wholly on joints and fractures. As a rule such openings are sufficiently wide and numerous only if the uppermost part of the massive rock, and drilling should be abandoned if no water has been encountered within a depth of 100 feet. On account of the great irregularity of the spacing of the joints the success of any bore in solid granite is largely a matter of chance, depending on whether the location is a fortunate one with respect to the arrangement of joints. Drilling into granite has not been attempted so far in the Goodlands area, presumably because the special equipment necessary was not available.

The quartz dykes

As in solid granite, successful bores in quartz depend on the presence of joints, and on the extent to which these joints persist and intersect others. Because of their scattered distribution quartz dykes are only of minor importance in the area as a whole, but there are at least two places where they offer promising groundwater prospects. Bore siting, however, is difficult because the outcrop area and the dip of the dykes is seldom ascertainable.

CONCLUSIONS

1. The normal groundwater in the Goodlands area is saline, and useful supplies will only be found under exceptional conditions.
2. Small supplies of domestic water could occur in isolated instances around the periphery of major granite outcrops, provided there is a concentration of run-off, and pervious soil.
3. Possibly between 50% and 75% of the total area has to be eliminated as a source for stock water. This includes all the heavy country and the low-lying, featureless sandplain.
4. High-level sandplain depressions and the long, sandy slopes, characteristic of the area, are worthy of testing by drilling, but success

will depend upon a favourable combination of the factors outlined above.

5. From surface evidence alone bore sites cannot be selected with any real degree of assurance. It is possible however to eliminate unprospective areas, and to outline others which are suitable for test drilling.

6. As development progresses, more and more demands will be made on the restricted bodies of usable groundwater, and this could render the salinity problem even more acute. Salinity increases, at least of a temporary nature, could also result from large-scale clearing. In due time, therefore, the groundwater positions in the Goodlands area should be reviewed in this context.

PORT HEDLAND TOWN WATER SUPPLY HYDROGEOLOGICAL INVESTIGATION OF THE YULE RIVER AREA

by P. Whincup

ABSTRACT

The Yule River alluvial valley, 42 miles west of Port Hedland, has been investigated as a possible groundwater source for the township. Fifty-eight shallow auger holes and thirty-two percussion holes were drilled in an area of 270 square miles.

Three aquifers termed the upper sand, lower sand, and bedrock aquifer were penetrated. Bore yields varied from less than a thousand to about thirteen thousand gallons per hour.

Approximate aquifer coefficients have been determined and used to calculate groundwater flow and recharge to the area. It is estimated that 1.3 million gallons of water per day can be withdrawn from the area without depleting the groundwater held in storage.

INTRODUCTION

Port Hedland is 1,124 miles north of Perth on the North-West Coastal Highway. Its development as the outlet port for Mt. Goldsworthy iron ore has resulted in an increase in population from 1,120 in 1961 to an estimated 5,000 in 1978 when the water requirements of the town will be one million gallons per day. A maximum of 200,000 gallons per day is available from the present pumping field at the Turner River (Farbridge, 1967).

The next nearest groundwater source to the town was considered to be the Yule River area (Allen, 1964) and at the request of the Public Works Department the area has been investigated to determine whether supplies of 800,000 gallons per day are available. Drilling was done between December 1965 and December 1966.

The work and comments of A. D. Allen are gratefully acknowledged.

CLIMATE

The climate may be described as tropical coastal typified by warm, dry winters and hot summers. The average annual rainfall of 11.8 inches (37 year records at Mundabullangana Station) falls mainly between January and March when the average maximum temperature is 94°F and the minimum 74°F. However the rainfall is cyclonic and therefore unreliable, ranging between 1.1 and 28.5 inches annually.

DRILLING PROGRAMME

Initially a rough two-mile grid of boresites was drilled by two Public Works Department 110A Gemco auger drills to delineate with reasonable accuracy the area of good quality water. Deeper percussion holes were then drilled to bedrock on favourable Gemco-drilled sites. Names, numbers, and locations of wells and bores are shown on Plate 1.

Fifty-eight Gemco holes were drilled (including several drilled twice), the maximum depth being about 80 feet. Many were abandoned in some instances before water was cut, when basaltic pebbles and cobbles were encountered at shallow depths.

Thirty-two deeper, six-inch, percussion bores were completed but these include several holes redrilled when difficulties were encountered e.g., 10, 10A, and 10B. The Mines Department drilled 15 bores using two Ruston Bucyrus 22W percussion rigs and the remainder were drilled on contract by Boomerang Boring Co. (12 bores) using two Wabco percussion rigs, and Drillwell Pty. Ltd. (5 bores) using an Ingersoll Rand Drillmaster rockdrill.

PHYSIOGRAPHY

The northerly-flowing Yule River is thought to be a consequent stream incised into the pediplain of the retreating Nullagine Scarp (Ryan, 1966). The pediplain is now evident on the western margin of the drilling area as a high-level sandplain underlain by shallow rock. The Archaean basement rocks occasionally crop out as low-lying hills. In the places the red surface sand has accumulated as east-west trending self dunes.

Fluviatile deposits form a silty flood plain which covers the drilling area. The deposits thicken and widen northwards towards the coast. Levees and river terraces are well developed along the present river course.

Drilling results and bedrock contours show that the river has changed course several times, and the remnants of an old river terrace can be seen at the surface between Bores 9 and 10. As a rule, however, the old river channels cannot be accurately delineated.

The river bed consists of coarse river sand and gravel which contain several impermanent pools, particularly along the eastern branch. Near the southern margin of the area the river bifurcates. The eastern branch has a wide, well defined channel whereas the western branch has a braided pattern with numerous anabranches.

GEOLOGY

The area falls within the Roebourne 1:250,000 Geological Sheet described by Ryan (1966). Rocks of Quaternary and Archaean age were penetrated in the drilling programme. Possible Tertiary rocks are grouped with the Quaternary.

A cross section through the area is shown on Plate 2.

Quaternary to Recent

The Quaternary to Recent alluvial sediments consist of a sequence of clay, silt, sand, and gravel with minor calcareous, siliceous and

ferruginous beds. Their thickness increases from 55 feet in the south to more than 230 feet in the northernmost bore. A very generalised sequence is described below.

A thin layer of coarse, brown, quartzo-feldspathic sand at the present surface is underlain by red-brown sandy silt and clay to a depth of 30 to 50 feet. The clays normally contain a small proportion of calcareous material as concretions, discrete layers, and encrustations. Above the water table gypsum and less commonly sodium carbonate and chloride may also be present.

Poorly sorted, silty sand and gravel occurring at a depth of about 40 or 50 feet are invariably at or below water level and contain iron-stained quartz, feldspar, chert, granite, agate, siltstone, quartzite, and various other rock types in addition to rounded pebbles and cobbles of basalt. The gravels are lenticular and their silt content varies widely. In old river channels the sands and gravels are far better developed; for example in Bores 9 and 10 where they are respectively 40 and 56 feet thick and extend downwards to the bedrock surface.

Calcareous material deposited in the gravel forms kunkar, which may be white, brownish or pinkish, and is friable to very hard, with occasional vugs and veinlets of calcite. Manganese and ferruginous staining are common and there are traces of opaline silica. The maximum thickness penetrated is approximately 20 feet. A kunkar horizon was penetrated at about the 40-foot level in most bores and it appears to have a sheet-like form across the area (see Plate 2). It may have been deposited in the wide Yule River drainage valley at or near a former land surface when groundwater levels were close to that surface. In Bore 7 a very hard layer of silcrete occurs at the same level.

In the shallower bedrock areas, light brown and yellow clay, in places slightly calcareous, extends downwards to the bedrock surface beneath the sand or gravel. Where the bedrock is deeper a second sandy and gravelly horizon, similar to that described above, occurs between about 100 and 150 feet. Kunkar is not as well developed in this lower horizon and pebbles are less common.

Sandy clay and silt underlie the lower sandy horizon and grade from a brown to a light brown, khaki-yellow, often pinkish colour. In Bore 40, the northernmost bore drilled, a fine to medium-grained ferruginous sandstone containing anhydrite is developed. This may indicate that the northernmost part of the drilling area was at one time subject to marine inundation. The clay contains occasional rounded hematite granules which become more numerous with increasing depth. Hematite was not noted in any bore above the first sandy bed.

At a depth of about 180 feet, four bores in the northeastern part of the area intersected a hard, white, kaolinitic claystone overlying a hematitic and limonitic laterite, which in turn rests on the weathered bedrock surface. A thin band of hematite is developed within the laterite. In general, rounded hematite granules are common near the bedrock surface and in several other bores a thin, white, kaolinitic claystone was observed. It is possible that the claystone and laterite, which are devoid of spores and pollen, are remnants of a Tertiary lateritized surface.

Archaeal

Archaeal outcrops are shown on Plate 1. They are correlated with the Roebourne Group of the Pilbara System (Ryan, 1966). Bedrock types intersected were granite gneiss, leucocratic granite, hornblende-biotite granite, diorite, quartz-muscovite gneiss, quartzite, grey mica schist, purple mica schist, purple siltstone, light green siltstone, and banded chert. The maximum thickness penetrated, in Bore 20, was approximately 300 feet. The bedrock is kunkarised and is intruded by numerous quartz veins. In addition, the thick section of light green shale in Bore 20 contained thin siliceous and ferruginous interbeds with traces of quartz conglomerate and banded chert.

The weathering profile of the bedrock varies widely. The soft purple, greenish and grey shales, siltstones, and schists are quite deeply weathered to soft clays. The granites and quartzites, however, are normally not deeply weathered.

It is possible to divide the area into four roughly equal, east-west trending sections, each of which has a dominant bedrock type. From south to north in order they are:

1. granitic rocks,
2. friable, light grey-brown and pink, fine-grained, chloritic and pyritic quartzite,
3. soft, grey and greenish shale, and mica schist,
4. soft, purple, micaceous schist, and siltstone.

Leucocratic and hornblende-biotite granites are not restricted to the area of granitic rocks and are possibly intrusive.

HYDROLOGY

Flooding of the river

The Yule River is approximately 130 miles long and has a catchment area of about 4,200 square miles. In 1966 the river flowed for two months (4th-9th April and 28th April to 11th June) as a result of cyclonic rains. During this period Mundabullangana Station recorded 16.6 inches of rain.

At peak flood the maximum depth of water in the East Yule River at the North-West Coastal Highway crossing was 13 feet 7 inches, the width of the river at this point being 1,000 feet. If the average velocity of the river was 5 mph (a low estimate) the peak flow was about 45,000 cusecs.

Although records are incomplete it is known that from 1945-1966 the river flowed at least six times, an average of once every 3½ years. There is no record of a flow between 1952 and 1963 so possibly the maximum interval between flows is 11 years. The duration of flow on most occasions was only 4 or 5 days.

Periodic sampling of the flood water showed little variation in salinity of the East Yule from 100 to 215 parts per million of total dissolved solids. The salinity of the West Yule River, however, gradually rose from 100 to 2,500 ppm. A pool in the West Yule at the Highway crossing then increased in salinity to 7,220 ppm by October, 1966 whereas Lee Ling's Pool on the East Yule, apparently fed by river underflow, maintained a salinity of 150 to 200 ppm. It is probable that there is no appreciable thickness of river gravels in the West Yule, in which case underflow along this branch is negligible.

Groundwater occurrence

There are considered to be three aquifers in the Yule River area: the upper sand, lower sand, and bedrock aquifers.

The *upper sand aquifer*, the largest producer, corresponds to the lenticular, sandy to gravelly, often kunkarised layer which occurs at depths of about 40 or 50 feet over much of the area. The degree of sorting varies considerably, as does the percentage content of silt and clay. Silt and clay which usually overlie the aquifer are of low permeability and cause partial confinement. The degree of confinement varies with the permeability of the overlying beds, and with the position of the water level relative to those beds. Where the static water level is in the upper part of the confining layer the fine-grained material functions as a confining bed; but when the water level declines into the more permeable material, the aquifer becomes progressively less confined. Near the river the aquifer is in direct hydraulic connection with the river gravel and is unconfined; similarly, where the alluvial material overlying the aquifer is very sandy (e.g., Bore 51) the aquifer is also virtually unconfined.

The aquifer ranges in thickness from 8 feet up to 40 feet and averages about 20 feet thick. In Bores 9, 10B, and possibly 23 and 35B, old river gravels constitute the highest yielding aquifers in the area.

Water levels range from about 15 feet to 36 feet below ground level. In Gemco-hole 36A a perched water table was cut at approximately 7 feet.

The lower sand aquifer corresponds to the sandy and gravelly layer occurring at depths of between 100 and 150 feet. It is separated from the upper sand aquifer by about 50 or 60 feet of clay and is considered to be confined. Along the river it is apparently recharged directly from the river gravel.

The aquifer is only developed in the northern half of the area, roughly north of the abandoned Depuch railway line.

The lower sand is thinner and contains less coarse material than the upper sand. Its thickness ranges between 4 and 22 feet, the average being 13 feet.

Water levels appear to be similar to those in the upper sand. However in Bore 7A the water level was 4 feet higher and in Bore 40 the water level rose 1 foot 6 inches when the lower sand was cut. Both these bores are close to the river.

Bedrock aquifer. Generally bedrock was not penetrated to any great depth but pump test and salinity results suggest that it contains appreciable volumes of water. In rocks such as granite, gneiss, and quartzite the water is derived from joints, fractures, and quartz veins. In the softer, more clayey material such as shale, siltstone, and schist the water is probably derived solely from fractures in the quartz veins.

The bedrock aquifer appears to be in direct hydraulic connection with the river-bed gravels at least near Bore 7A. This suggests a thickness for the river gravels of perhaps 100 feet.

Groundwater quality

The area underlain by domestic quality water (i.e., water containing less than 1,000 ppm) is about 230 square miles. In the majority of bores water of greatest salinity occurred in the upper part of the upper sand and salinities decreased progressively with increasing depth. In fact, during several pump tests salinities improved to values less than those encountered during drilling. Thus in Bore 6 the total dissolved solids decreased from 1,360 ppm at 36 feet to 225 ppm at 200 feet, but the final salinity from a pump-test over the interval 37 to 78 feet was 195 ppm. The fresher water was apparently drawn in from the bedrock.

Isohalsines drawn on the best quality water in each bore are shown on Plate 3. They are parallel to the river and show a general increase in salinity away from it. This is indicative of recharge from the river and there is little evidence of localised recharge influencing the deeper salinities.

As a rule the upper, more saline water seldom extends more than 10 to 15 feet into the upper sand. This high salinity layer is a result of fluctuating water levels and of the high specific retention of the clay and silt which overlie the upper sand. Water levels are high during and after floods, and rise well within the clay and silt. When levels drop, water retained in the clay and silt becomes highly saline. Where evapotranspiration takes place, calcium carbonate and gypsum may be deposited. When water levels again rise, the rising fresher water is contaminated by the adsorbed salts and saline water. As a result the most pronounced extremes of salinity in the alluvium are encountered where the rises in water level are greatest and where the uncontaminated groundwater is freshest i.e., near the river. This is demonstrated by the high salinity variations in Bores 6, 12, and 40 which are alongside the river. Water in the bedrock is generally fresher than that in the alluvium.

Using salinity readings from station wells and bores which generally penetrate only a few feet into the upper sand, 1,000 ppm isohalsines for the top saline layer are shown on Plate 4. They are plotted for February, May, and June 1966 when water levels were progressively rising. It can be clearly seen that progressive contamination of the rising fresh water leads to a corresponding shrinkage in the apparent area of dom-

estic-quality water. The isohalsines are parallel to the line of the river except in the northeast, where fresh water recharge from a well defined creek has elongated the isohalsines to the northeast, and in the central western section where there is an area of saline water intrusion. Neither of these effects is reflected by the deeper, fresher water.

Chemically the groundwater near the river is of a calcium bicarbonate type, but with increasing distance away from the river it changes to a sodium chloride type. Groundwater temperatures vary from 30.5 to 31.5°C. The water is alkaline (average pH 7.8) as a result of drainage from calcareous and basic Archaean rocks. Hardness, considered to be troublesome in excess of 200 to 300 ppm CaCO_3 , averages 170 ppm, which is moderately high. The iron concentration as measured in the laboratory was rarely more than 0.1 ppm. However the precipitated iron is not measured and the actual iron content will be larger. Nevertheless the total iron concentration should not exceed the permissible 0.4 ppm. Fluoride concentrations were only determined towards the end of the programme and of seven measurements two were slightly in excess of the upper recommended limit of 1.4 ppm (maximum recorded 2 ppm).

The change from a calcium bicarbonate to a sodium chloride type water which is indicative of increasing distance travelled through the aquifer is shown on Figure 3, where concentrations of the mineral ions in water from Bores 7, 3, 2, and 1 are plotted as milliequivalents (denoted by r) on semi-logarithmic paper (Schoeller, 1959). These four bores were chosen because they lie in a line away from the river in the direction of groundwater movement. Noticeable chemical trends, apart from an increase in total salinity, are a progressive increase in rMg/rCa and rCl/rNa and a progressive decrease in rHCO_3 from Bore 7 through Bores 3 and 2 to Bore 1. These changes are indicative of recharge of the aquifer from the river (Schoeller, 1959).

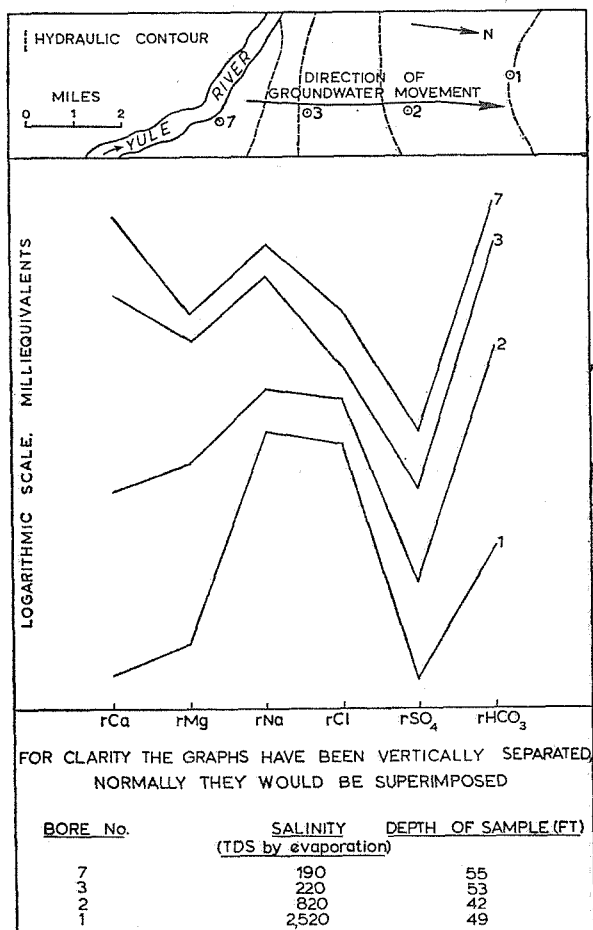


FIGURE 3. GRAPH SHOWING VARIATION IN CHEMICAL QUALITY OF GROUNDWATER WITH DISTANCE TRAVELLED THROUGH AQUIFER IN YULE RIVER AREA

In Bores 7 and 7A which are alongside the river, a comparison of total salinity and chemical quality between river floodwater and ground-water in the upper sand, lower sand, and bed rock aquifers reveals no significant differences. This suggests that the river is direct hydraulic continuity with each of the three aquifers.

Pump test results and evaluation of formation constants

Where suitable aquifers were penetrated, 24-hour pump tests were conducted. Yields ranged from less than 1,000 to 12,700 gallons per hour. Results were analysed by the modified non-equilibrium method. In only one instance (Bore 10A/10B) was an observation bore available for use and results from this test were analysed by the Theis non-equilibrium method (Todd, 1963, and Walton, 1960).

Pump test results are summarised below :

Table 1
PUMP TEST RESULTS

Bore No.	Aquifer		Thickness (ft.)	Yield (gph.)	Specific Capacity (gph./ft. of drawdown)	Transmissibility (gpd./ft.)	Permeability (gpd./ft. ²)
	(feet from surface)	upper (u), lower (l) or bedrock (b)					
2	36-68	u	32	1,770	390	3,300	100
3	112-120; 125-126	l	9	5,000	1,120	13,700	1,520
4	56-80; 113-130	u + l	41	5,150	130	3,250	80
5	32-70	u	38	3,750	320	2,250	60
6	37-78	u	41	4,000	390	11,800	290
7	38-55	u	17	4,700	670	9,850	580
7A	(i) 110-130	l	20	2,350	30	4,200	210
	(ii) 250-270	b	20	4,200	230	4,300	210
8B	55-73	u	18	< 1,000?	...	...	...
9	52-92	u	40	5,300	1,060	35,700	890
10B	35-75; 89-105	u	56	12,700	1,450	162,000	2,900
11	57-93	u	36	1,580	50	460	10
13	(i) 29-37	u	8	4,200	760	6,160	770
	(ii) 54-75	u	21	3,320	410	4,840	240
18B	137-154	l	17	2,510	70	420	20
20	(i) 38-56	u	18	2,650	190	1,420	80
	(ii) 160-168	u + b	760 +	5,000	360	11,600	?
21	17-33	u	16	1,480	140	440	30
23	70-120	u	50	5,200	1,040	35,200	700
28	40-70	u	30	< 1,480	< 30	...	...
33	25-65	u	40	1,580	90	320	10
35B	40-80	u	40	8,500	1,060	40,000	1,000
40	165-185	l	20	4,800	220	9,000	480
44A	30-60	u	30	1,580	180	...	...
50	28-40; 97-110	u + l	25	3,000	170	930	70

The average permeability of the tested bores from the above table is 500 gpd/ft² but when assumed zero permeabilities for non-tested bores are included, the figure for mean permeability becomes 400 gpd/ft². There does not appear to be any significant permeability difference between the upper and lower sand aquifers (both about 400 gpd/ft²) but the one determination of bedrock permeability indicates a much lower value for this aquifer (210 gpd/ft²).

Changes in slope on the graphical plots of the pump test data reveal boundary conditions which are a result of the lenticular and discontinuous nature of the aquifers. Permeability values vary from almost zero up to about 3,000 gpd/ft². Unfortunately, analysis of results from a pumped bore is unreliable as well loss and other factors are not known. The permeabilities given in the above table are therefore to some extent inaccurate and any estimates of storage or recharge based on those values must be regarded as very approximate.

More accurate figures are available from the pump test on Bore 10B where Bore 10A, 90 feet distant, was used for observation. The results show that a boundary condition came into effect at about 5 hours and only data after that time can be analysed. The permeability derived from this analysis (Theis method) is shown below compared to values calculated by the modified non-equilibrium method.

Bore No.	Method	Permeability (gpd/ft. ²)
10A (observation)	Theis non-equilibrium	2,900
10A	Modified non-equilibrium	2,350
10B (pumping)	Modified non-equilibrium	3,650

The high ratio of the vertical permeability of the aquifer to that of the semi-confining clay is demonstrated by the instantaneous release of water from storage during the initial period of pump-testing. During this time only, the aquifer functions as a confined system. After the initial period of pumping it acts more as a water table aquifer.

The calculation of specific yield gives a value of 0.0112, i.e. intermediate between the values given by Todd (1963) for water table (S = 0.02 to 0.2) and confined aquifers (S = 0.00005 to 0.005). The highest yielding section of the aquifer in Bores 10A/10B is the lower section (89 to 105 feet). Unfortunately the slotted casing in the observation bore penetrated only the upper, more silty and clayey section (35 to 80 feet) and it is probable that the value of specific yield applies more to this section. Similar semi-confined silty sands and gravels in the Humboldt River Valley, Nevada (Cohen, 1964) have a specific yield of 0.04.

The permeability calculated from the pump-test on Bores 10A/10B is 2,900 gpd/ft² compared to the mean permeability of 400 gpd/ft² for the whole area. Therefore it is probable that the mean specific yield of aquifers on the flanks of the Yule River may be as low as 0.0015 (i.e., 400 x 0.0112). However if account is taken of

the as yet untested river bed sands, which may have a specific yield as high as 0.20 to 0.30, a mean specific yield of 0.005 is considered to be a conservative estimate.

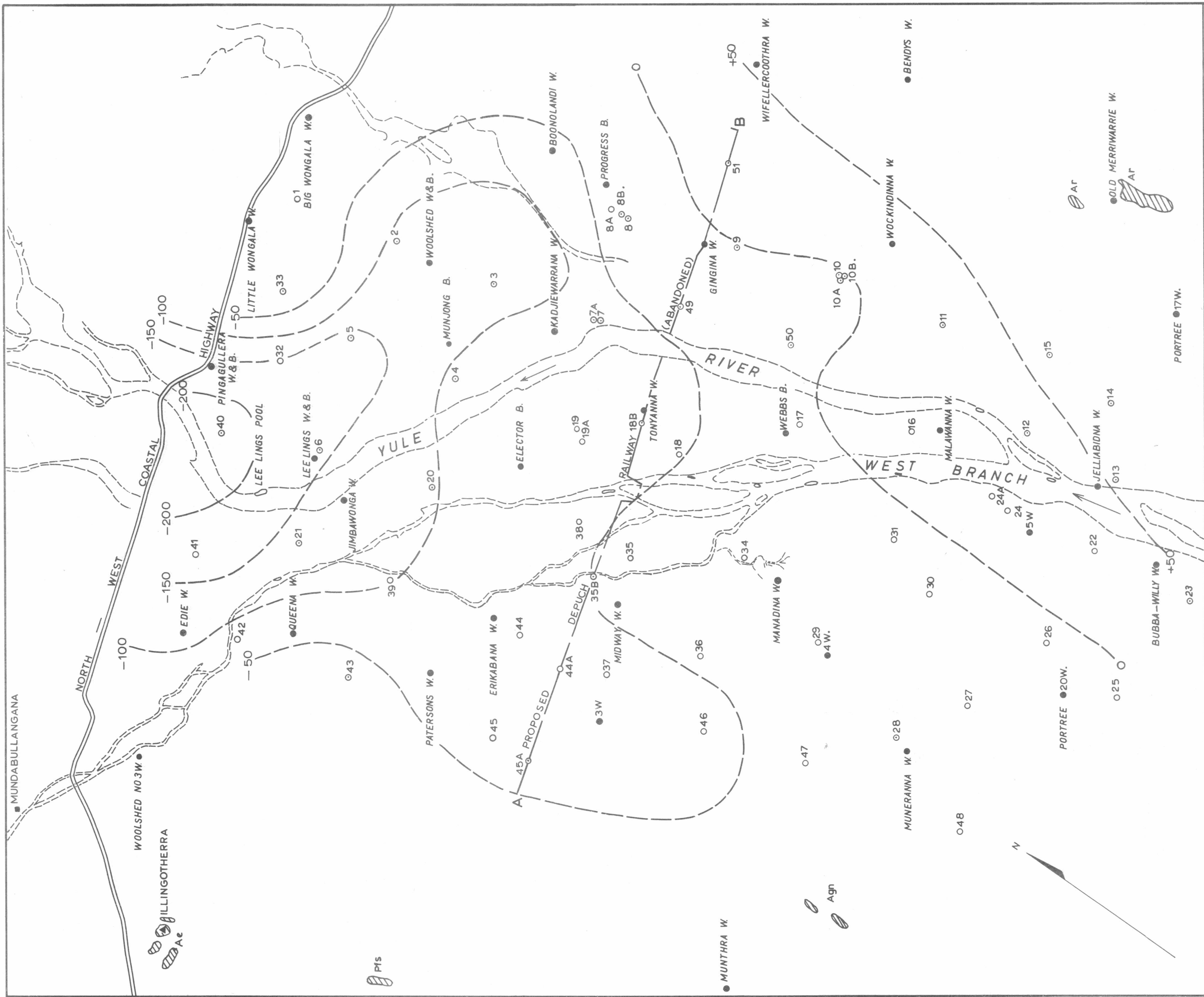
Groundwater movement

The direction of groundwater movement is perpendicular to the hydraulic contours shown on Plate 3 for October 1966. Groundwater flow is in a northerly direction along the river and in a northeasterly or northwesterly direction away from the river in the interfluvies. Recharge from the West Yule appears to be ineffective about 5 miles below its diversion from the East Yule. The East Yule on the other hand is a major source of recharge at least as far north as the Coastal Highway.

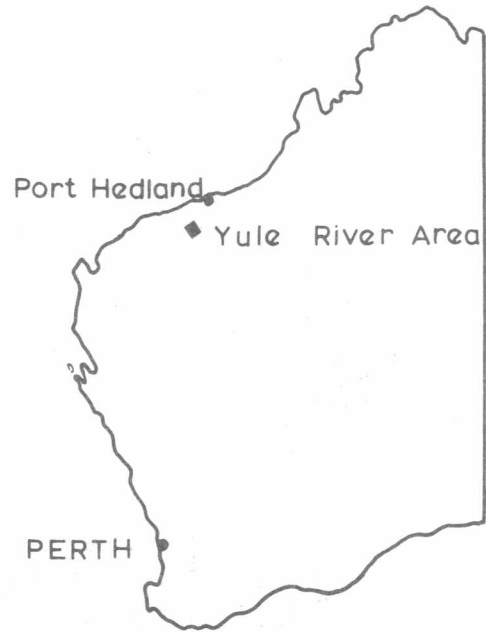
The hydraulic gradient is fairly constant to within about 6 miles of the Highway (i.e., approximately as far as Munjong Bore) and then flattens out. This suggests either that the permeability is increasing in that direction, which is contrary to the calculations made from pumping tests north and south of Munjong Bore, or that conditions had more or less stabilised after a long drought several years ago, and recent additions to the groundwater have caused a local build-up near the intake, not yet transmitted farther out.

A comparison is given below of longitudinal hydraulic gradients and rates of groundwater movement before and after the flooding of the river. It shows that after flooding the gradients and hence the rates of groundwater movement are appreciably higher.

	South of Munjong Bore (average permeability 470 gpd/ft. ²)	North of Munjong Bore (average permeability 140 gpd/ft. ²)
Hydraulic gradients Feb. 1966 (river not flowed for 3 years)	6.1 ft/mile	3.3 ft/mile
Rate of groundwater movement	0.088 ft/day	0.014 ft/day
Hydraulic gradients Oct. 1966 (river flowed April-June)	6.4 ft/mile	4.3 ft/mile
Rate of groundwater movement	0.090 ft/day	0.018 ft/day



LOCALITY MAP

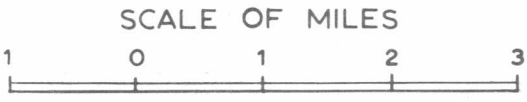


REFERENCE

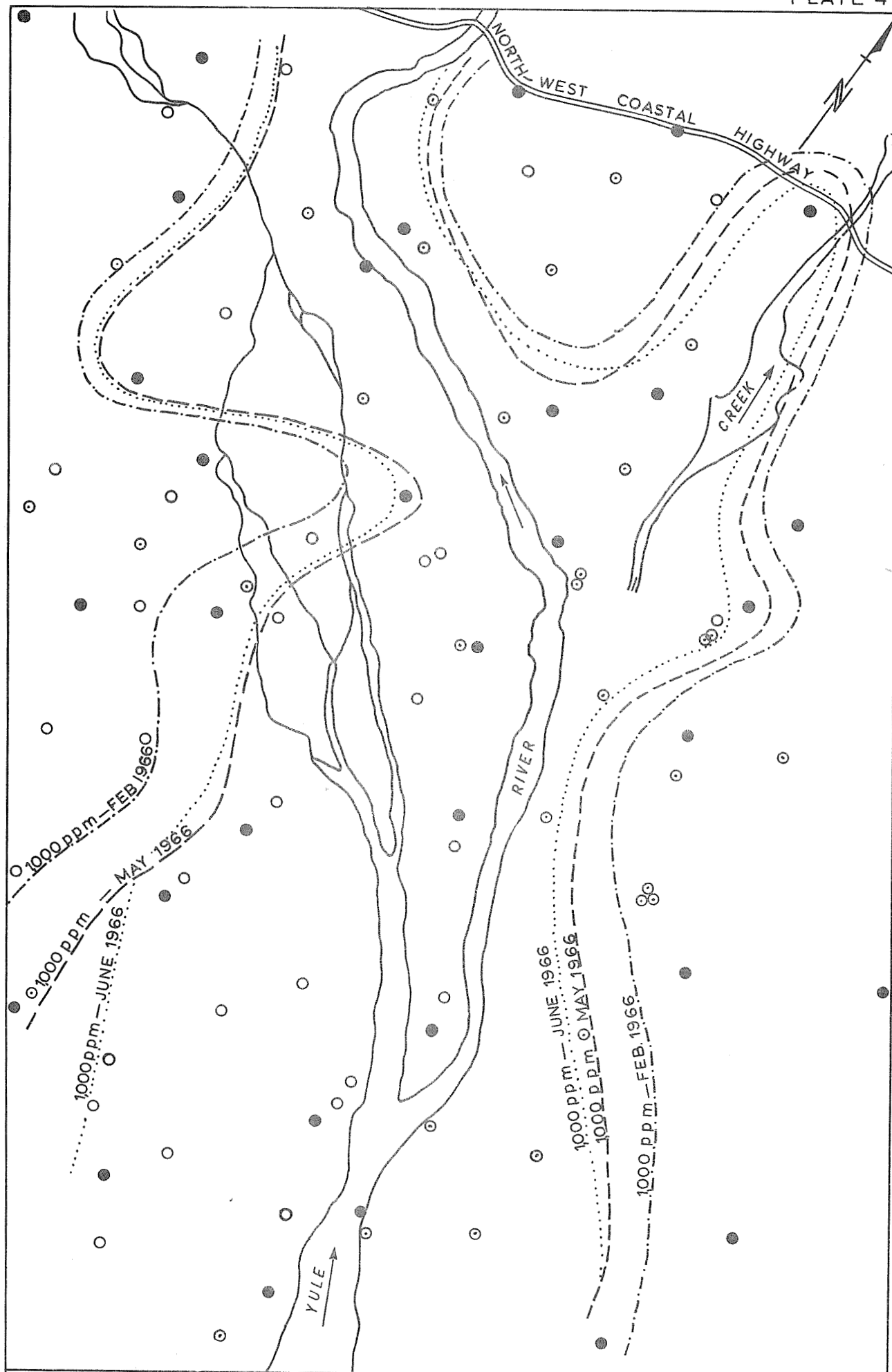
PROTEROZOIC	Pfs	Sandstone and tuff
	Agn	Granite gneiss
ARCHAEAN	Ae	Porphyry, breccia, and siliceous rocks
	Ar	Quartz-greywacke, siltstone, and calcareous shale

SYMBOLS

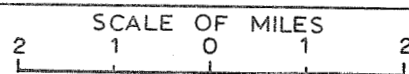
- PERCUSSION HOLE (LEFT FOR OBSERVATION)
- GEMCO AUGER HOLE (ABANDONED)
- STATION WELL OR BORE
- BEDROCK CONTOURS (RELATIVE TO LOW WATER MARK, FREMANTLE)



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
YULE RIVER AREA
PLAN SHOWING BEDROCK OUTCROPS,
BEDROCK CONTOURS, AND LOCATION
OF BORES AND WELLS
To accompany report by P. Whincup



- OBSERVATION BORE
- ABANDONED GEMCO HOLE
- STATION WELL OR BORE



SALINITY MEASUREMENTS WERE MADE ON SAMPLES FROM STATION WELLS AND BORES WHICH ONLY PENETRATE THE UPPER MORE SALINE PART OF THE AQUIFER

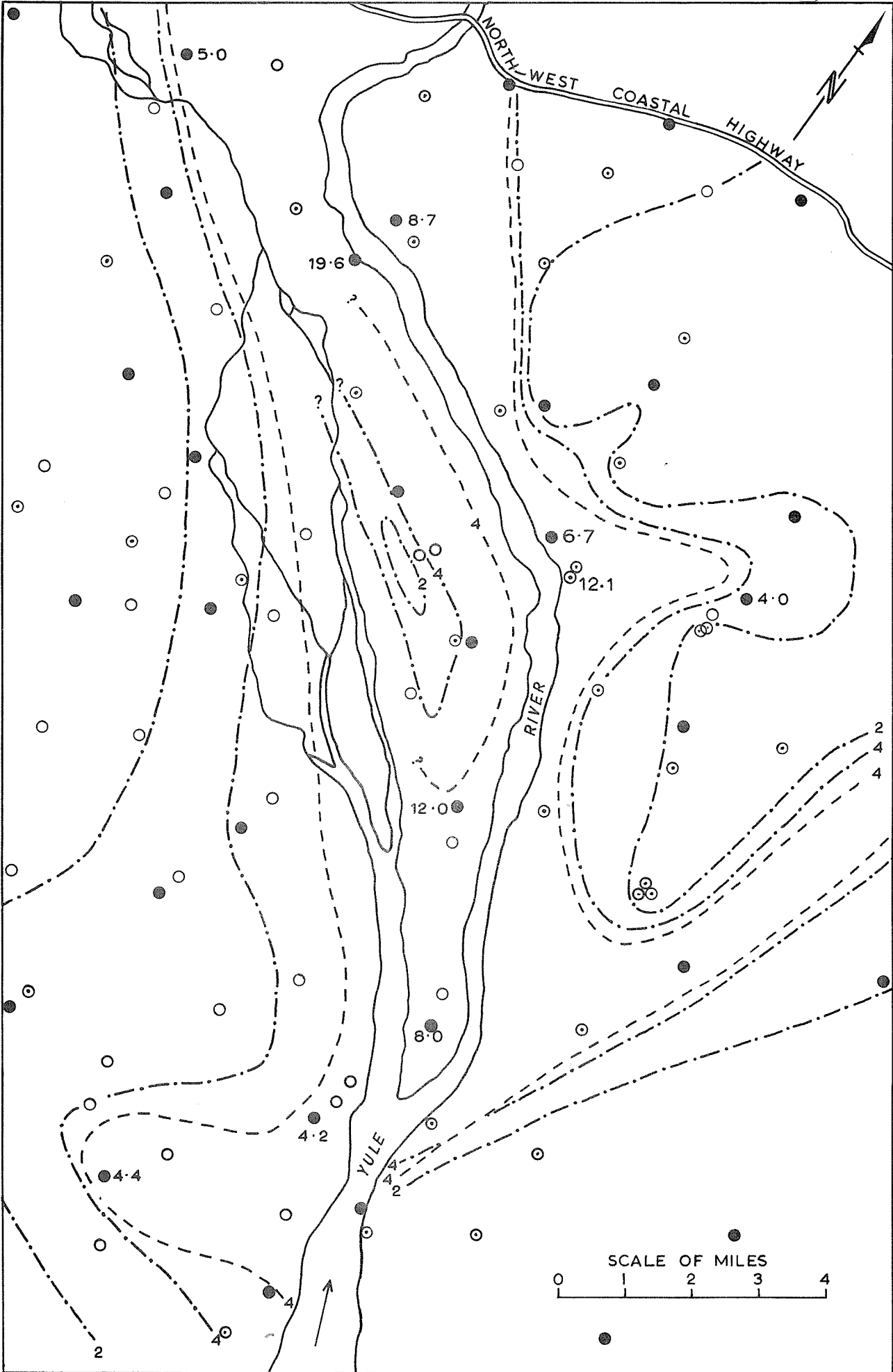
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

YULE RIVER AREA

ISOHALSINES ON THE OVERLYING SALINE GROUNDWATER

FEBRUARY TO JUNE 1966

To accompany report by P. Whincup



4 - - - - CONTOUR SHOWING RISE IN FEET OF WATER LEVELS
FROM THE 26th. FEB. TO THE 22nd MAY, 1966
2 - - - - CONTOUR SHOWING RISE IN FEET OF WATER LEVELS
FROM THE 26th. FEB. TO THE 17th AUG, 1966

○ OBSERVATION BORE
○ ABANDONED GEMCO HOLE
● STATION WELL OR BORE

WHERE RISES IN LEVEL ON 22nd MAY
WERE MORE THAN 4 FEET
THE FIGURE IS SHOWN ON THE PLAN

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
YULE RIVER AREA
CONTOURS SHOWING RISES IN WATER LEVELS
AFTER FLOODING
To accompany report by P. Whincup

Recharge

Hydraulic and salinity patterns show that recharge occurs almost entirely from the river. Minor localised recharge, as indicated by slight variations in hydraulic contours and upper, saline isohalsines, is negligible.

Rises in water level, calculated by subtracting water level readings in February from water levels measured at intervals after the river had flooded, are summarised on Plate 5. Contours on the 4-foot rise in water level from February to May 1966 are shown as are the contours on the 2 and 4-foot rise from February to August 1966. The latter contours demonstrate that in August, three months after the river had flooded, water levels were still rising in the interfluvies. The rises in water level are greater near the river, the maximum recorded being 20 feet 6 inches at Jimbawonga Well.

In the more permeable zones the water level does not rise as much as in the less permeable zones. Thus the large area of small water level rises near Bores 9 and 10B is an indication of high permeabilities in that area.

Rises in water level have been used to determine the volume of water entering the upper sand aquifer during the river flooding, as shown in the table below.

Average rise in water level (feet)	Area (sq. miles)	Increase in volume of saturated aquifer
1.5	54	81 X 5280 ²
3	66	198
5	60	300
7	30	210
8	19	152
		Total 941 X 5280 ²

Increase in volume of saturated aquifer = 941 x 5280² cu ft.
 Volume available for withdrawal = Specific yield x Increase in volume of saturated aquifer = 0.005 x 941 x 5280² x 6.25 gallons = 800 million gallons (approx.)

Assuming that the river floods once every 3.5 years the amount of water per day available for withdrawal, if it can be fully recovered from the aquifer,
 = $\frac{800 \times 10^6}{3.5 \times 365}$ gallons per day
 = 640,000 gallons per day

This calculation assumes no decline in level resulting from outflow, although in theory all recharge would be so lost after 3.5 years. However, if the production field is restricted in area, over-abstraction will draw water in from all sides and there will be no outflow lost from this dewatered area. The 640,000 gallons per day would then be the maximum available immediately after a flood occurs.

The volume of water entering the lower, confined aquifers would be considerably less than that entering the upper sand aquifer.

Subsurface flow

Estimates have been made of subsurface flow across the line of the abandoned Depuch railway which is roughly perpendicular to the direction of groundwater movement. The figures for permeability and aquifer thickness are the average for Bores 51, 49, 18B, 35B, and 44A.
 Length of cross section between 1,000 ppm isohalsines = 10½ miles
 Average permeability = 360 gpd/ft²
 Gradient (figure for Feb. and Oct. 1966 is similar) = 5 ft/mile
 Average aquifer thickness (upper and lower sand combined) = 38 feet
 Subsurface flow = Permeability x Gradient x Thickness x Width
 = $360 \times \frac{5}{5280} \times 38 \times 10.5 \times 5280$ gallons/day
 = 720,000 gallons per day.

Total storage in upper and lower sand aquifers

The area underlain by the upper sand aquifer is 230 square miles and the average aquifer thickness (from 28 bores) is 27 feet. The corresponding figures for the lower sand aquifer are 80 square miles and 13 feet (from 12 bores).
 Total volume of aquifers = [(230 x 27) + (80 x 13)] [5280²] cu ft.

Total Volume of water stored
 = Total volume x Specific yield
 = [(230 x 27) + (80 x 13)] [5280² x 6.25 x 0.005] gallons
 = 6,800 million gallons

Bore spacing

In order to make estimates of a suitable production bore spacing, drawdowns after 3½ years continuous pumping (the average recharge interval) have been calculated for five bores i.e. Nos. 3, 7, 9B, 10B, and 50. The drawdowns were derived from the modified non-equilibrium method and it was assumed that drawdowns through this time interval would bear a constant relationship to those experienced at the end of the 24-hour pump tests. However, if further boundary conditions were to come into effect, as is possible, drawdowns could be considerably greater.

In addition to the drawdowns in the pumped bores, the drawdown interferences at distances of 500 and 2,000 feet have been calculated with additional calculations at 4,000 and 8,000 feet for Bores 7 and 50. These figures were derived from the following equations:

$$r^2 = \frac{Tut}{2242S} \text{ and } d = \frac{114.6 QW(u)}{T} \text{ (see Todd, 1963)}$$

where r = distance from pumped bore (feet)

T = transmissibility (gallons per day per foot)

t = time (minutes)

S = specific yield

d = drawdown (feet)

Q = yield (gallons per minute)

u and W(u) = well constants.

Results are summarised below but are only approximate as transmissibilities vary widely, even over a distance of 500 feet. The specific yields have been taken as 0.01 in Bores 9B and 10B and 0.001 in the other bores.

Bore No.	Assumed S	Q	Available draw-down (feet)	Calculated drawdown after 3½ years				
				In pumped bore (feet)	At a distance of			
					500 feet	2,000 feet	4,000 feet	8,000 feet
3	0.001	90	90	14	9½	5½	....	....
7	0.001	80	220	21	9½	7	5	4
9B	0.01	170	62	20	5	3½	....	....
10B	0.01	200	74	9	1½	1	....	....
50	0.001	50	216	85	43	27	20	11½

It can be seen that along the high transmissibility old river bed intersected in Bores 9B and 10B, drawdowns and drawdown interferences are very small. Bore spacing along the old river bed could be of the order of 500 feet and a similar spacing could be considered along the present river course, if development is undertaken there.

However Bore 7 is probably more typical of interfluvial production bores and a spacing of 2,000 feet for such bores would be the minimum figure. Thus considering Bore 9B:

Drawdown in Bore 9B after 3½ years = 20 feet
 Drawdown interference from four production bores similar to Bore 7, each 2,000 feet distant from bore 9B = 4 x 7 feet = 28 feet
 Drawdown from four production bores, each 4,000 feet distant = 4 x 5 feet = 20 feet
 Total Drawdown = 68 feet
 Available Drawdown = 62 feet

Low transmissibility aquifers, such as those cut in Bore 50 should not be developed, as even at distances of 8,000 feet, drawdowns are considerable.

The most economical means of developing the field appears to be by siting production bores along the buried river channel between Bores 9 and 10B and along the present river course.

CONCLUSIONS AND RECOMMENDATIONS

Development of the Yule River area is recommended. Based on aquifer constants which must be regarded as very approximate it is calculated that a very maximum of 1.3 million gallons per day of domestic quality water might be available immediately after a river flood, and this could fall to 720,000 gallons per day without drawing on storage. In addition, some of the 6,300 million gallons of stored water could be mined if necessary, plus some extra from the underlying bedrock. Estimated township needs for 1978 can therefore be met, if the Turner River reserves are included.

The most favourable area for initial development is that within which Bores 9B, 10B, and 49 are situated and less particularly the northerly continuation of that area through Bores 7 and 7A to 3. Bores 9B and 10B intersected gravel laid down in an old course of the river and each is capable of producing between 10,000 and 15,000 gallons per hour.

Development should preferably be concentrated near the river to draw on river underflow and also to avoid pulling in saline water from the interfluvies. If the required supply of 0.8 million gallons per day is taken from a small area, ground water will be mined, considering that the volume available from the whole area is 1.3 million gallons per day. Therefore production bores should be separated as far as is economic. A separation of 2,000 feet is recommended in the interfluvies but in areas of high transmissibility such as along the present river course and the old river channel between Bores 9 and 10B, a minimum separation of 500 feet is possible. Mining of water on a small scale however is not dangerous as it will permit greater recharge of the aquifers during river floods than is possible under natural conditions.

It is possible the river bed should be drilled to test the thickness of the river sands and gravels, as sumps in the river bed could be capable of producing large supplies. It appears that the river sands

are in direct contact with the bedrock aquifer indicating a thickness of perhaps 100 feet of coarse fluvial material.

Controlled pump-testing of up to 48 hours duration should be carried out with observation bores, to obtain more information on specific yields and thus modify the calculated figures for storage and recharge.

Monthly readings of water levels in observation bores should be taken to delineate the pattern of natural water level movement and the degree of disturbance by pumping when major abstraction commences. Salinity readings should also be taken, perhaps at three-monthly intervals.

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EXPLORATORY DRILLING FOR GROUNDWATER AT JURIE BAY

by R. Milbourne

ABSTRACT

An adequate supply of low salinity groundwater can be obtained from the Pleistocene Coastal Limestone 3 miles east of Jurien Bay. Recharge is both local and from the east, where laterite capped breakaways flank the intake area. Groundwater salinity increases towards the coast.

INTRODUCTION

Jurien Bay is a small township located on the coast about 175 miles by road north of Perth (Plate 6). It is principally a crayfish processing and fishing centre and is increasing in popularity as a seasonal holiday resort.

The Mines Department was requested by the Public Works Department to locate suitable groundwater for a town water supply, and subsequently undertook an exploratory drilling programme in 1962. One deep bore was drilled to 682 feet, and seven shallow bores were drilled to depths between 17 feet and 35 feet. This drilling (Berliat and Morgan, 1962) showed that

a limited quantity of water (1,200 to 1,400 ppm TDS) could be obtained from below fixed sand dunes, $\frac{1}{4}$ mile from the coast, at depths between 25 feet and 35 feet.

The population of the town at Jurien Bay is expanding and the Public Works Department again requested the assistance of the Mines Department in locating further supplies of suitable groundwater. Subsequently another drilling programme was undertaken between December 1965 and April 1966, and seven exploration bores were drilled to depths between 120 feet and 150 feet. This drilling was located $1\frac{1}{4}$ to $3\frac{1}{4}$ miles east of Jurien Bay and extended from northeast to southwest for about $2\frac{1}{4}$ miles, forming a triangle with the apex pointing northward, flanked to the east by the subsurface Beagle Fault, and to the west by the coast.

There are no rainfall records available for the drilling area, but the short term annual rainfall at Cockleshell Gully (about 10 miles north) has been recorded as 23.76 inches per annum and is assumed to be fairly representative of the drilling area.

PHYSIOGRAPHY

The topography is dominated by Quaternary Coastal Limestone which rises to form a minor escarpment (the 'greater ridge'), 2 miles east of Jurien Bay and roughly at R.L. 100 feet (Plate 6). The following four natural divisions occur in the topography eastwards from the Jurien Bay coast.

1. A graduation from the strandline to mobile and fixed sand dunes about $\frac{1}{4}$ to $\frac{1}{2}$ mile inland.
2. Sandy coastal lowland which extends for approximately 1 mile up to and including the low sandy 'lesser ridge'. This ridge trends northeast and is almost parallel to the coast.
3. A shallow trough separates the 'lesser ridge' from the 'greater ridge' or limestone scarp, and this limestone continues eastward for about 5 miles as rounded hills with 'pinnacle' outcrops. This merges into the following division.

4. Sands derived from the Jurassic-Cretaceous Cadda Formation forming laterite-capped breakaways about 10 miles from the coast.

EXPLORATORY DRILLING

The availability of groundwater in division 1 has been established by Berliat and Morgan, who concluded that a limited quantity of suitable groundwater could be obtained from below the fixed sand dunes $\frac{1}{4}$ mile from the coast. Chemical analyses from this drilling are included in Table 2.

Exploratory drilling during 1966 has shown that larger quantities of low salinity groundwater can be obtained in the Coastal Limestone between the 'greater ridge' and the Beagle Fault. A summary of the hydrology obtained from drilling is included in Table 1, and the respective chemical analyses are given in Table 2.

Table 1
SUMMARY OF RESULTS—JURIEN BAY WATER BORES

GSWA Bores (Plate 6)	1	2	3	4	5	6	7	8	9	10	11	12
Total depth	628'	35'	24'	30'	33'	127'	120'	130'	150'	150'	150'	150'
Reduced levels	10' app.	10' app.	4' app.	10' app.	10' app.	6.15'	13.60'	10.04'	24.08'	105.25'	64.27'	87.33'
Aquifer (below N.S.)	10-87'	11-35'	13-24'	14-30'	12-33'	27-37'	33-44'	27-37'	37-47'	98-100'	78-88'	100-110'
Standing water level	500-595'	9'	?	9.75'	12'	5' 5"	12' 7"	10' 10"	23' 0"	96' 0"	64' 9"	86' 8"
Pumping rate 1 (gph)	not tested	530	not tested	not tested	2,000	1,800	2,196	700	2,200	bailed dry 2000 gpd	2,200	2,600
Drawdown	.....	5'	.....	.....	12'	1"	1"	13' 0"	8"	34' 0"	2"	3"
Salinity (ppm TDS)	too high	860 (NaCl)	too high	too high	1,070	1,430	920	1,050	670	730	690	640
Pumping rate 2 (gph)	.....	.....	.....	.....	1,200	2,000*	10,200†	.....	3,500	.....	10,800†	10,600†
Drawdown	.....	.....	.....	.....	8'	3"	12"	.....	1' 3"	.....	2' 4"	10"
Salinity (ppm TDS)	.....	.....	.....	.....	1,070	1,480	940	.....	700	.....	700	640
Pumping rate 3 (gph)	.....	.....	.....	.....	.....	7,000	16,200	.....	6,000†	.....	.....	18,000
Drawdown	.....	.....	.....	.....	.....	11"	2' 3"	.....	10' 1"	.....	.....	2' 0"
Salinity (ppm TDS)	.....	.....	.....	.....	.....	1,790	950	.....	800	.....	.....	640

* 8 hour pump test.

† 48 hour pump test.

Table 2
STANDARD CHEMICAL ANALYSES—JURIEN BAY WATER BORES

Bore No.	1*	2A*	4*	5*	6	7	7	8	9	9	10	11	11	12	12
Nature of sample	s	s	s	s	f	i	e	f	i	e	f	i	e	i	e
Specific conductivity (micromhos 20°C)	.....	.....	.....	.....	2110	1310	1340	1500	970	1000	1040	1020	1000	930	920
pH	6.7	7.7	7.3	7.6	7.4	7.2	7.4	7.5	7.4	7.4	7.9	7.3	7.6	7.4	7.2
Mineral matter—															
Total dissolved solids ppm by—															
evaporation	49,300	1166	2670	1268	1290	850	760	910	600	620	620	640	630	590	580
conductivity	1283	2937	1395	1480	920	940	1050	680	700	730	710	700	650	650	640
NaCl	45,700	.....	.....	905	507	493	564	317	337	387	347	351	303	301	301
Total hardness	8,180	455	670	487	412	321	323	380	283	261	282	283	288	283	283
Total alkalinity	.....	.....	.....	238	240	238	281	228	238	181	222	222	228	228	228
Ca	1280	57	92	50	99	94	95	93	79	81	77	88	87	92	90
Mg	1210	76	107	88	40	21	21	36	21	22	17	15	16	14	14
Na	15,400	200	677	228	305	177	161	189	112	119	126	119	122	99	101
K	570	6	24	6	12	9	8	6	2	3	5	4	4	3	4
Fe	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
HCO ₃	64	427	462	438	290	293	290	342	278	290	221	271	271	278	278
SO ₄	3160	45	135	52	74	41	21	35	25	24	27	24	28	37	21
Cl	27,700	353	1170	404	549	307	299	342	192	204	235	210	213	183	183
NO ₃	2	2	3	4	2	2	2	1	5	5	2	2	1	2	0.1
SiO ₂	.....	.....	.....	.....	13	12	11	12	8	9	7	10	11	9	9

* After Berliat and Morgan (1962).

s Static sample.

i Sample taken at beginning of pump test (48 hour).

e Sample taken at end of pump test (48 hour).

f Sample taken at end of pump test (8 hour).

Bore 6 encountered water at 12 feet (3,880 ppm TDS) in quartz sand containing seaweed and abundant coarse shelly grit, typical of lagoonal sediments deposited as a result of an actively advancing coast. Coastal Limestone was found at 27 feet and the groundwater salinity within the limestone was 1,430 ppm TDS. This salinity rose to 1,790 ppm as the pumping rate increased from 1,800 gph to 7,000 gph but dropped again to 1,480 ppm when the pumping rate was reduced to 2,000 gph, suggesting a degree of salt encroachment proportional to the pumping rate. A one inch drawdown was recorded during the 1,800

to 2,000 gph pump tests and an 11 inch drawdown was recorded during the 7,000 gph pump test. The recovery time was too rapid to be recorded. Bore 7 was drilled in limestone about 1 mile southeast of Bore 6 and pump tested from 2,200 to 16,200 gph without appreciable variation in salinity (920 to 950 ppm TDS). The drawdown varied from 1 inch to 2 feet 3 inches, and the maximum recovery rate of 2 minutes 25 seconds was recorded. This suggests that a large quantity of groundwater of less than 1,000 ppm TDS can be obtained from the Coastal Limestone at this site.

Bore 8 is located about halfway between Bores 6 and 7 and the drilling has shown that 12 feet of fine-grained eolian beach sand containing numerous gastropod shells overlies the Coastal Limestone. This bore was pump tested at a maximum of 700 gph for a drawdown of 13 feet, the salinity being 1,050 ppm. A discontinuity apparently exists in the aquifer between this bore and the two previous bores.

Bore 9, 2½ miles to the northeast, was pump tested from 2,200 to 6,000 gph, and produced low salinity (670-700 ppm TDS) groundwater from the Coastal Limestone. Drawdowns varied from 8 inches to 10 feet 1 inch with a maximum recovery time of 2 minutes. The bore was in danger of forking at 7,000 gph.

Bore 10 proved to be the least productive of this programme, yielding an estimated 2,000 gpd supply of 730 ppm TDS groundwater. The sub surface Beagle Fault passes close to this bore and may have some influence on its hydrology.

Bore 11, situated about halfway between Bores 9 and 10, was pump tested at 2,200 and 10,800 gph without any appreciable increase in salinity (690 to 700 ppm TDS), with drawdowns of 2 inches to 2 feet 4 inches respectively, and a maximum recovery time of 2 minutes. This bore gave good results for this programme and is very suitable for the town water supply.

Bore 12, located 2 miles northeast of Bore 11 was pump tested from 2,600 to 18,000 gph, and, within this range, the groundwater salinity remained constant at 640 ppm. The drawdown increased from 3 inches to 24 inches, and the maximum recovery time was 2 minutes 55 seconds. This bore is also suitable for the town water supply.

PALYNOLOGY

Samples of silt and silty sand were palynologically examined from Bores 6, 7, 8, 10, and 11 and the results are summarised below:

Bore	Depth	Age
6	127 feet	Middle Triassic
7	99 feet	Middle Triassic
8	130 feet	Middle Triassic
10	150 feet	barren
11	96-116 feet	probable Quaternary

GEOLOGY

Sections A-A₁ and B-B₁ (Plate 6) are constructed from borehole data and infer the subsurface geology and structure.

The section through A-A₁ shows that the probable Quaternary sediments between the Middle Triassic siltstone and Pleistocene calcarenite thickens towards the north. A shallow trough exists between Bores 11 and 12, forming a probable recharge axis from the east-northeast.

The section through B-B₁ shows that Middle Triassic clayey siltstone is separated from the overlying sediments by an unconformity. Between this unconformity and the base of the Pleistocene Coastal Limestone is a wedge of sediments thinning to the west and believed to have been deposited during the Quaternary.

Recent eolian calcarenite has been deposited on the wave cut limestone and in the minor depressions and valleys immediately to the east.

HYDROLOGY

The water table of the drilling area is fairly constant at about sea level, with the exception of Bore 10 which, in addition to a low groundwater yield, had a water level of 9 feet above sea level.

The section along B-B₁ shows the aquifer extending through Bores 6, 7, 8, and 11, with the standing water levels close to sea level. An apparent domelike subsurface feature is probably responsible for the discontinuance of the aquifer and the higher water level at Bore 10.

Groundwater is obtained from Bore 6 at a depth of 12 feet, but the salinity (3,880 ppm TDS) is higher than that of the groundwater obtained from the limestone at 30 feet, indicating that partly diluted connate seawater still remains in the overlying sand. The top of the aquifer probably coincides with the top of the Coastal Limestone, resulting in the upward seepage of pressure water into the overlying sand, and the continual reduction in salinity by flushing.

The section along A-A₁ shows that the aquifer forms a shallow trough from Bore 9 to Bores 12 and 11, suggesting a direction of recharge from the northeast and at right angles to the salinity contours. The aquifer is at its shallowest at Bore 9, where the capacity is limited (10 feet drawdown at 6,000 gph) by another apparent domelike subsurface feature.

A considerable amount of rainfall is absorbed into the Coastal Limestone, forming an additional source of recharge.

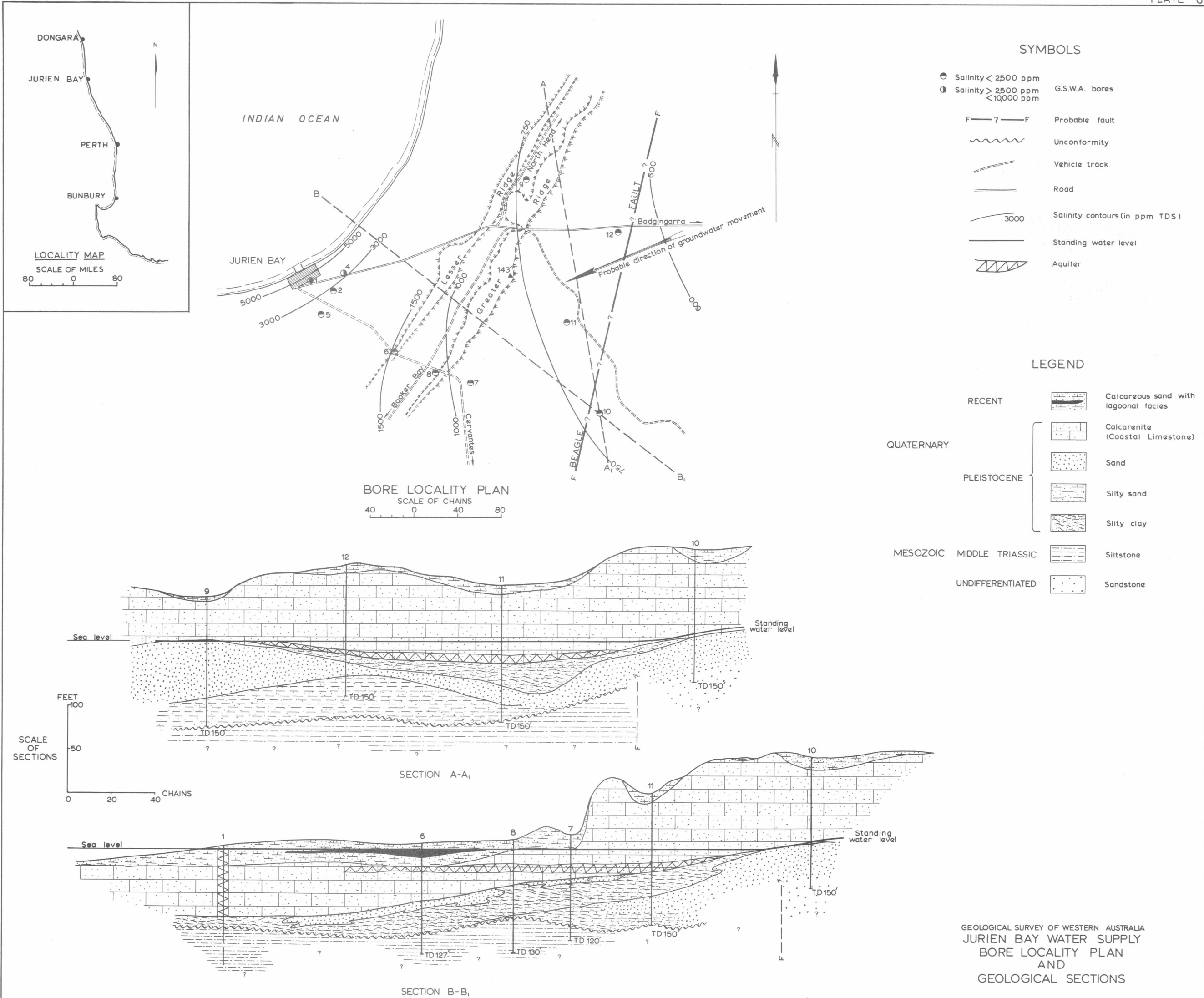
CONCLUSIONS AND RECOMMENDATIONS

Within the area of the current exploration programme the Coastal Limestone appears capable of yielding large quantities of low salinity groundwater from the hills to the east of the Jurien Bay coastal lowland.

It is recommended that the siting of production holes for the Jurien Bay township water supply be restricted to the triangle formed by the Bores 9, 11, and 12.

REFERENCE

- Berliat, K., and Morgan, K. H., 1962, Report on exploratory drilling at Jurien Bay, W.A.: West. Australia Geol. Survey. Rec. 1962/1 (unpublished).



PORT HEDLAND TOWN WATER SUPPLY, TURNER RIVER EXPLORATORY DRILLING

by R. A. Farbridge
(with additional data by T. T. Bestow and J. R. Passmore)

ABSTRACT

During a hydrological investigation of the lower Turner River, 22 bores were drilled, from which water and strata samples were tested. Sixteen bores were pump-tested at rates of 200 to 6,000 gph. Recharge occurs from the river, but saline water exists close to the production area.

Further development is not recommended. If recharge occurs within every 3 years, present production represents a safe maximum, but if the river flows less frequently, then the present rate of pumping exceeds the normal inflow into the bore field.

INTRODUCTION

The Turner River area was investigated on behalf of the Public Works Department to find out if the existing production of 200,000 gallons per day could be increased to the future requirement of 1½ million gallons per day.

Location

The Turner River flows northwards and crosses the North-West Coastal Highway about 19 miles west of Port Hedland (Fig. 4). The area investigated was mainly south of the highway, and extended 9½ miles upstream.

Previous work

Sands in the east branch of the river near Boodarie homestead were tested in 1925 and 1926. Hobson (1948a, b) summarised these results and also recommended drilling of the present P.W.D. production area and Pippingarra Creek 16 miles to the east.

Allen (1964) suggested the present exploratory drilling to determine the extent of the low salinity water body, the thickness of alluvium, and the amount of water available.

Present investigation

Between March and December 1965, 22 exploratory bores were drilled by a percussion cable tool rig, over an area of 54 square miles.

CLIMATE AND VEGETATION

The average annual rainfall is 12.56 inches, but yearly falls between 40.13 inches and 1.25 inches have been recorded. This rainfall is cyclonic and falls mainly during the period January to March. It is irregular and of scattered distribution. Summers are hot and dry, with a high potential evaporation of 98 inches (calculated value for Port Hedland airport).

The area is one of spinifex sandplain with clay pans; eucalyptus grow along drainage lines and mangroves fringe the coast.

TOPOGRAPHY AND DRAINAGE

The coastal plain has a gentle slope down to the north of about 7½ feet per mile. Low hills of basement rock crop out about 13 miles upstream of the coastal highway. The northerly flowing rivers have irregular, often braided channels and in some places are confined by banks. Sandplain or clay pans cover the interfluvies. Northerly sand ridges possibly represent abandoned river channels or river banks.

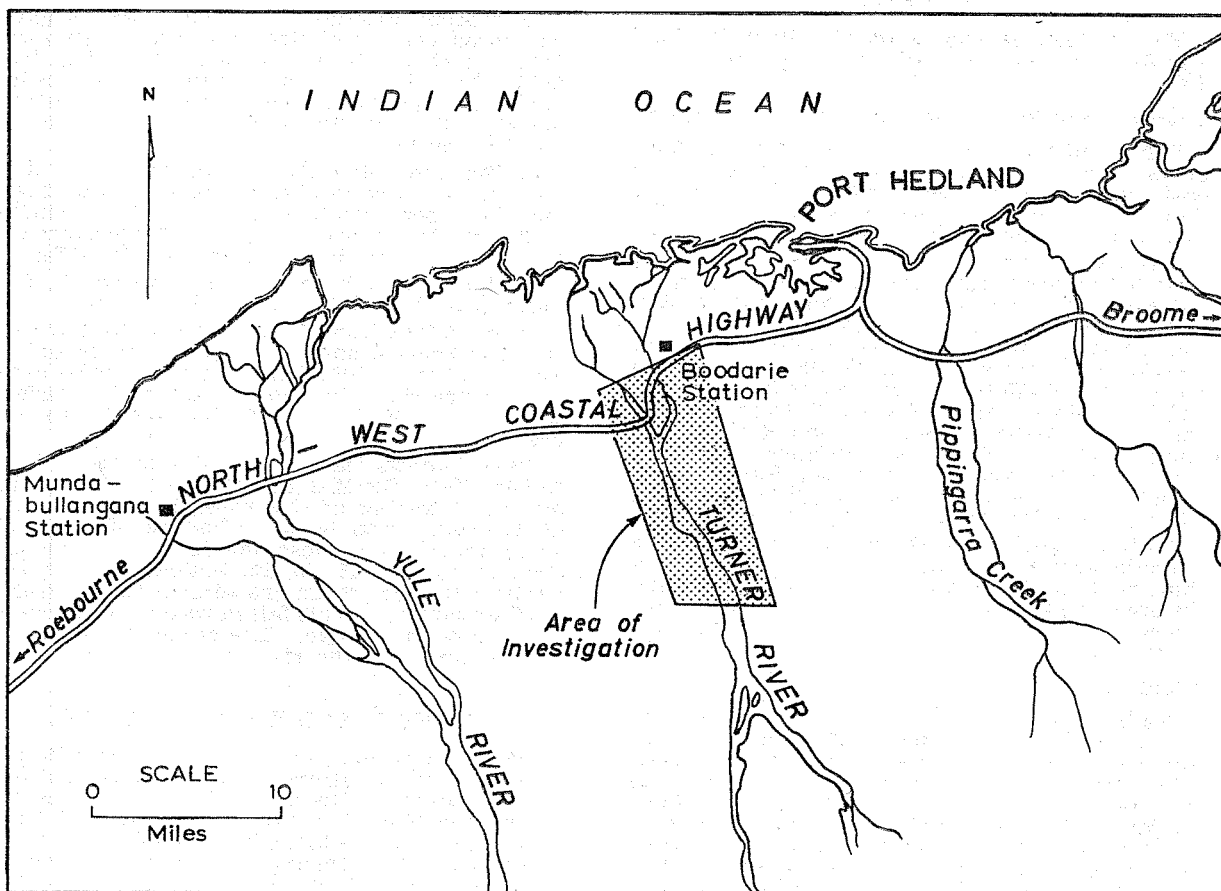


FIGURE 4 LOCALITY PLAN, TURNER RIVER AREA

The Turner River rises near Pullgunah, about 90 miles south-southeast of Port Hedland, and has a catchment area estimated to be 1,450 square miles.

Impersistent pools occur in the river bed after heavy rain or river flow; two months after the 1964/65 wet season, none remained. The river flows infrequently, and seldom reaches the P.W.D. pumping area. Surface flow was reported in 1961, 1965, and 1966. In 1965 the river flowed for a short time to a point 7 miles south of the highway. After heavy rain, P.W.D. sumps in the river bed sands fill with water, although there may be no river flow.

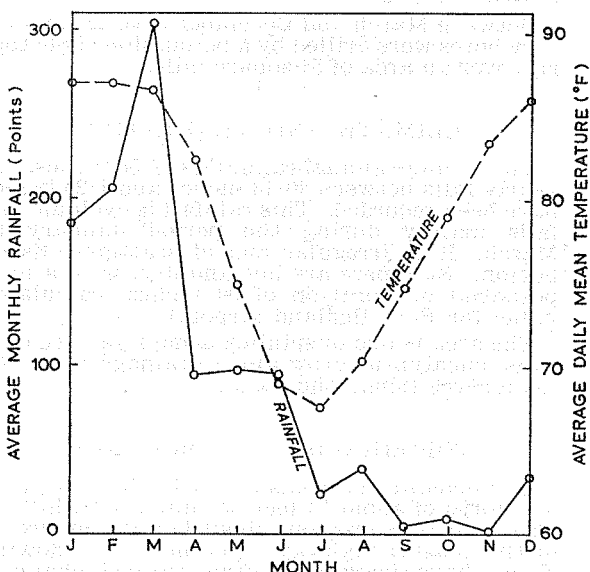


FIGURE 5: AVERAGE MONTHLY RAINFALL (30 year records) & AVERAGE DAILY MEAN TEMPERATURE FOR PORT HEDLAND

GEOLOGY

The geology is shown on the Port Hedland and Roebourne 1:250,000 Sheets (Low, 1965; Ryan, 1966).

Basement and its relationship to recent sediments

Three and a half miles east-southeast of Bore 14 outcrops of rectangularly jointed Archaean basic volcanics (Pilbara System, described as Warrawoona by Low) occur as a lens in the dominant Archaean granite and granite-gneiss.

Basement rocks encountered during drilling include the following types: pale-green aphanitic siliceous rock, quartz-feldspar-muscovite gneiss, hornblende-mica-gneiss, and quartz-feldspar tourmaline pegmatites. These rocks have thick weathering profiles, rich in kaolinitic clays and micas, of 35 to 75 feet thickness in Bores 2, 6, 8, and 16. In Bore 2, and in some P.W.D. production bores, the weathered bedrock zone contains the main aquifer. Siliceous horizons cemented with calcium carbonate (termed kunkar) are sometimes present in the weathered profile, having probably been secondarily introduced.

Drilling indicates that the basement floor is a northwards sloping undulating plain cut by a short northerly trending valley (Plate 9) beneath the present junction of the East and West Turner rivers, where thick alluvial sections have been penetrated.

Alluvium

The basement is covered by a wedge of alluvial and possibly eluvial material of poorly consolidated clay and sand, with minor gravel, thickening towards the north. Kunkar horizons are common in the alluvium. A maximum thickness of 145 feet of alluvium was cut in Bore 15. Bores penetrate a sandy-clay or clayey-sand surface layer 30 to 40 feet thick, below which is the aquifer zone. All strata contain high clay-silt fractions, and there are few "clean" sands or gravels. Bores on linear sand ridges also encounter sandy-clay-silt sections at depth.

The sediments are poorly sorted and the sphericity of sand grains is low. Quartz and feldspar sands are dominant, with minor jaspilite, chert, and siltstone fragments.

Kunkar layers occur below the water table. The kunkar has a calcium carbonate matrix, often hematized and with amorphous silica and dendritic manganese. Poorly consolidated highly calcareous clays and fine sands are common.

Correlation of strata between bores has not been found possible (Plate 8), because sedimentation in braided river channels subject to flash flows, produces lenticular strata. Later evidence from pump testing supports this view.

Strata samples from P.W.D. Bore 5, from 106 to 112 feet and 142 to 147 feet, were examined by H. S. Edgell. From the microflora, he considered them to be from a late Tertiary to Quaternary terrestrial-riverine deposit laid down during a period of lower sea-level.

GROUNDWATER HYDROLOGY

Drilling indicates thin clayey sand aquifers with a mean thickness 20 to 25 feet, the material including minor gravels and kunkar.

Water is cut at between 30 and 40 feet, apparently confined by the top sand-clay-silt layer. Unconfined water probably occurs in the poorly permeable materials above the aquifer zone, but is released too slowly to be detected in drilling.

The most productive aquifers may be kunkar layers, as bores yielding 2,000 to 3,000 gph have an abundance of kunkar in the aquifer. These good yields could perhaps be accounted for by the occurrence of solution channels in the kunkar.

Bore 2 (Plate 7 and 8) has a high yielding aquifer in weathered bedrock containing kunkar, and it is possible that the waters found in this zone and in the alluvium are connected, as they have similar chemical characteristics.

The curvature of the piezometric contours (Plate 7) indicates northerly movement of groundwater, apparently with a higher rate of flow along the line of the river than elsewhere. The steeper gradients on the flanks suggest decreased permeabilities in the alluvials away from the river. Downstream of the P.W.D. bore field, there is a distinct change in hydraulic gradient, the downstream one being approximately a fifth of that upstream. There are two possible reasons:

1. The area downstream of the bore field contains a thick section of alluvials, and there may be a permeability change in the vicinity, although this seems unlikely as yields upstream and downstream do not significantly differ.
2. More probably, pumping from the P.W.D. bores has altered the original gradient.

Cross section lines A and B (Plate 8) show that the piezometric surface slopes away from the Turner River, which must be the intake area. The depression in the piezometric surface around the P.W.D. bore field is a complex zone of depletion.

Plate 7 shows the static water levels in November, 1965. By March, 1966, there was a significant lowering of the water levels in 20 out of 22 observation bores. Changes of as much as 21 inches were observed in bores near the river (e.g., 8, 9, 15, 20, 12) indicating that the aquifers in this region are subject to the greatest fluctuations. This fall in water levels means a decrease in storage. The static water levels rose again after the river flowed in 1966.

SALINITY AND WATER QUALITY

During drilling, there was no significant change in water salinity with depth except that in some bores, a thin, very saline layer occurred at the top (e.g., Bore 4) probably caused by a rising water table leaching salts from the unsaturated zone. During the pump testing of some bores (e.g., Bores 4, 11), salinity decreased by as much as 40%. This probably means that a thin upper saline layer was initially drawn on, and later exhausted by pumping.

The isohaline contour plan (Plate 7) is based on a mean, 'most-reliable' salinity for each bore. The 1,000 ppm isohaline delineates the area of domestic quality water. An elongated freshwater body (less than 1,000 ppm) lies parallel to the river, again suggesting intake from this source.

The rapid increase of salinity north of the coastal highway is ascribed to sea water penetration of the alluvium, and the isolated freshwater bores, in small patches of coastal limestone, are fed by local rainwater.

Directly westward of the P.W.D. bore field, the isohalines are closely spaced. Water too saline for domestic use occurs 1½ miles from the production bores (2,800 ppm in Bore 10).

The saline water re-entrant west of the P.W.D. bore field has two possible explanations:

1. The high salinities in Bores 10 and 20 may be partly spurious, because of unrepresentative sampling. A saline water layer, characteristic of the top of the aquifer, may have contaminated other samples from deeper aquifers during their collection, so increasing their salinity by 20 to 30%.

2. Aquifers in Bore 20, and to a lesser extent Bore 10, have a higher clay content than those in surrounding bores. Bore yields are correspondingly low.

The piezometric contours (Plate 7) reach a high point to the west of the P.W.D. bore field. This indicates that fresh water from the river intake is moving north, northeast, and northwest. The slow passage of water through the zone of low permeability is possibly responsible for the high salinities in Bores 10 and 20.

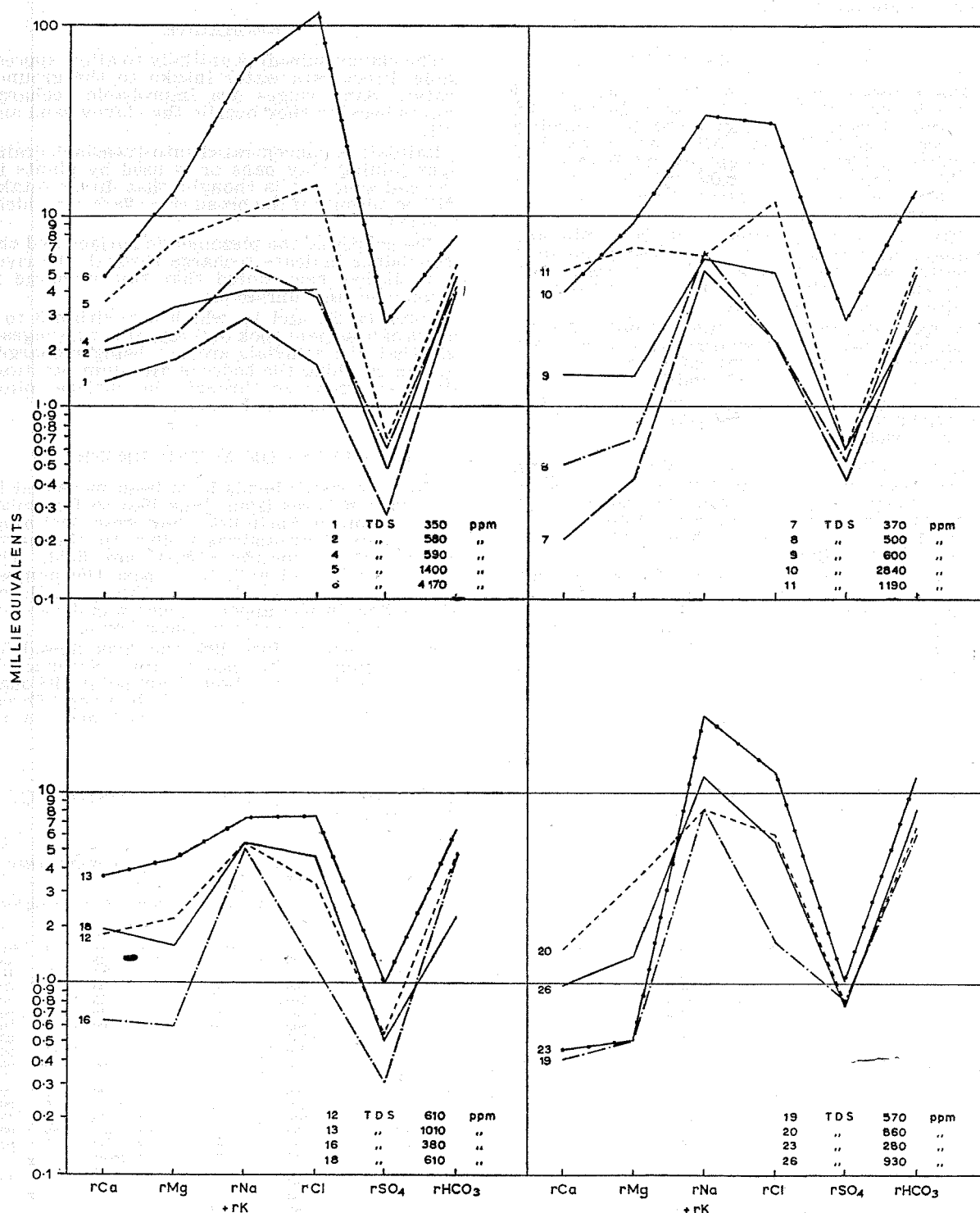


FIGURE 6 : SEMI-LOGARITHMIC GRAPHICAL REPRESENTATION OF CHEMICAL ANALYSES OF WATER FROM NUMBERED BOREHOLES

Analyses of the water from exploratory bores have been plotted on semi-logarithmic graph paper, using the Schoeller method (see Fig. 6) and the results suggest that:

1. Waters from weathered bedrock are chemically similar to those from alluvial aquifers, suggesting a hydraulic connection between basement and alluvium.
2. The saline interfluvial waters are rich in chloride, sodium and bicarbonate ions.
3. All waters have high bicarbonate ion, and are neutral or slightly alkaline. This is probably caused by solution of calcium carbonate in waters percolating through kunkar in the alluvials.
4. In Bores 2, 4, 9, 12, and 18, total iron exceeds 0.3 ppm. Otherwise water samples conform to U.S. Public Health Service 1946 minimum standards (see Todd). All samples were odourless and usually colourless.

PUMP TEST RESULTS

Pump test results are shown in Table 1. In the southeast of the drilling area, Bores 3, 12, 23, and 14 were dry. Ten bores had supplies of less than 1,000 gph. All other bores had supplies of 1,000 to 3,000 gph except Bore 2, the yield of which exceeded 6,000 gph. This bore is unusual because the water comes from the weathered bedrock.

The lateral impersistence of the thin and clayey aquifers accounts for these pump test results, as even good aquifer materials may give small supplies (e.g., Bore 4) because of limited storage capacity.

Kunkar beds in the alluvium are fairly permeable, and may be the source of the moderate supplies (1,000 to 3,000 gph) obtained from bores such as Nos. 5, 6, 7, 11, 13, and 15.

Drawdown-time data were plotted on semi-logarithmic scale, and there were certain general characteristics:

1. It is difficult to obtain a static drawdown level at a constant pump rate, because successive boundary conditions are reached during a long pumping test. The drawdown may remain static for several hours, and then rapidly decline, as occurred in Bore 5.

The original outputs of bores frequently cannot be duplicated if a new pump test is done after apparent recovery, and it is therefore difficult to determine the true yield of a bore.

This drawdown behaviour indicates the successive depletion of a series of impersistent aquifers, the progressive dewatering of which leads eventually to a decrease in pump rates, and failure to duplicate original yields.

2. Times of recovery to 90% of the original static water levels are usually less than 10 minutes (Table 1) but complete recovery times may be of very long duration, reflecting the restrictions imposed on groundwater movement by permeability changes and the frequent presence of lenses of clay and silt.

An analysis of semi-logarithmic graphs of drawdown against time, plotted for pump data on Bore 18, gave the following aquifer coefficients:

$$\begin{aligned} \text{Transmissibility } T &= 2,365 \text{ gpd/ft} \\ \text{Permeability } P &= 94.6 \text{ gpd/ft}^2 \end{aligned}$$

A modified non-equilibrium method, after Cooper and Jacob, 1946, was applied, assuming an aquifer thickness in Bore 18 of 25 feet. The semi-logarithmic graph of drawdown against time for pump data from other bores could not be used to obtain aquifer coefficients.

RECHARGE

The clayey subsoil is unlikely to allow appreciable direct rain water intake to the groundwater. Sand ridges are improbable recharge points because they overlie the clayey sand and silt.

Rainfall is concentrated into transient drainages joining clay pans or is used by plants in the soil zone. It is thought that direct intake will occur only if the broad river flats are widely flooded.

The shapes of the piezometric surface and the isohalsines indicate recharge through the river bed. It has been noted that this recharge is spasmodic and unreliable.

Bores 14, 23, and 12, which are within 3 to 4 miles of basement rock outcrop, are dry, suggesting that the alluvials are not being recharged by run-off along the bedrock-alluvium junction. However, recharge through the surface joints in the bedrock could occur.

ESTIMATES OF WATER RESERVES

Monthly water levels have been measured in observation bores from June 1965 to December 1966. Prior to April 1966 they were declining, as a result of groundwater flow to the north and extraction for the P.W.D. bore field. The Turner River had not flowed past the pumped bores since February 27, 1963 although in March 1965 a flow in the upper reaches was dissipated only 5 miles upstream of these bores.

From April to June 1966 the river flowed for about 3 months after heavy rain. Water levels rose at nearly every observation point although the duration and magnitude of the rises differed. In most places they had reached maxima by

Table 1

PORT HEDLAND TOWN WATER SUPPLY, TURNER RIVER EXPLORATORY DRILLING, SUMMARY OF PUMP TEST RESULTS

Bore No.	Depth	SWL	Available drawdown	Draw-down	Suction depth	Pumping rate	Duration	RECOVERY TIME			
								to 90% SWL		Complete	
	feet	feet	feet	feet	feet	gph	hours	min.	sec.	min.	sec.
1	80	34.3	30	>20	58	<200	1	2	30	3	45
*2	111	59.5	35.5	4.5	90	5,800	5 1/2	3	15	3	15
4	84	30.75	53?	6.3	75	600	7 1/2	3	00	3	30
5	90	29.4	45	22.4	76	1,570	13	1	55	1	30
6	149	29.5	43	22.4	74	1,250	8	1	40	3	00
7	114	25.6	84	38	68	2,800	15 1/2	9	00	>30	00
8	133	24.7	35	19	58	2,000	4 1/2	4	30	4	30
9	102	33.9	27	26	...	1,200	4 1/2	...	...	>15	00
10	104	31.7	37	23	61	<200	1 1/2	13	00	28	00
11	64.5	31.6	32	10.9	55	1,960	20	2	00	20	00
12	86.5*	50.7	34	12 +	...	<200	1 1/2	1	30	6	00
13	75.6	35.4	25	16.5	62	1,650	8	>4	30	2	45
15	152	30.5	30	27.6	64	1,890	8	2	30	>30	00
16	112	36	44?	36.6	76	480	8	2	30	5	00
17	107	20.9	55?	27.6	62	960	9	70% recov- in 3 min.	...	...	...
18	104	47.9	32?	28.5	95	860	9	7	30	8	45
19	92	29	60?	48.7	82	800	9	...	...	...	...
20	132	29.5	20	?	...	500	1 1/2	...	...	...	...
26	110	48.5	22	19	...	<400	1 1/2	...	...	...	...

* 5,800 gph was maximum pump capacity. Bore should be tested with higher capacity pump.

early December 1966 but a few were still rising. The displacements (as much as 10.5 ft) were greatest in bores near the river. The rate of water level rise was also greatest in these bores.

Changes in storage in the aquifer during the periods of decline and recharge are estimated from the water levels. Data on the pumpage from the bore field have been provided by the Public Works Department. Estimates of the flow of groundwater through a section C-D (Plate 7) across the river are based on the value of permeability 95 gal/day/sq ft calculated from the test pumping of Bore 18. The actual mean permeability may differ from that assumed in the calculations that follow, because the nature of the aquifer under the river is not known.

1. Subsurface flow

As shown on Plate 7 and Figure 7 the piezometric surface has been depressed around the pumping field. Within a certain area open to the south along the Turner River, water is drawn towards the pumping bores, whereas outside this area it flows to the northwest, north, and northeast. Its northern part is outlined on Plate 7, and is referred to as the area of draw.

All of the groundwater entering the area of draw between periods of river flow moves through the section C-D, which is 1.9 miles wide and

situated between Bores 1 and 4. The hydraulic gradient across the section is 6.9 feet per mile. A mean aquifer thickness of 30 feet is assumed, and a permeability of 95 gal/day/sq ft.

$$\begin{aligned} \text{Inflow} &= \text{area of cross section} \times \text{permeability} \\ &\quad \times \text{hydraulic gradient} \\ &= 30 \times 1.9 \times 95 \times 6.9 \text{ gal/day} \\ &= 3.74 \times 10^4 \text{ gal/day (approx.)} \end{aligned}$$

2. Reduction of storage between periods of river flow

Water levels measured over periods of 7 to 9 months from June, July or August 1965 to March 1966 in six bores in and near the area of draw are used to estimate the average decline over that area. The changes in level are listed in Table 2. Bores 8 and 10 exhibit anomalous results which are nevertheless included in the calculations.

Average decline in eight months: 1.5 feet (approx.)

The area of draw covers approx. 8 square miles.

Therefore volume of aquifer dewatered over 8 months = $1.5 \times 8 \times 5,280^2$ cu ft
= 335×10^6 cu ft (approx.)

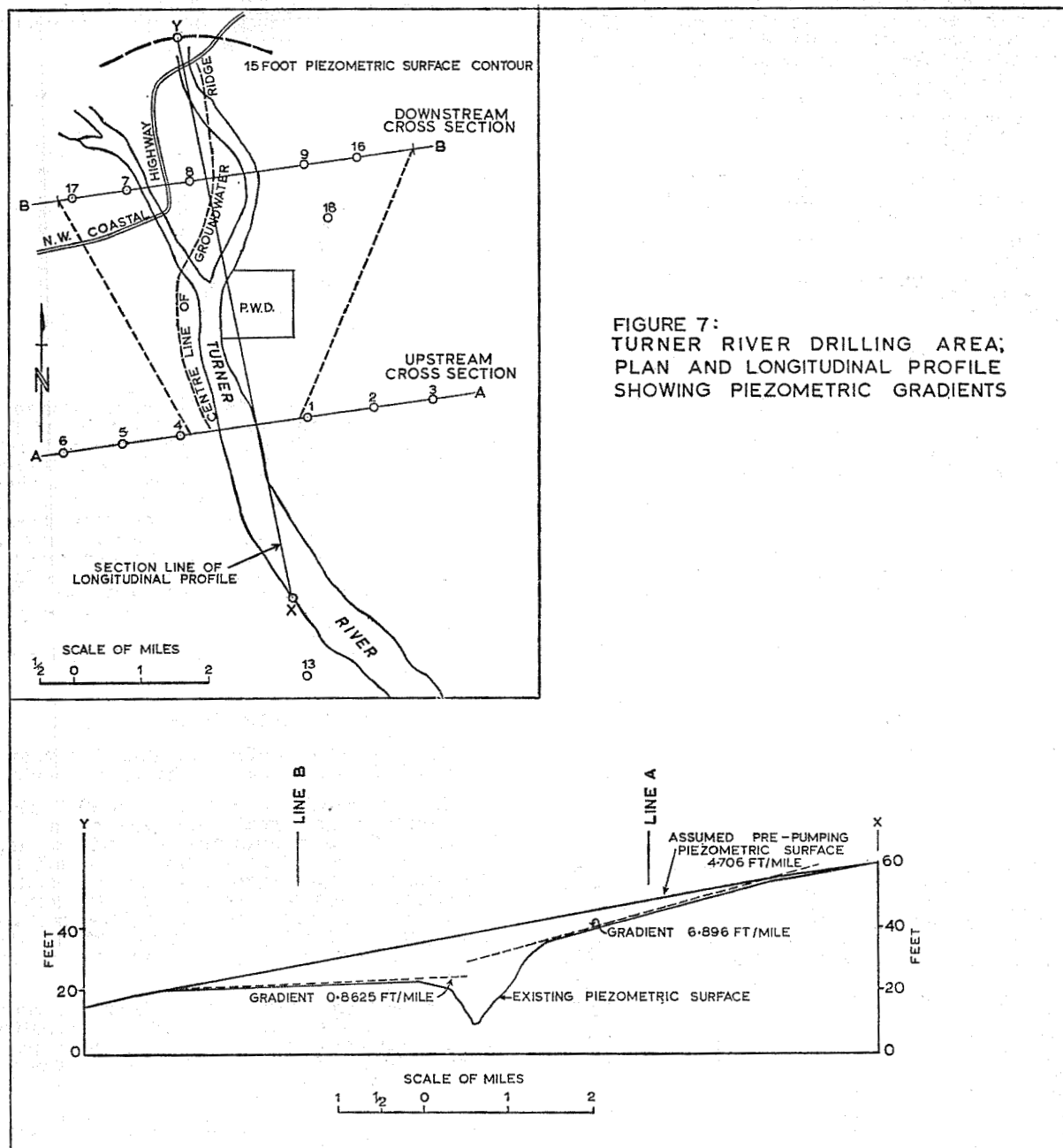


FIGURE 7:
TURNER RIVER DRILLING AREA;
PLAN AND LONGITUDINAL PROFILE
SHOWING PIEZOMETRIC GRADIENTS

Table 2
DECLINE IN WATER LEVELS IN SIX BORES
BEFORE THE 1965-66 RIVER FLOW

Bore No.	Date	SWL	Date	SWL	Decline	Period
		ft		ft	ft	months
1	June 65	35.67	Mar. 66	37.38	1.71	9
4	July 65	31.46	Mar. 66	32.71	1.25	8
8	June 65	24.27	Mar. 66	27.88	3.61	9
9	June 65	34.77	Mar. 66	36.56	1.79	9
10	July 65	34.40	Mar. 66	34.29	+0.17	8
18	Aug. 65	48.42	Mar. 66	49.75	1.33	7

3. Extraction of groundwater

During the 8 months from July 1965 to March 1966, water was pumped at the average rate of 0.208 x 10⁶ gal/day.

Inflow has been calculated (above) to be 3.74 x 10⁶ gal/day.

Therefore the net extraction from storage was 0.171 x 10⁶ gal/day i.e., 41.6 x 10⁶ gal or 6.78 x 10⁶ cu ft over 8 months.

Then, as the change in storage is 335 x 10⁶ cu ft (see 2 above), the storage coefficient = $\frac{6.68 \times 10^6}{335} = 0.02$

4. Recharge

The rises in water levels in eight bores in and near the area of draw in the 9 months March to December 1966 are listed in Table 3. They average 5.1 feet. It is assumed that the area of draw is approximately the same as before recharge took place, that is 8 square miles.

Volume of aquifer resaturated
= 8 x 5,280² x 5.1
= 1,140 x 10⁶ cu ft

With the storage coefficient of 0.02, the volume of recharge = 0.02 x 1,140 x 10⁶ x 6.23 gal
= 142 x 10⁶ gal

Pumpage continued during the period of recharge.

Using the pumping rate from the previous 9 months, the total abstraction was 272 x 0.208 x 10⁶ gal = 56.6 x 10⁶ gal

Total recharge = change in storage + pumpage
= 142 x 10⁶ + 56.6 x 10⁶ gal
= 199 x 10⁶ gal

At the present pumping rate the net extraction of water (pumpage-inflow) over one year = 365 x 0.171 x 10⁶ = 62.4 x 10⁶ gal. The recharged $\frac{199 \times 10^6}{62.4 \times 10^6} = 3.2$ years.

Table 3
RISES IN WATER LEVELS IN EIGHT BORES
AFTER THE 1966 RIVER FLOW

Bore No.	SWL Mar. 3, 1966	SWL Dec. 5, 1966	Increase
	ft	ft	
1	37.38	34.67	2.71
4	32.73	28.54	4.19
8	27.85	17.31	10.54
9	36.56	30.50	6.06
10	34.29	29.56	4.73
18	49.75	48.25	1.50
TR2	36.94	34.60	2.34
TR8	38.81	30.33	8.48

Plotting of the rises in water level, after recharge occurs, shows that a relatively quick initial rise takes place, the curve gradually flattening and then slowly declining. In the 4 months prior to the river flow, the same levels, measured in the 14 bores listed in Table 4 scattered over the whole area of investigation had an average decline of 0.75 feet in 4 months, or 0.19 feet per month. Since the figure of 0.19 applies to the end of a cycle, admittedly not an extremely severe one, it has been assumed with some validity that the rate of decline will probably never greatly exceed this figure. In the calculation which follows, the figure of 0.19 feet decline per month, which represents the depletion rate arising from both pumpage

and natural outflow, will therefore give a value rather less than the real one for the total time it would take to consume the amount of recharge added by each river flow.

As pumpage and outflow continued all through the recharge period, which in this case was about 9 months, the theoretical depletion, at the constant rate indicated by the figure of 0.19 feet per month would have been 0.19 x 9 = 1.71 feet. Recharge made good this loss as well as producing the water level rises, which average 4.5 feet for all the bores in the area, including the area of draw (Tables 3, 4). Therefore total recharge, in terms of water levels, is 4.5 + 1.7 = 6.2 feet.

But when no recharge is taking place, the decline in water level at the rate of 0.19 feet per month would cause a drop in the water level of 0.19 x 12 = 2.3 feet per year.

But since the 1966 flood was theoretically equivalent to a total rise of 6.2 feet, the addition it made to storage would be completely consumed in $\frac{6.2}{2.3}$ years = 2.7 years. This is of the same order as the figure of 3.2 years calculated in section 4 above, but is lower, probably for the reasons discussed.

Table 4
RISES IN WATER LEVELS IN AN
ADDITIONAL FOURTEEN BORES AFTER THE
1966 RIVER FLOW

Bore No.	SWL Mar. 3, 1966	SWL Dec. 5, 1966	Increase
	ft	ft	
2	61.23	61.44	0.21
5	31.50	27.94	3.56
6	31.08	29.42	1.66
7	28.10	19.52	8.58
11	32.75	30.29	2.46
12	53.42	47.73	5.69
13	37.33	33.79	3.54
15	32.65	26.21	6.44
16	38.50	35.00	3.50
17	23.46	16.83	6.63
19	30.12	23.29	6.83
20	32.44	25.25	7.19
23	41.83	41.04	0.79
26	49.29	47.98	1.31

When recharge takes place in a similar manner to that of 1966, in which the river flowed for 3 months, the addition to storage would last for just over 3 years, after which the base storage of the aquifer would be depleted. In practice, the volume of recharge may vary according to the length of time for which the river flows; the life of the recharged water would vary in the same way. There are no long-term records of the frequency of river flow, but over the last few years the river appears to have flowed often enough to replace the water being extracted at the present rate.

However, droughts of more than 3 years have been reported.

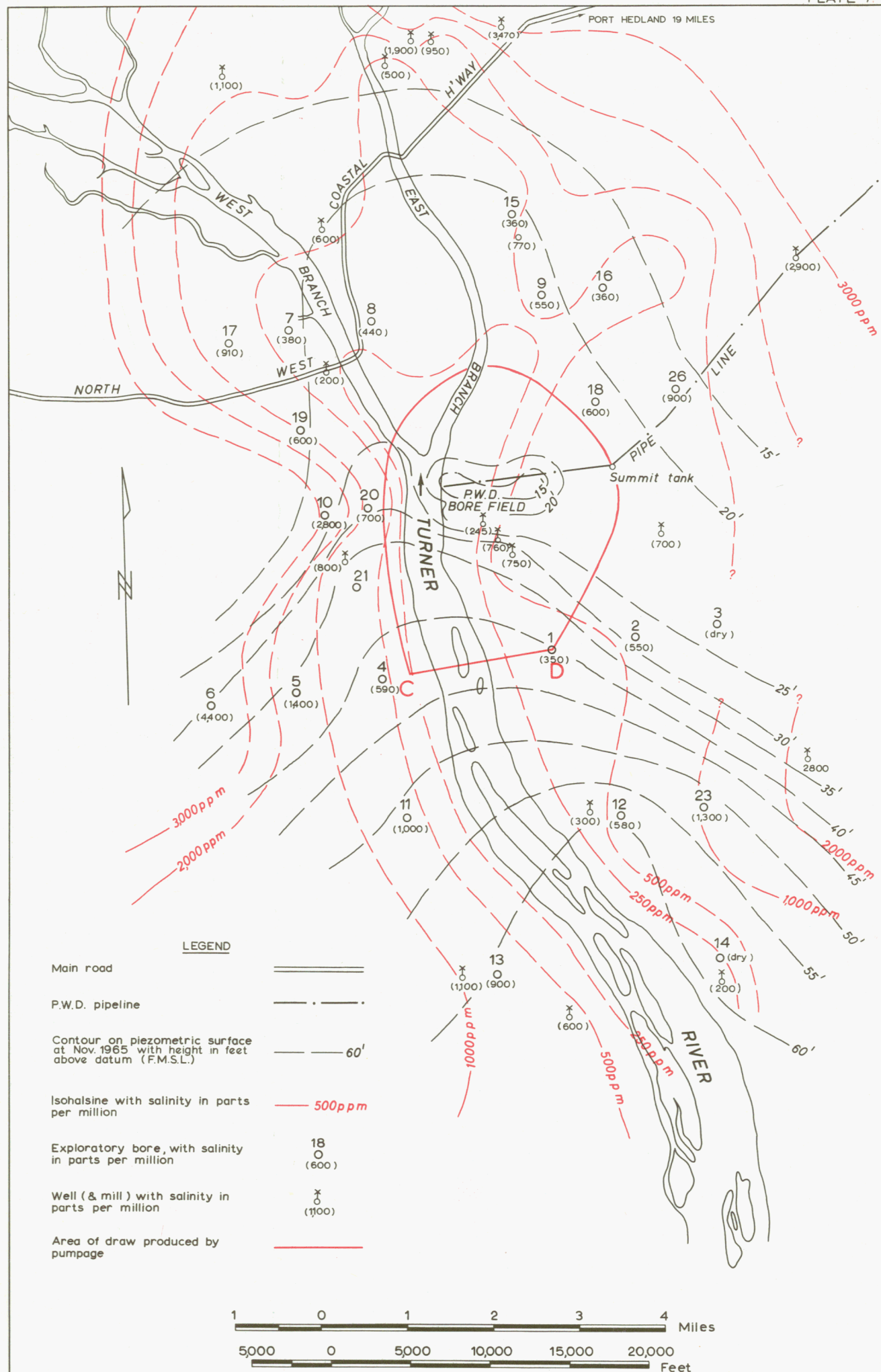
CONCLUSIONS

1. The available aquifers are thin, clayey, and of limited extent, and their recharge is irregular.

2. If a comparable flow to that of 1966 takes place once every 3 years, the present rate of pumping can be maintained without drawing on base storage. If no recharge occurred for more than 3 years, storage would be depleted by pumping, and the freshwater body mined. Overpumping could result in a salinity increase in the bore field, and it is recommended that the present rate of abstraction should not be increased.

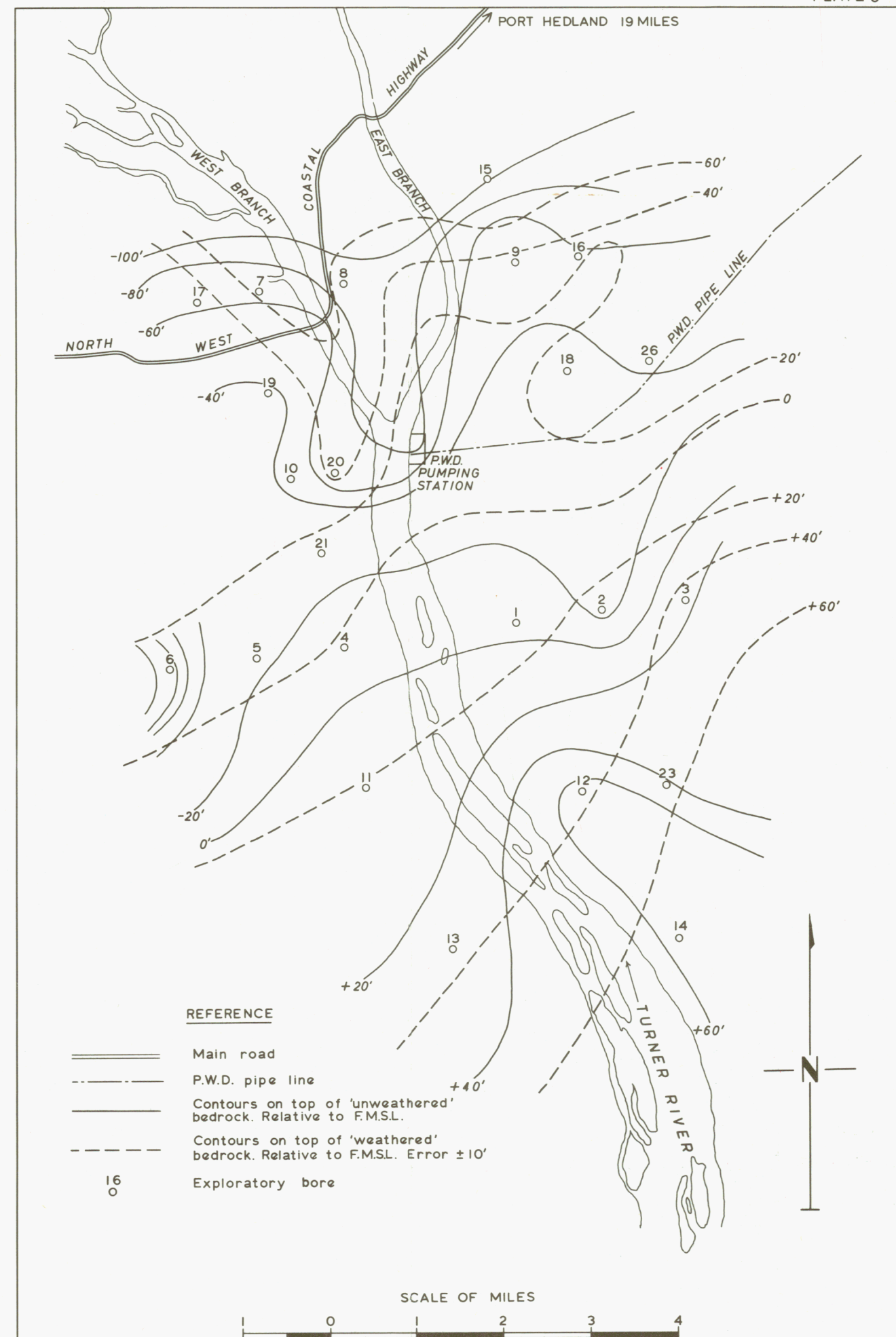
3. An increase in the area of draw, by wider bore distribution, could more effectively utilise water available from recharge. Owing to poor permeabilities, the choice of new sites is probably limited to the vicinity of Bores 2, 7, and 8.

4. Static water levels in all bores should be taken monthly in the future. This will provide information on the extent of river recharge and



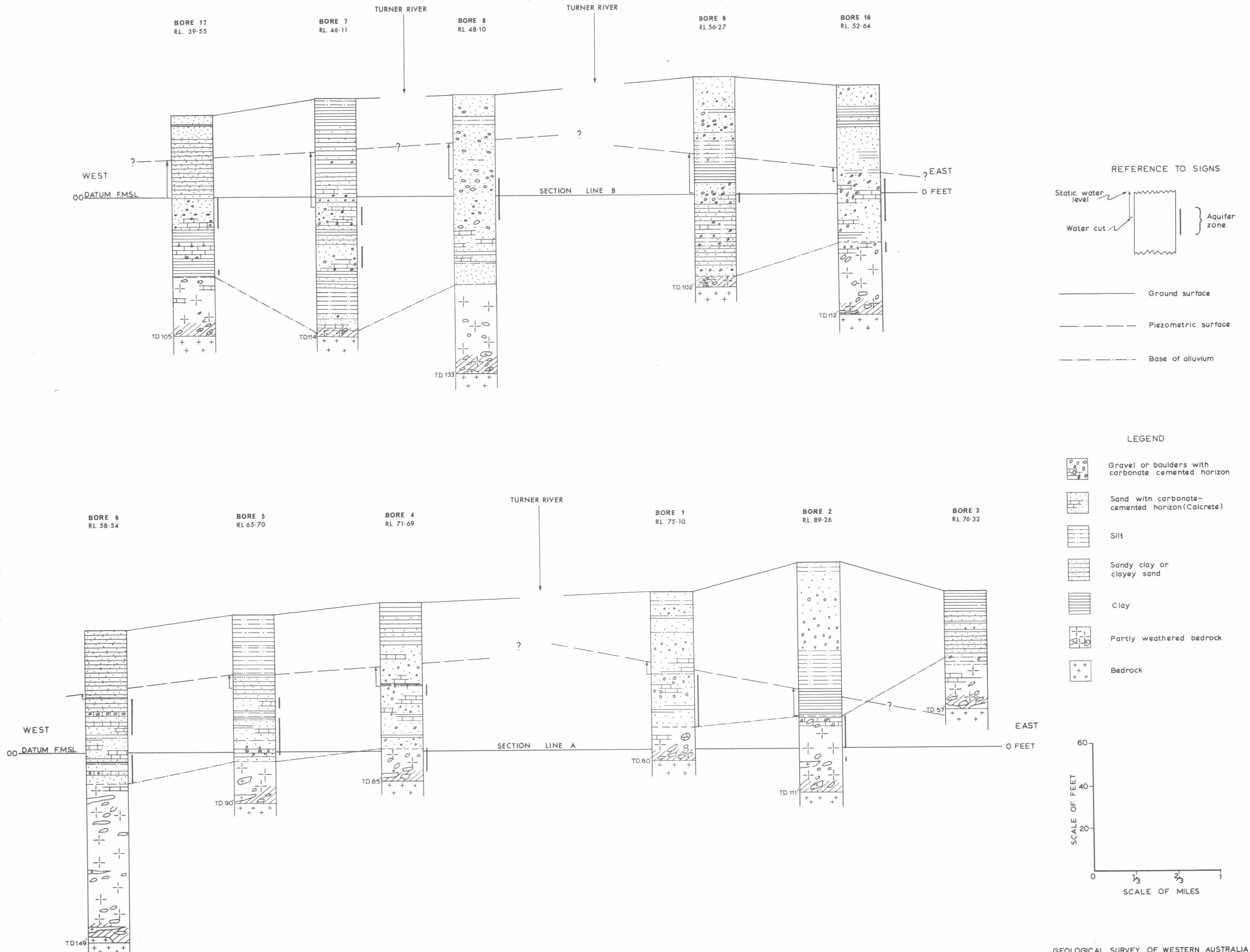
TURNER RIVER DRILLING AREA SHOWING CONTOURS ON PIEZOMETRIC SURFACE AND ISOHALSINES

To accompany report by R. Farbridge, 1966



TURNER RIVER DRILLING AREA
CONTOURS ON BASE OF ALLUVIAL MATERIAL
AND ON TOP OF UNWEATHERED BEDROCK

To accompany report by R. Farbridge, 1966



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
TURNER RIVER AREA
CROSS SECTIONS A AND B

To accompany report by R. Farbridge, 1966

will help to determine the long term behaviour of the piezometric surface relative to the P.W.D. bore field. Detailed records should be kept of the periods during which river flow takes place. Future salinity checks, particularly on Bores 10, 18, and 20, are desirable to detect any salinity increases.

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EXPLORATORY DRILLING FOR UNDERGROUND WATER, GINGIN BROOK AREA, PERTH BASIN

by C. C. Sanders

ABSTRACT

Six exploratory water bores were drilled across the Perth Basin from Gingin to the west coast. The maximum depth drilled was 2,610 feet and Jurassic sediments were the oldest encountered.

Three aquifers were recognised in the Mesozoic rocks, but there was no test pumping. Domestic quality water is restricted but there is ample stock quality water. The Quaternary sediments form an extensive, shallow, unconfined aquifer, which probably contains a substantial quantity of domestic quality water.

INTRODUCTION

This exploratory drilling is part of a long-term investigation of the hydrogeology of the Perth Basin, and was done by the Mines Department between May, 1965 and August, 1966. About 50 miles north of Perth, six rotary bores were drilled across the Perth Basin from Gingin in the east to Guilderton in the west, a distance of about 25 miles.

Gingin Brook Bores 1 to 4 were on a line extending in a westerly direction from near Gingin, and spaced at intervals of 7 to 9 miles. Subsequently Bores 5 and 6 were drilled in the centre of the line.

Palynological determinations were made from core and sludge samples by B. S. Ingram and B. E. Balme, whose work is gratefully acknowledged.

PHYSIOGRAPHY

The area is on the coastal plain near the middle of the Perth Basin, and is bounded on the east by the Darling Fault and on the west by the coast. A plateau of late Mesozoic rocks about 10 miles wide abuts against the Darling Fault 8 miles east of Gingin, and near Gingin townsite this plateau has been largely eroded by Gingin Brook and its tributaries. Two miles to the west, an escarpment appears to be the physiographic expression of a concealed fault down-thrown to the west and trending N24°W. Westward of this escarpment a plain of low relief dips gently seaward, forming a northern extension of the Swan Coastal system described by McArthur and Bettenay (1960). The natural drainage lies along the valleys of the Moore River and Gingin Brook.

DRILLING AND TESTING PROCEDURES

Drillhole cuttings were collected every 10 feet, and cores were cut mainly in clayey horizons at intervals of about 200 feet.

Gamma ray, spontaneous potential, long and short normal resistivities, and point resistivity logs were run at 1,000 feet depth and at total depth. In addition, Bore 2 was logged by Schlumberger Seaco Inc. for WAPET. Lithologic boundaries were fixed and sites for formation tests were determined from the gamma ray log. The long normal resistivity log proved useful for computing the salinity of formation water using the results of drill stem tests as calibration points and selecting a formation factor of six.

Water samples were collected with a Johnston Formation Tester. Results were often disappointing as in some cases poorly consolidated sediments were drawn into the tester and blocked the bottom choke, and the sometimes low static water levels caused contamination of formation water by drilling fluid in the drill stem. Uncontaminated water samples were submitted to the Government Chemical Laboratories for standard analyses and these are summarised in Table 4.

GEOLOGY

STRATIGRAPHY

McWhae and others (1958) describe the extensive and essentially continuous continental deposition which occurred in the Perth Basin during the Upper Jurassic and Lower Cretaceous epochs. A period of tectonism associated with local movement on the Darling Fault Zone followed, establishing shallow marine conditions over much of the central Perth Basin by Upper Cretaceous times, followed by regional emergence during the Tertiary period.

A thick Mesozoic succession and a thin veneer of Quaternary sediments were intersected during drilling. The Upper Jurassic and Lower Cretaceous beds correlate with the Yarragadee Formation farther north, and with the South Perth Formation near Perth and Bullsbrook. For the sake of uniformity of nomenclature with recent work in the Perth Basin (Pudovskis, 1962; Lowry, 1965), the Upper Jurassic-Lower Cretaceous section is herein referred to as Yarragadee Formation.

In this report this formation is divided into two units, partly on palynological grounds but also from lithological considerations. The result

is that Units I and II shown in Table I below correspond with Zones A and B-C of Ingram (1967). He has been able to subdivide Unit II into two floral zones B and C, but this has little lithological expression except in the western segment of the drilled area where a possible disconformity has been recognised.

Table 1
SUBDIVISION OF THE YARRAGADEE
FORMATION, GINGIN BROOK

Unit	Palynological Zone (Ingram, 1967)	Stage	Lithology
II	Zone C	Neocomian—Aptian	Interbedded carbonaceous claystone and sandstone (Bores 1, 2, 3, 4, 5 and 6)
		Possible local disconformity	
	Zone B	? Neocomian	Thick sandstone and thin claystone with occasional calcareous beds (Bores 2, 3 and 6)
I		Disconformity	
	Zone A	Tithonian—Neocomian	Non-marine sandstone and carbonaceous claystone (Bores 2 and 3)

A doubtful lithologic break marks the Upper Jurassic—Lower Cretaceous boundary, but this cannot yet be defined accurately on palynological evidence.

The Middle Cretaceous is represented by the Osborne Formation, and the Upper Cretaceous by the Molecap Greensand, Gingin Chalk, and Lancelin Beds. The last mentioned unit was proposed by Edgell (1964) for Campanian age marine strata recognised in bores at Lancelin.

The Quaternary sediments consist of eolian Coastal Limestone.

Mesozoic stratigraphic correlations are shown in Table 2.

UPPER JURASSIC

Yarragadee Formation Unit I

The predominantly non-marine Upper Jurassic sediments are correlated with the Yarragadee Formation of the central and northern Perth Basin, and possibly with the Claremont Sandstone in the Perth area. Balme (pers. comm.) has identified long ranging Upper Jurassic—Lower Cretaceous microflora from Bores 2 and 3. The assemblages contain no typically Cretaceous forms and the associations of species are more characteristic of Upper Jurassic than Cretaceous sediments, but the palynomorphs appear younger than those from the type section of the Claremont Sandstone.

Typically the Upper Jurassic sequence consists of alternating bands of sandstone and grey claystone, pyritic in places, with indeterminate plant remains and lignite. The sandstone is light grey, fine to medium-grained, clayey, and composed of well sorted, subrounded grains of quartz and minor feldspar. Garnet is a common accessory mineral. The claystone is dark grey, often carbonaceous, well indurated and hard, but rarely banded.

Upper Jurassic sediments were intersected in Bores 2 and 3 but were not fully penetrated, the maximum penetration being 870 feet in Bore 3. The section consists of thick sandstone and claystone giving a characteristic blocky graph for the gamma ray log.

The beds are non-marine, formed in a swampy, lacustrine environment by continuous deposition of alternating strata, resulting from frequent inundation by terrigenous mud and clastic material derived from the Precambrian plateau to the east.

Upper Jurassic sediments were intersected below 2,410 feet in Bore 2. The sequence is of interest because geophysical evidence suggests

a major unconformity at a depth of about 2,000 feet thought to represent the Lower or Middle Jurassic and the Upper Jurassic boundary.

Palynological evidence indicates a sedimentary break between 2,010 feet and 2,495 feet, but it is unlikely that the hiatus is of comparable magnitude to that occurring in bores to the south of Perth, where Lower Cretaceous rests on Lower Jurassic sediments. It seems likely that the bore did not go deep enough to reach the unconformity (Plate 10).

LOWER CRETACEOUS

Yarragadee Formation Unit II

The Lower Cretaceous succession is equivalent to the South Perth Formation of Fairbridge (1953) and the upper part of the Yarragadee Formation described by McWhae and others (1958).

The unit is a sequence of interbedded, mainly non-marine sandstone, siltstone, and claystone with very common lignite and garnet. Thin calcareous beds occur frequently but are not laterally persistent across the basin.

Seismic evidence from the middle of the drilled area shows that the formation has a regional eastward dip of about two degrees. Correlation between the bores is difficult and it is likely that numerous large interconnected swamps covered the area during deposition.

The greatest thickness of section, 2,260 feet, was penetrated in Bore 2 where it is feldspathic, micaceous, pyritic, and carbonaceous and consists of alternating sandstone, siltstone, and claystone. The sandstone is light grey, medium to coarse-grained; the grains are moderately sorted and are subangular to subrounded. The siltstone and claystone are dark grey, soft, and puggy. A deepening of the basin towards the east is indicated in Bore 5. The sequence here is marked by an influx of fine terrigenous material particularly garnet, the presence of carbonaceous matter, and the frequency of calcareous beds which are chemical and syngenetic in character.

Thick arkosic sands are interspersed with minor clay and silt from 60 to 265 feet in Bore 5. Below 265 feet the sequence is predominantly a uniform siltstone. The gamma ray log of the Gingin town bore situated about one mile to the east indicates a possible correlation of the sands between 360 and 455 feet with those occurring between 174 and 265 feet in Bore 5. This suggests that the sediments are dipping at about two degrees to the east.

In Bore 1 near the Darling Fault zone the facies consists of shale and claystone with minor sandstone. The shale is variably coloured, mainly grey to dark brown, micaceous, carbonaceous, pyritic, and exhibits prominent lamination. The bands, in a core sample taken at 1,000 feet, dip at about 5°. The dip direction is probably eastward.

The sandstone is grey, medium to very coarse-grained, consisting of subrounded, poorly sorted quartz and granitic fragments.

The sequence in Bores 4 and 6 consists of alternating thin lenses of sandstone and claystone. The section was deposited in a marginal marine environment and is characterised by a lack of calcareous strata. Marine influences are more pronounced in Bore 4, indicating that marine incursions were generally restricted to the west of the drilled area.

The section in Bore 4 consists of feldspathic sandstone interbedded with dark grey carbonaceous claystone and siltstone. The claystone is micaceous, uniform in texture, generally well indurated and lacks bedding or lamination. Lignite and pyrite are common accessory minerals. The sandstone sequence thickens below 1,100 feet and consists of coarse to medium-sized quartz and feldspar grains, subangular in shape and poorly sorted.

In Bore 6 the sequence is mainly non-marine with minor paralic intercalations which reach a maximum development at about 1,800 feet. The strata are thinly interbedded sandstones,

Table 2

CRETACEOUS CORRELATIONS IN PERTH BASIN, WESTERN AUSTRALIA																					
CRETACEOUS	UPPER	Geraldton* Mingenew					Dandaragan* Gingin					Gingin (Proposed herein)					Perth Area*				
		SENONIAN	Maestrichtian																		
			Campanian																		
			Santonian																		
			Coniacian																		
		Turonian																			
	LOWER	Cenomanian																			
		Albian																			
		Aptian																			
		Neocomian																			
JURASSIC	UPPER	Tithonian																			
		Kimmeridgian																			
		Oxfordian																			
	MIDDLE	Callovian																			
		Bathonian																			
		Bajocian																			

* McWhae and others, 1958.

claystones, and siltstones. A minor hiatus is indicated at 2,070 feet, between a predominantly dark grey, micaceous siltstone sequence below and the sandstone-claystone succession above.

This sedimentary break is recognised by Ingram (1967) as the boundary between his floral zones B and C.

UPPER CRETACEOUS

The Upper Cretaceous is represented by the Osborne Formation, Molecap Greensand, Gingin Chalk, and Lancelin Beds.

Osborne Formation

The Osborne Formation (McWhae and others, 1958) occurs in Bores 1, 4 and 6 where it rests disconformably on Unit II of the Yarragadee Formation. The sequence is typically a dark green to black, glauconitic, carbonaceous claystone. The presence of glauconite and frequent microplankton in core samples indicates shallow marine deposition.

The formation attains its maximum thickness of 343 feet in Bore 6, thinning westwards to 315 feet in Bore 4. Between Bores 3 and 6 the formation is apparently faulted out by a normal fault with a westerly downthrow of at least 2,000 feet (Plate 10).

In Bore 1 the Osborne Formation is only 250 feet thick but its base is 64 feet above sea level, and 510 feet higher than at Bore 6. Near Gingin the formation is absent and has apparently lensed out between the town bore and Bore 1.

The age of the Osborne Formation in the Gingin Brook bores is Albian—Cenomanian (B. Ingram).

Molecap Greensand

The Molecap Greensand (Fairbridge, 1953) was penetrated only in Bore 1 where it unconformably overlies the Osborne Formation. The unit attains a thickness of about 50 feet in the bore and is thought to be Coniacian in age.

Gingin Chalk and Lancelin Beds

Upper Cretaceous calcareous strata of Santonian to Campanian age were penetrated by Bores 4 and 6.

On lithological grounds the succession may be divided into two units. The lower silty limestone unit containing *Inoceramus* fragments was penetrated between 180 feet and 215 feet in Bore 4. It contains abundant foraminifera which A. E. Cockbain (pers. comm.) considers similar to specimens from the type section of the Gingin Chalk, near Gingin. He tentatively suggests that this unit is of lowest Campanian age, but a Santonian age for the strata from 200 feet to 210 feet could not be ruled out.

The upper unit, a calcareous, glauconitic siltstone occurring between 130 feet and 180 feet in Bore 4 is considered by Cockbain to be definitely Campanian in age and to correlate with the Lancelin Beds (Edgell, 1964). Lithologically the sequence is similar to the Lancelin Beds which are grey marls containing abundant fragments of *Inoceramus*, and is atypical of the Gingin Chalk which is a pure white chalk.

In Bore 6, 70 feet of calcareous siltstone was penetrated. Cockbain assigned a Santonian—Campanian age to these strata, but the two could not be differentiated with any confidence.

Quaternary succession

Quaternary eolian limestone and dune sands rest unconformably on Upper and Lower Cretaceous sediments over much of the western area and border the present-day coast, reaching at least 114 feet in thickness in the Guilderton town bore.

The level of the Quaternary—Cretaceous unconformity rises gently from about 80 feet below sea level at Guilderton to 10 feet above sea level in Bore 2, disappearing altogether at the Upper Cretaceous escarpment 3 miles west of Gingin.

TECTONIC HISTORY

For many years the Perth Basin was thought to have a gentle basinal structure, deepest in the middle and shallowing towards the north and

south. Recent exploratory drilling for oil and water has shown the region to be one of tectonic complexity.

At a depth of about 2,000 feet a major seismic unconformity resembling a marine scarp is suggested by geophysical work undertaken by WAPET. The feature is thought to mark the junction between the Lower or Middle Jurassic and the Upper Jurassic. Bore 2, (total depth 2,495 feet) was sited above the crest of the unconformity, but on palynological evidence, apparently failed to penetrate it.

A thick Upper Jurassic—Lower Cretaceous paralic to non-marine section was deposited above the unconformity as a result of renewed movement along the Darling Fault zone. This produced an uneven subsidence of the floor of the basin and an eastward dip.

During Middle Cretaceous times a shallow marine transgression, probably from the north, deposited the Osborne Formation disconformably on the preceding Lower Cretaceous. The sea then regressed giving rise to the hiatus which separates the Osborne Formation from the Upper Cretaceous succession. The succeeding Molecap Greensand was also deposited under shallow water conditions, as part of a shallow marine transgression which was initially restricted to an embayment. This bordered the Darling Fault where subsidence was greatest. The Molecap Greensand was succeeded conformably by the Gingin Chalk. By late Santonian—early Campanian times the marine influence regressed westward, depositing the Lancelin Beds in the Guilderton—Lancelin area.

Minor movements along the Darling Fault at the end of the Tertiary (McWhae and others, 1958) caused the development of slippage faults above existing fractures in the Lower Mesozoic sediments. Rotation of a block about 8 miles wide abutting the Darling Fault zone imposed a gentle eastward dip on the Upper Cretaceous succession (Low, 1964), and the coastal belt was downthrown to the west as much as 2,000 feet by faults, trending north-south, and situated about 9 miles inland.

Subsequently the whole area was eroded and is marked by the Quaternary unconformity. Pleistocene eolianite and dune sands were deposited over the erosion surface as far inland as 14 miles.

HYDROLOGY

AQUIFER SYSTEMS

Aquifers of Upper Jurassic, Lower Cretaceous, Upper Cretaceous, and Quaternary age were intersected in the drilling.

Yarragadee Formation Unit I

An Upper Jurassic aquifer similar to the Claremont Sandstone was the main drilling target. A confined aquifer of this age, consisting of coarse feldspathic sandstone interbedded with thick claystone, was encountered only in Bore 3 but is considered younger than the Claremont Sandstone.

This aquifer was tested at a depth of 1,700 feet where a static water level of 89 feet above sea level was recorded. The water salinity was 1,320 ppm TDS. Gamma ray and electric logs of the bore show strata containing low salinity water occurring at depths of 1,900 feet and 2,100 feet. The latter horizon is a clean sandstone about 400 feet thick with a possible water salinity of 500 ppm TDS, and apparently having no hydraulic connection with the more saline water above.

The origin of this water and its direction of movement are not apparent. In other areas also, some bores have better quality deep waters than their shallower aquifers contain, and more work will be needed to find the reason. It is just possible that water from the Moore River and Gingin Brook is seeping down the fault zone west of Bore 3, but one would expect the shallower aquifers to benefit even more from such a source, as they should be at least equally permeable.

Yarragadee Formation Unit II

Unit II is an extensively developed confined aquifer having a maximum thickness of 2,200

feet in Bores 2 and 6. It consists of grey, fine to coarse, feldspathic sandstone with interbedded claystone and siltstone. East of Bore 2 a decrease in permeability of the aquifer is the result of an appreciable increase in the silt content as is evident in Bores 1 and 5.

This aquifer is separated from the Upper Jurassic aquifer in Bore 2 by a thick claystone section and in Bore 3 by thin shaly beds. Correlation of the aquifer between these bores is complicated by a strong easterly dip and by imper-sistence of strata which causes considerable horizontal and vertical permeability variations. The different beds within the aquifer are, how-ever, well defined and are considered to form one hydraulically interconnected system.

In Bores 2 and 3 static water levels of 161 feet and 130 feet above sea level were recorded from sands at 870 feet and 240 feet respectively, which are roughly the same aquifer horizon. The hydraulic gradient between the two bores falls gently to the west at 4 feet per mile (Plate No. 11). The pressure water from the 240 feet level in Bore 3 has a hydrostatic head of 27 feet above ground level and an estimated yield of 40,000 gallons per hour.

The hydraulic gradient of 4 feet per mile is maintained at least as far east as Bore 1 where a static water level of 320 feet above sea level was recorded.

Between Bores 3 and 6 two inferred step faults have downthrown the unit by at least 2,000 feet to the west. The form of the piezometric sur-face over the fault zone is uncertain, but it appears to increase appreciably in gradient to 18 feet per mile since a static head of 35 feet above sea level was recorded in Bore 6.

Recharge probably takes place along the Darling Fault zone and by seepage from Gingin Brook percolating down through the Quaternary limestones. Effective recharge from Gingin Brook is suggested by the chemical similarity between water in the brook and samples from Bores 3 and 6. Intake may also occur along the north-trending fault zone between these bores.

It must be noted however, that some fault zones in the northern Perth Basin, particularly at Arrino, are thought to act as effective barriers to water movement across or down the fracture lines. Milbourne (pers. comm.) reports that these zones are kaolinitic which may explain their impervious nature. Kaolinite was not noted from any of the Gingin Brook bores.

Without any test pumping of the Lower Cre-taceous and Upper Jurassic aquifers it is dif-ficult to comment on the quantity of stored water available, but it is probably quite large

since sandstone sections are mainly thick and inter-connected.

Upper Cretaceous

The Molecap Greensand forms the only aquifer of this age encountered in the drilling. Litho-logically this aquifer consists of unconsolidated glauconitic sandstone and siltstone. It is separated from the Lower Cretaceous aquifer system by the Osborne Formation in Bore 1 and by an unconformity at the type section at Molecap Hill near Gingin. The Osborne For-mation is a most effective aquiclude and water held up by it issues as springs in the dissected Ginginup area forming the source of Gingin Brook. Recharge is direct from rainfall and along the Darling Fault zone where many small streams apparently disappear into the ground.

Quaternary

Details of the shallow unconfined aquifer located in all bores west of No. 5 are given in Table 3. The aquifer consists of unconsolidated superficial sand, eolinite, and Coastal Limestone.

Table 3
QUATERNARY AQUIFER

Bore No.	2	3*	6	4	Guild-erton
R.L. of bore head	ft. 191.5	ft. 103.2	ft. 69.2	ft. 32.5	ft. 30.0
Depth to water table	20	40	60	18	30.0
Thickness of aquifer....	150	100	80	125	>114
R.L. of water table....	170	130	9	24	0

* Bore 3 was sited alongside Gingin Brook and pressure water with a hydrostatic head of 27 feet above ground level was encountered at 40 feet.

The Quaternary aquifer extends south to the Bullsbrook and Gnangara areas where it forms an extensive groundwater province. A contour map and the water table profile suggests that the main intake for the aquifer occurs in the region between Bullsbrook and Gingin, direct recharge being effected by precipitation. A large quan-tity of water would be available from this aquifer.

The groundwater is moving westward under a gentle gradient, movement probably being controlled by the subsurface erosion slope on the Mesozoic rocks.

QUALITY OF THE UNDERGROUND WATER

The chemical nature of the underground water is indicated by standard chemical analyses and these are given in Table 4. Schoeller's (1959)

Table 4
WATER ANALYSES BY GOVERNMENT CHEMICAL LABORATORIES—GINGIN BROOK BORES

Bore		1	Gingin Town Bore	5A	5	2	3			6			4				
Aquifer Section tested Depth in feet		380- 400	380- 400	20- 200	Gingin Brook	50- 100	914- 955	30- 100	240- 260	1400- 1500	1657- 1727	1110- 1170	1820- 1910	2270- 2400	35- 45	600	1734- 1758
Specific Conductivity 20°C (Micromhos)		460	290	1530	420	1290	1810	1110	1200	2050	1890	1170	1530	2510	2240	750	1650
pH		7.8	6.6	5.6	6.7	8.1	9.2	7.7	6.9	7.4	7.4	6.9	7.4	8.0	8.4	6.9	7.8
Mineral matter ppm	Calcium, Ca	22	2	14	4	52	49	59	18	38	46	21	28	11	36	11	34
	Magnesium, Mg	7	4	25	8	19	1	21	21	22	30	19	19	15	13	11	21
	Sodium, Na	74	49	270	76	235	354	161	210	387	311	198	271	564	479	166	295
	Potassium, K	5	9	11	2	7	18	6	11	32	36	13	19	23	9	11	24
	Bicarbonate, HCO ₃	128	15	30	27	366	104	247	92	256	238	107	149	366	375	161	232
	Carbonate, CO ₃						39								8		
	Sulphate, SO ₄	24	12	37	13	64	53	5	34	90	63	30	61	149	138	29	77
	Chloride, Cl	85	81	480	123	255	495	272	348	541	496	324	408	631	519	203	407
	Nitrate, NO ₃		< 1	1	1	1	< 1				1	1	1	1	< 1		1
	Iron, Fe	0.2	0.9	<0.1	0.5	6	<0.1	0.1	0.5	<0.1			<0.1	0.1	0.8	<0.1	0.2	0.2
Total ppm	By conductivity	320	200	1070	290	900	1270	780	850	1440	1320	820	880	1760	1570	520	1160
	By evaporation	310	170	890	260	850	1070	690	730	1220	1100	690	1070	1610	1430	500	1000
Hardness	Total	84	21	138	43	208	126	233	131	186	238	130	148	89	143	73	171
	Bicarbonate	84	12					203	76	186					143		
	Non-carbonate		9					30	55								
	Calcium	55	5					147	45	95					90		
	Magnesium	29	16					86	86	91					53		

method of plotting ions as milli-equivalents on semi-logarithmic graph paper has been used to compare chemical characteristics of water from various aquifers. Most samples selected for analysis were considered to be uncontaminated by drilling fluids.

Yarragadee Formation aquifers

The *Unit I* aquifer was tested over the interval 1,657 to 1,727 feet in Bore 3. The quality of the water is fair, being 1,320 ppm TDS and is chemically similar, but slightly less saline, than the water from the overlying lower Cretaceous aquifer. The water is also slightly acidic, the pH being 6.9.

The bore was not tested below 1,727 feet but the resistivity log shows domestic quality water of about 500 ppm TDS occurring at a depth of 2,100 feet.

Water from the *Unit II* aquifer shows considerable variation in chemical character and a gradual increase in the concentration of dissolved solids from east to west.

In Bores 1 and 5 domestic quality water of between 320 and 430 ppm TDS occurs in clean sand interspersed with minor clay and silt above 400 feet. There is a marked deterioration in quality with depth, resulting from a downward decrease in permeability. The Gingin town bore located near Gingin Brook, $\frac{1}{4}$ mile east of Bore 5, has similar aquifer characteristics, but is fresher with 200 ppm TDS. Bore 5A sunk alongside the brook a few hundred yards south of Bore 5 encountered artesian water with a hydrostatic head of 10 feet above ground level, at only 40 feet depth. The water here contains 1,070 ppm TDS with a pH of 5.6. The acidity is attributed to a high feldspar content in the sediment forming the aquifer, but appears to be a localised feature.

The water in all these bores is chemically comparable to Gingin Brook indicating it is the main source of recharge.

In Bores 2 and 3 the near surface water is also controlled by Gingin Brook. In Bore 2 water of 380 ppm TDS was intersected at 360 feet depth. Unfortunately the sample was contaminated with drilling fluid which prevents accurate chemical comparisons. Below 400 feet the water deteriorates to between 1,090 and 1,200 ppm TDS, remaining at this latter value to a depth of 2,400 feet.

In Bore 3 the water is artesian at 240 feet and has a salinity of 850 ppm TDS. There is a considerable increase in the concentration of dissolved solids below 400 feet reaching a maximum of 1,440 ppm TDS at 1,400 feet.

In this area the salinity variations within the aquifer are large enough to affect the suitability of the waters for specific purposes. Generally domestic quality water is restricted to the near surface horizons. This however, may be due to the close proximity of Gingin Brook but is probably common to the whole area owing to leakage from the Quaternary aquifer. The water below 500 feet does not reach the standard for domestic use, but is of excellent stock quality and could be used to irrigate the more salt-tolerant fodder crops.

In Bore 4 an artesian flow of small yield was encountered at a depth of 600 feet. The water salinity was 520 ppm TDS with a pH of 6.9. The salinity of the confined water gradually increases with depth to 1,050 ppm TDS at 1,750 feet.

Domestic quality water occurs throughout Bore 6, the average total salt content being about 800 ppm TDS. The best water is at 515 to 665 feet where it is 680 ppm TDS and slightly acidic. The water at 1,100 feet is 820 ppm TDS and is chemically comparable to the water at 240 feet in Bore 3. Below 1,170 feet the water becomes mildly alkaline.

Water in the Yarragadee Formation aquifers in the Gingin Brook area is chemically dissimilar to that sampled in the Bullsbrook bores where the water is generally fresher (Whincup, 1966). Here recharge is mainly from the Darling Fault zone with water moving gradually westward. Near Gingin, recharge is associated with Gingin Brook and accordingly the water may not

be representative of the underground water elsewhere in the basin. Structurally the Bullsbrook area is quite different from the Gingin area but the presence of thick aquifers of the same age is recognised. A hydraulic connection between the two areas cannot be established from available data.

Upper Cretaceous aquifer

Water in the Molecap Greensand is of domestic quality and many shallow wells east of Gingin, penetrate this aquifer. Landholders report that the water is very soft, and this is probably due to the glauconitic nature of the rocks.

Quaternary aquifer

Potable water is found in the Quaternary aquifer over the whole area west of Gingin. The average total salt content is about 700 ppm TDS often increasing markedly with depth. This is evident in Bore 4 where water salinity increases from 700 to 1,570 ppm TDS within 18 feet. At Guilderton salinities are higher than normal, ranging from 1,380 to 2,200 ppm TDS as a result of sea water contamination.

CONCLUSIONS

The exploratory drilling programme has provided important new stratigraphic and hydrological information in this part of the Perth Basin. The Upper Jurassic—Lower Cretaceous aquifer system known from Mandurah to Bullsbrook has now been seen to extend as far north as Gingin, but it may not be hydraulically connected.

Over the whole drilling area underground water is available from at least four independent superimposed aquifers. The volume of stored water available was not tested but is probably quite large due to the thickness of the sandstones forming the aquifers.

The Upper Jurassic aquifer was penetrated in Bore 3 below 1,600 feet. Domestic quality water is indicated by electric logs as occurring at 2,100 feet but water above this depth is too saline for domestic purposes.

An extensive Lower Cretaceous section was encountered in all bores. Its maximum development is in Bore 2 where it attains a thickness of 2,260 feet. Water of domestic quality is restricted to within 500 feet of the surface in the middle of the drilling area. Below this depth the water is saline but still of excellent stock quality.

In the western segment of the area the Lower Cretaceous aquifer occurs below the thick, impervious Osborne Formation. The water in this aquifer is generally of domestic quality.

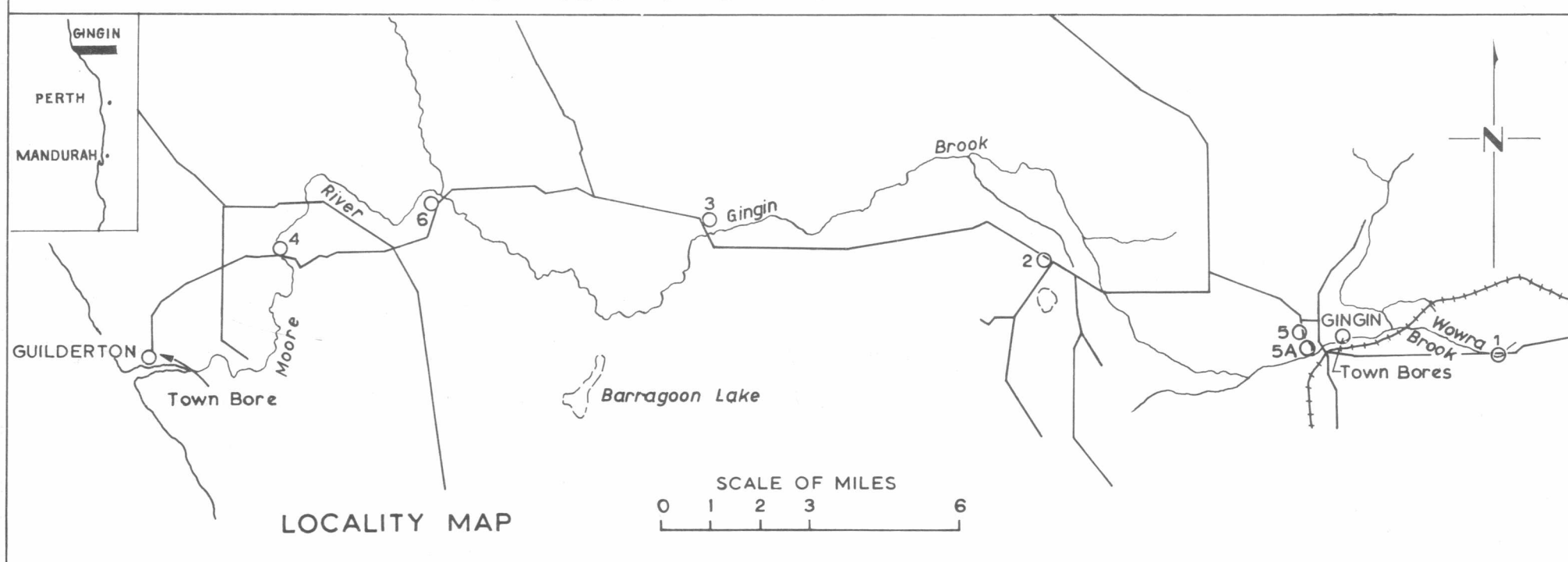
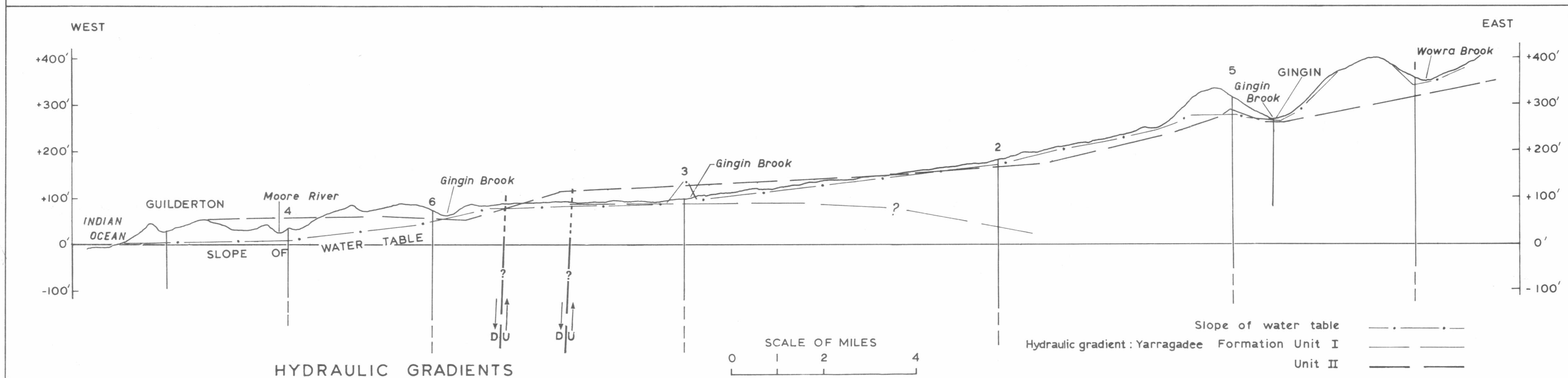
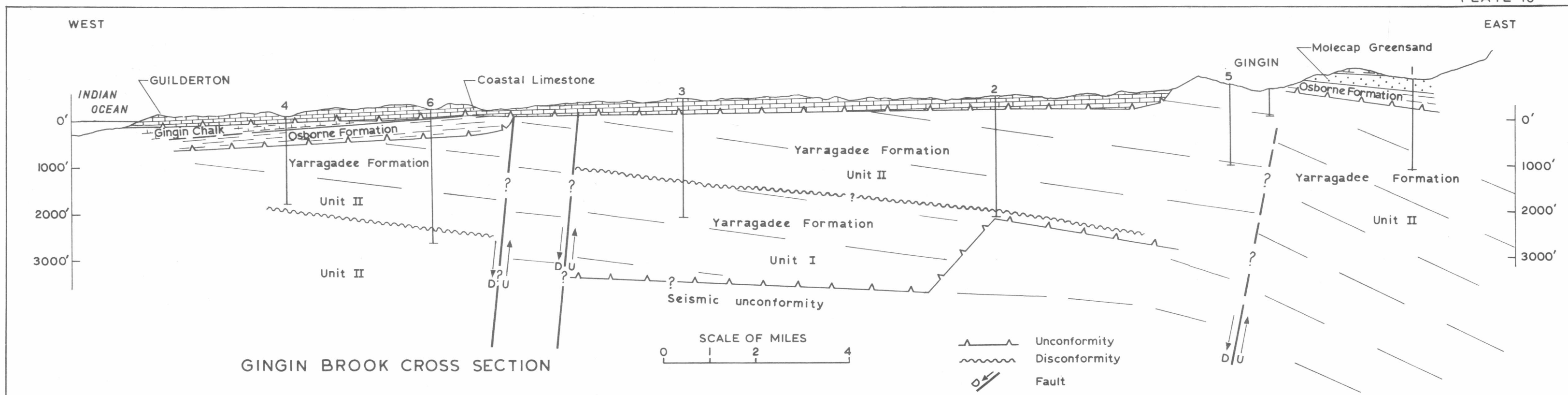
The Molecap Greensand of Upper Cretaceous age forms a thin aquifer containing potable water, in the eastern segment of the drilled area.

A shallow, unconfined Quaternary aquifer was penetrated in all bores west of Bore 5. This aquifer generally holds domestic quality water and is seen to be a northern extension of the large groundwater province at Gnangara, just north of Perth.

The water in the Yarragadee Formation aquifers in the Gingin area is not directly comparable with that from the South Perth Formation and Claremont Sandstone known from bores near Bullsbrook and Perth. The underground water in these areas is generally fresher than in the Gingin Brook bores. Structurally the areas are quite different but the presence of thick aquifers of the same age is recognised. A comprehensive drilling programme in the Muchea—Yanchep area would be required to establish hydraulic connection between Gingin and Bullsbrook.

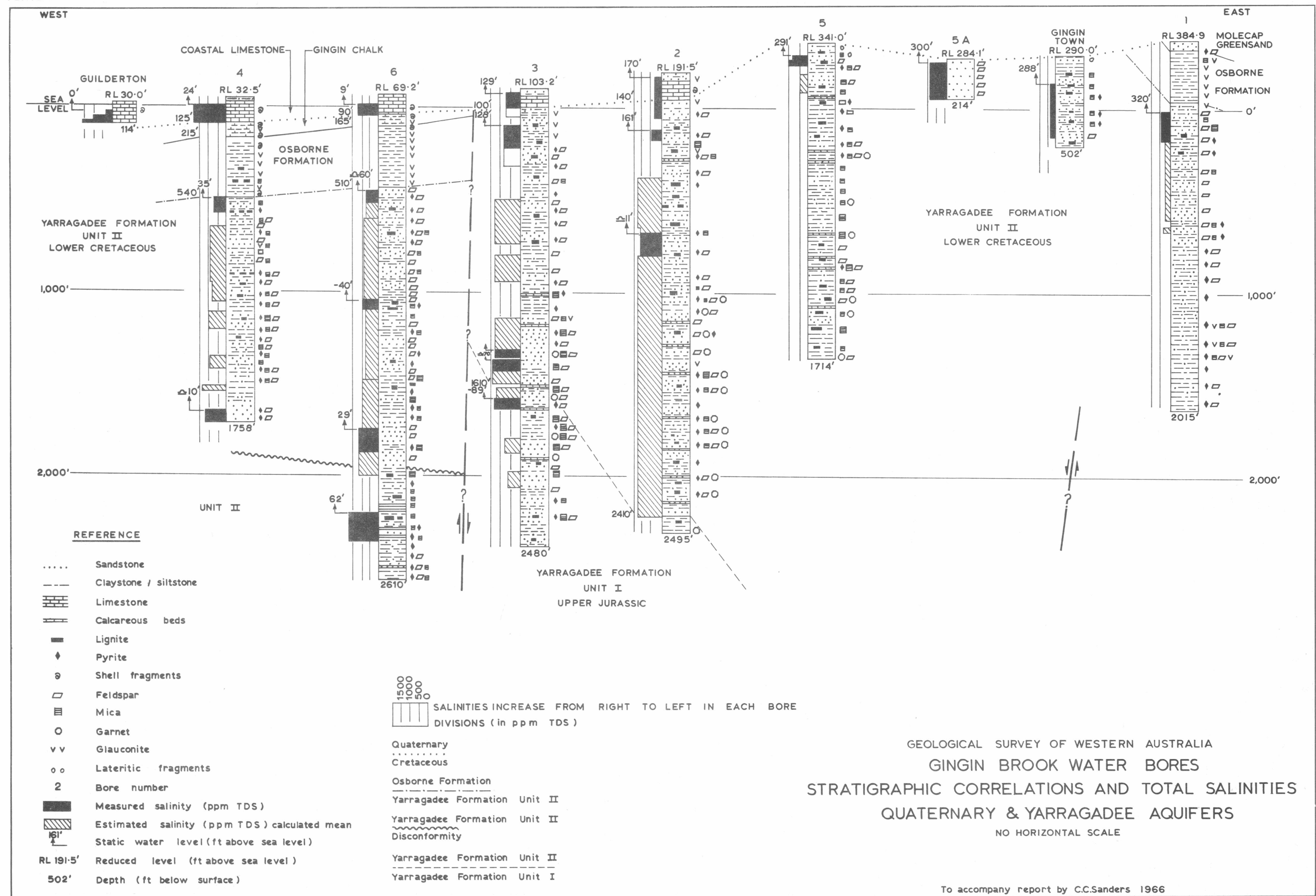
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GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GINGIN BROOK WATER BORES
LOCALITY PLAN AND SECTIONS

To accompany report by C.C.Sanders, 1966



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GEOLOGICAL RECONNAISSANCE AT MACDONALD GORGE DAM SITE, WEST KIMBERLEY

by F. R. Gordon

INTRODUCTION

The Public Works Department scheme for the regulation and development of the rivers of the West Kimberley area includes two possible dams and a diversion structure on the Margaret River, which is the most important tributary of the Fitzroy River system. Its middle reaches, extending through the Louisa Range, the Mueller Range, the Mt. Cummings Plateau, and the King Leopold Range, are largely rock bound. Many good dam sites are available and one of the best is situated in a major topographic constriction at Macdonald Gorge in the King Leopold Range, before the river debouches on to the alluvial flats and flood plains of Fitzroyland.

GEOLOGICAL SETTING

Topography

Macdonald Gorge has long been regarded as an obvious choice for a dam site because the natural barrier of the King Leopold Range is breached by a narrow steep sided rock gorge and there is a wide flat storage area immediately upstream, known as the Mt. Ball Basin.

On the left bank the walls of the gorge rise at an average slope of about 52° to 300 feet above the alluvium in the river bed. The right bank on the survey line is steeper, with an average slope of 60°, and rises immediately to about 250 feet above the river bed. It is noteworthy that on both cliffs there is a 40 foot high section of vertical or overhanging wall at the foot of the slope. Although water jetting has been done in the river bed by P.W.D. no results are available, and in view of the difficulties encountered at the Ord site, it is recommended that the bottom should be re-determined with auger drillholes.

The cliff on the north side of the gorge has been breached by a sawcut gorge (herein named Ratio Gully) up to 250 feet deep, that continues for some miles to the north in the centre of the King Leopold Range. A similar feature, but not so profound, divides the range on the southern side of the gorge.

The Mt. Ball Basin opens out immediately upstream of the King Leopold Range. It is roughly oval in shape with the river forming the shorter axis. To the east, the basin ends where subdued foot-hills appear on each side of the river. Further to the east the river runs in a gorge through another major quartzite escarpment which forms the No. 2 dam site, 4½ miles upstream from the No. 1 site.

Subdued outcrops of weathered and eroded igneous rocks of the Lamboo Complex appear through the broad composite valley plain of the Margaret and Leopold Rivers to the west of the King Leopold Range. The westerly flowing Margaret River joins the Leopold River 4 miles

west of the dam site, and the combined flow is known as the Margaret River, and continues in a southwesterly direction.

About 3 miles to the north of the gorge, there is another natural break through the King Leopold Range at Jenney's Glen. This is a possible emergency spillway site.

Rock types

The main rock types and their distribution are shown in Plate 14. The Mt. Ramsay 1:250,000 Sheet area has recently been mapped by a joint party from the Bureau of Mineral Resources and the W.A. Geological Survey (Roberts and others, 1965) and this work has provided a geological setting for the project, and given a nomenclature to the rock types. Details of the stratigraphy of the area are shown on the accompanying map.

The *alluvium* consists of mud, silt, sand, and gravel. In the creek beds and over the extensive flood plains of the Margaret River, the alluvium is generally sandy or silty. In the river bed itself, particularly in the vicinity of Macdonald Gorge, layers of mud are common and there are lenses of decaying vegetation. Probably most of the bed alluvium is renewed each year and the "permanent" pools that form in the dry season vary in size but little in position, indicating some control from bedrock structure.

The *residual soils* which reflect the variable nature of the underlying bedrock, consist of sand, soil, black soil, and some alluvium, and the major part of this material has been developed more or less *in situ*.

The *Burramundi Conglomerate* consists of rounded to subangular boulders, cobbles, and pebbles of various Precambrian rocks especially quartzite set in a matrix of sand, often ferruginized, but in many exposures the larger stones are practically touching. The formation was originally named by Guppy and others (1958) and has been included by Playford and Lowry (1966) in 'Undifferentiated Conglomerates' of uncertain Devonian—Permian age.

The *Hart Dolerite* is exposed adjacent to the King Leopold Range and in the Mt. Ball Basin where it forms low-lying partly soil covered boulder strewn areas.

The formation consists of massive, greenish black, medium to coarse-grained dolerite, usually well jointed in outcrop. The dolerite occurs as sills intrusive into the O'Donnell Formation and the Luman Siltstone (Roberts and others, 1965).

Carson Volcanics. This formation consists of green black, fine to coarse-grained, sometimes amygdaloidal basalt, which is interbedded with

thin beds of pink to mauve current-bedded feldspathic sandstone. The volcanics are not resistant to weathering and generally occupy low ground between ridges and escarpments of King Leopold Sandstone and Warton Sandstone (Roberts and others, 1965). Stratigraphically they lie conformably between these two formations.

The *King Leopold Sandstone* consists of white to pink, blocky to massive, medium to coarse-grained quartz sandstone. It is commonly current-bedded, with frequent pebble bands and ripple marks. There are minor occurrences of feldspathic sandstone. The rock is particularly resistant to weathering and forms strong steep sided ridges and cuestas.

Valentine Siltstone. This formation is normally poorly exposed and it is usually seen in valleys. The rock consists of grey to brown fissile shale and siltstone. Narrow zones of this formation crop out north of the Macdonald Gorge.

O'Donnell Formation. This formation consists of olive and brown shale, siltstone, and silty shale in the upper part, and medium to coarse-grained siliceous quartz sandstone at the base. The upper members are poorly resistant to weathering, and rounded, maroon coloured hills develop. The basal arenite is resistant to weathering and forms strong ridges.

Violet Valley Granite. This is a member of the Lamboo Complex and consists of equigranular, medium to coarse-grained biotite granite. It characteristically occurs in large exfoliating outcrops of low relief.

The *Bow River Granite* is a member of the Lamboo Complex, and consists of porphyritic and coarse-grained granites, with minor occurrences of granodiorite and aplite. The granites have little topographic expression in their exposure in the valley of the Leopold River, west of the King Leopold Range.

The *Olympio Formation* is a member of the Halls Creek Group, and consists of grey to brown thick-bedded massive quartz greywacke and feldspathic greywacke intercalated with thin-bedded siltstone, fissile shale, and carbonaceous siltstone. The topographic expression varies considerably between rounded steep hills and low rises with poor outcrop.

Faulting

The dam site is situated in a zone of severe faulting that extends from Mount Huxley in the south, to Mount Winifred in the north. The zone is about 10 miles wide, and the larger faults strike north or east of north, while another strong set has an easterly trend. North of the Margaret River there has been minor faulting with a north-easterly trend.

The various faults in the vicinity of the dam site as interpreted from air photos are shown in Plate 14. It must be emphasised that detailed mapping is needed to define the number and location of faults that trend northerly along the strike of the King Leopold Sandstone. There are several possibilities that fit the geomorphological pattern shown by photo interpretation.

The only fault apparent on a regional scale that has a direct influence on the foundation area of the dam is found in the central portion of the gorge in the King Leopold Range, striking at right angles to the Margaret River and dipping at 70° to 80° to the west. This fault, known as the Ratio Gully Fault, crosses the proposed centre line at an acute angle of about 35°, close to the foot of the cliff on the southern abutment. In the gorge there are at least 5 other visible faults parallel to the main one, and usually marginal to the major folded structures. Breccia zones are associated with some of them.

In the gorge area only one fault was noted parallel to the flow of the river. This was seen on the downstream end of the gorge on the left hand bank, where a block about 100 feet wide is separated from the main bulk of the King Leopold Range.

Folding

In the strongly faulted area of the King Leopold Range in Macdonald Gorge, large drag folds are developed on a spectacular scale.

Panoramic views of the north and south walls of the gorge in the vicinity of the survey line have been included to indicate the variety and complexity of the folding (Plate 12). Detailed mapping will be needed to clarify the problems that will have to be solved, including the best location of the centre line, and the amount of diamond drilling that will be needed to gauge the permeability of the foundation area. As a consequence of the folding and faulting some large gapes have opened up, and the extent and size of these openings are probably unique.

SITE APPRAISAL

As already noted the King Leopold Range in the vicinity of Macdonald Gorge has been divided along its length by the Ratio Gully Fault. The resulting blocks on either bank are dissimilar. The downstream block on the south abutment is not topographically as prominent as the upstream block, and large-scale block gliding and deep weathering mean that this downstream block is not desirable as a foundation area.

On the northern abutment, the downstream block is topographically the stronger, while the upstream block is subdued. Although all the major faulting and folding has been confined to the downstream block, the upstream block is not a suitable foundation area for a dam because of lack of relief and breaching of the reservoir rim to the north.

This means that the preferred centre line will cross the Ratio Gully Fault at an acute angle. It also means that many of the folded structures, which appear to trend parallel to the fault, will not cross the centre line. Folded quartzite beds will occur in the foundation area of the dam, and in view of the tightness of the folding and the distance apart of the walls of the gorge (approximately 360 feet), correlations from wall to wall will be almost impossible to make. Diamond drilling of the river bed will need to be on an intensive scale but it is doubtful if the full pattern will be revealed until the foundation area is excavated. The structure of the rock in the river bed will have a dominating influence on the topography of the bedrock, and some highly irregular patterns may be expected, requiring the excavation of deep fissures and the large scale use of dental concrete. Filling of the gapes opened in the folds to prevent consolidation of the rock under load and to seal off leakage paths, will need a programme of curtain and blanket grouting.

The vertical walls in the lower part of the gorge almost certainly extend below the alluvium in the river bed. This situation is ideal for the construction of a concrete dam, but imposes certain difficulties on the construction of the clay core of a rockfill dam.

The topographic saddle at Jenney's Glen was not visited. From air-photo interpretation it appears that erosion after faulting oblique to the range has exposed a tongue of Hart Dolerite through the King Leopold Range.

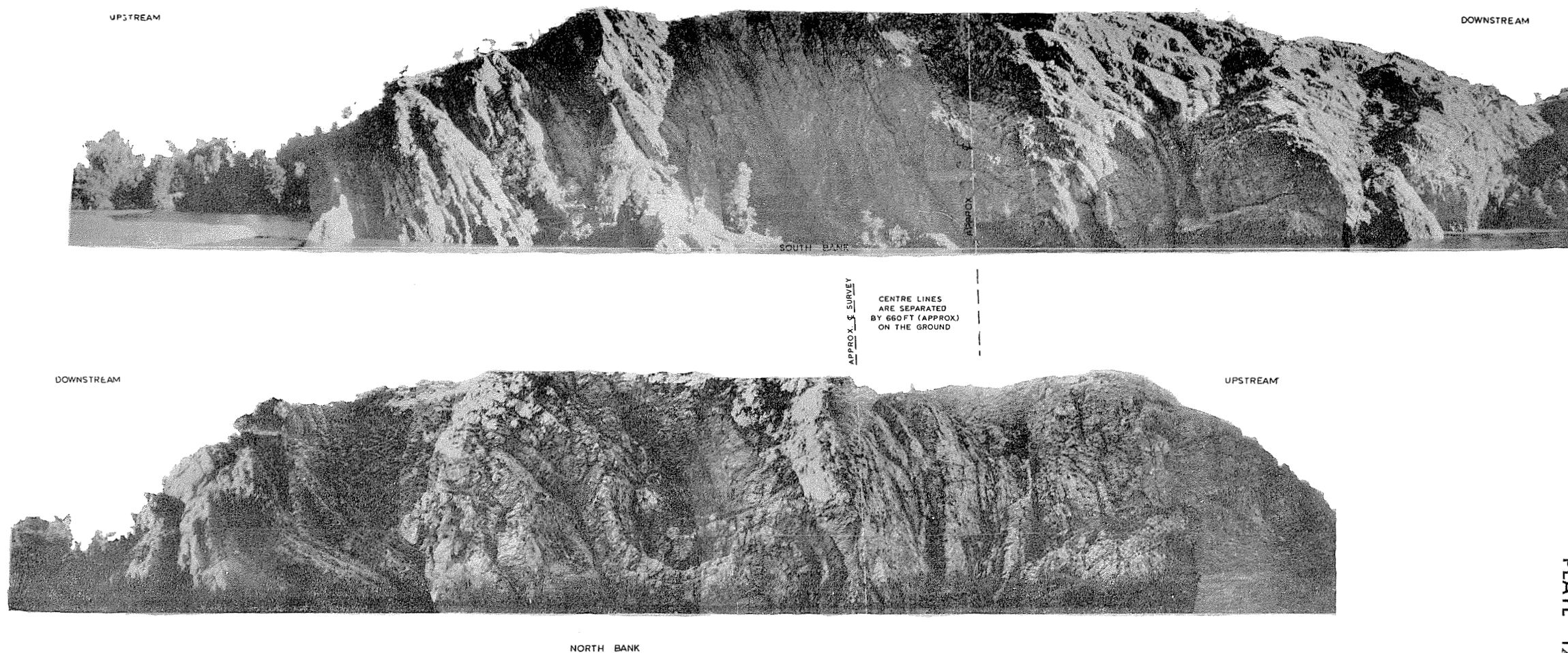
CONSTRUCTION MATERIALS

All the rock necessary to build a rock fill dam is immediately available on the site. However material for the clay core will involve considerable proving and testing. A possible source is on the south side of the Mt. Ball Basin where the following sequence is seen in the rapidly eroding creek beds:

- 0- 4 feet, recent silt and soil
- 4-14 feet, reddish loam
- 14-24 feet, horizontally bedded gravel
- 24-30 feet, calcareous cemented gravel.

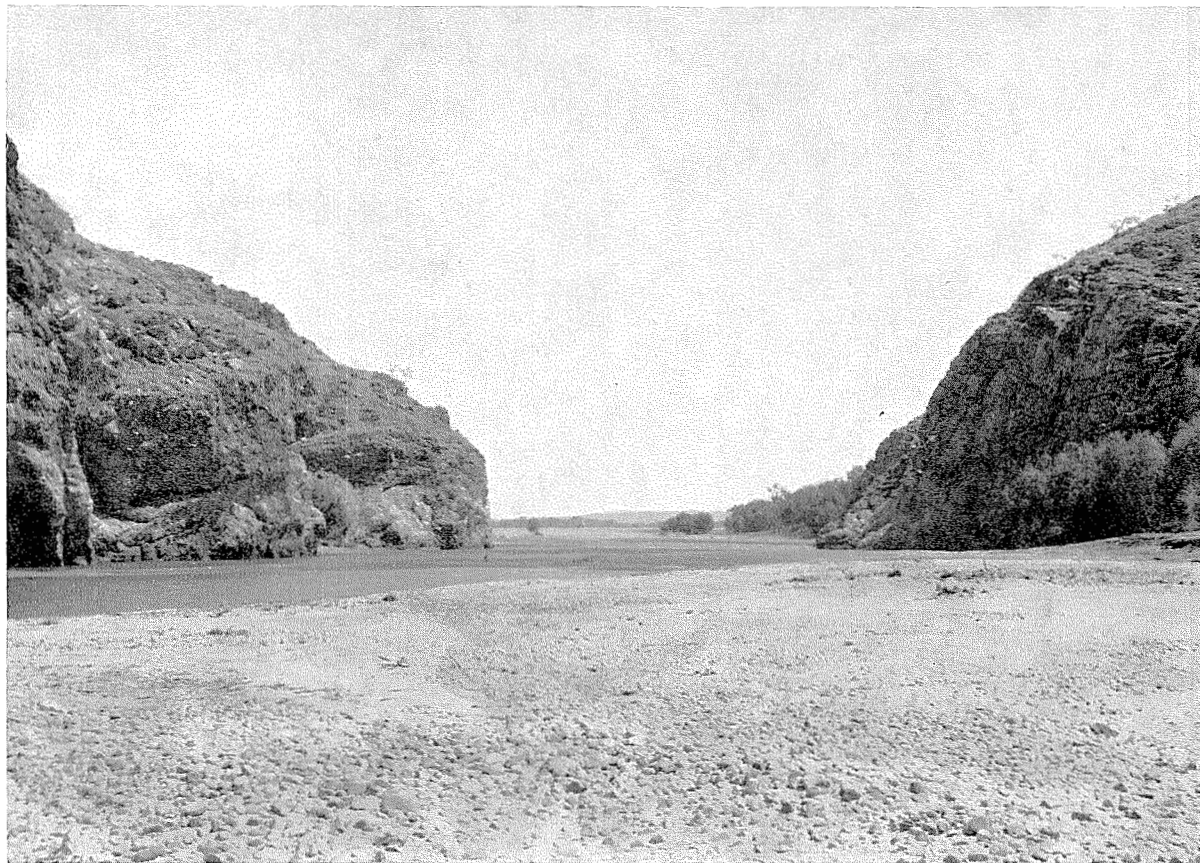
The 10 foot thick, old, reddish loamy soil is a possible clay core material.

The gravels of the Margaret River have a considerable component of chalcedony, derived by alteration of the bedded limestone of the Lawford Beds. If the agate and chalcedony



MACDONALD GORGE DAM SITE—PANORAMIC VIEWS OF NORTH AND SOUTH BANKS (F1148)

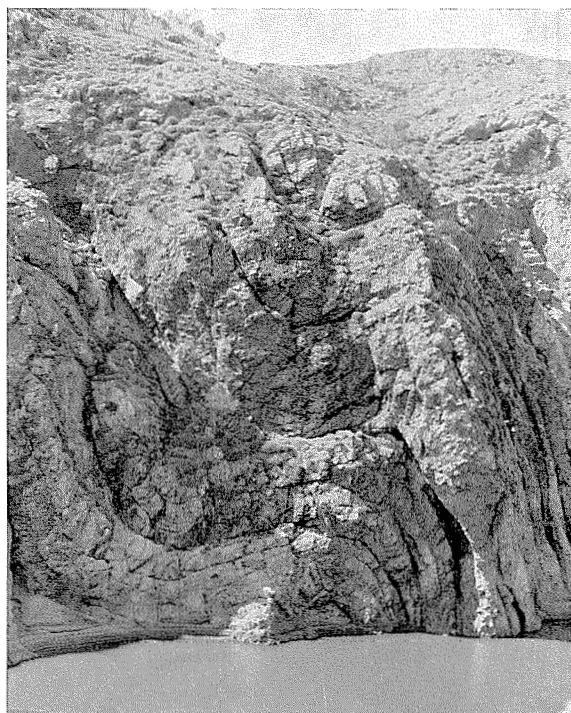
PLATE 13



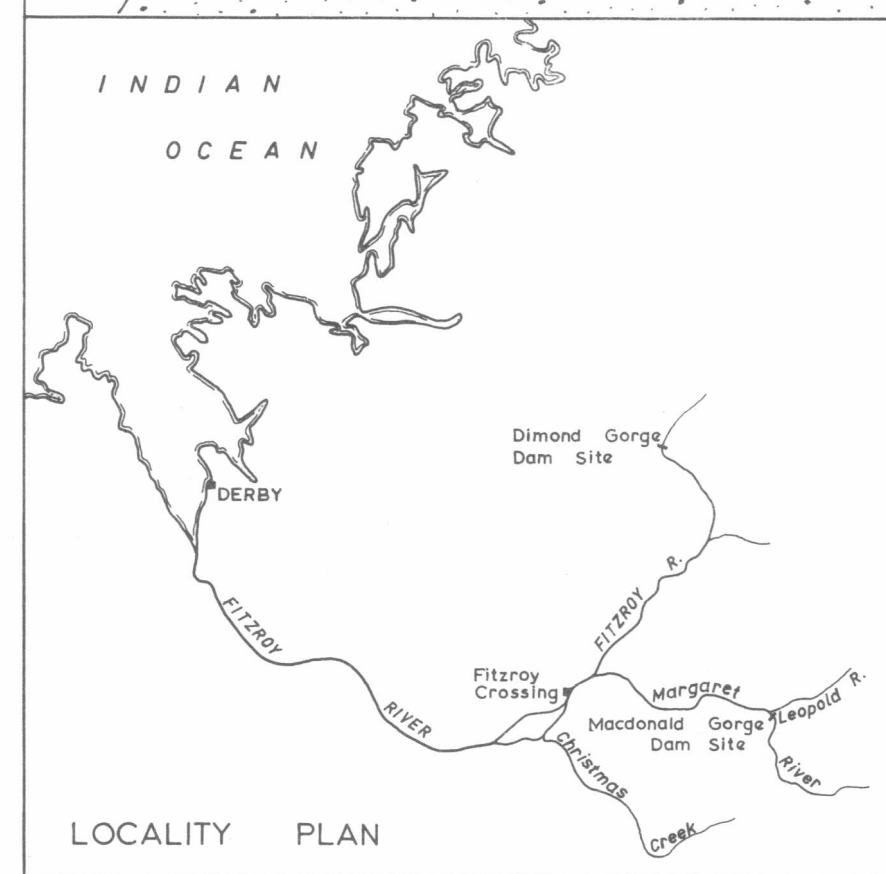
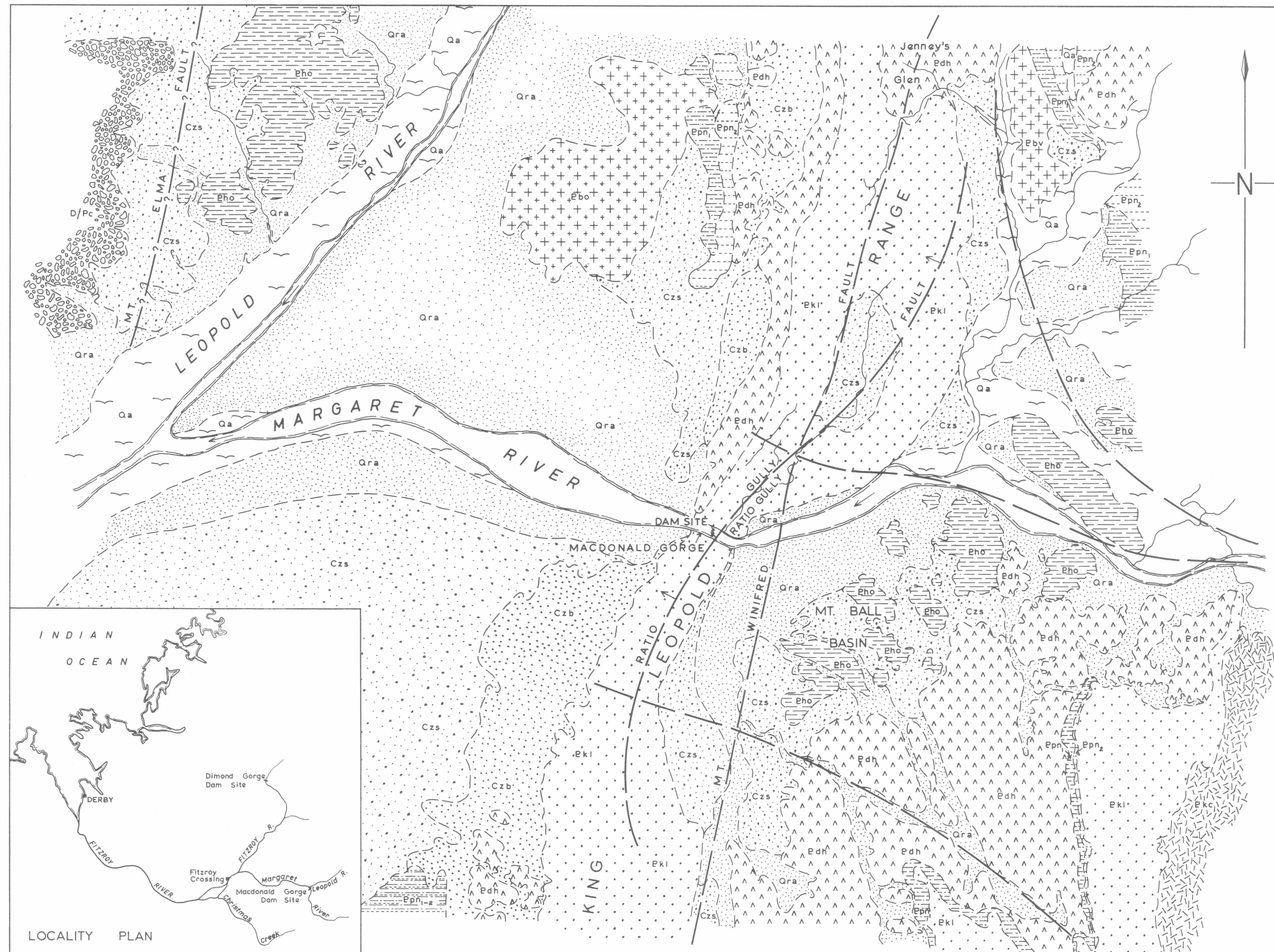
A—Macdonald Gorge looking west. Dam centre line crosses gorge in immediate foreground. Ratio Gully Fault crosses from lower right to near tree filled embayment, left centre ; F 1142.



B—Folding in King Leopold Sandstone immediately upstream of centre line on right abutment ; F 1146.



C—Folding showing well developed gapes immediately upstream of centre line, left abutment ; F 1147.



REFERENCE

CAINOZOIC	QUATERNARY		Qa	Alluvium
	UNDIFFERENTIATED		Qra	Sand
PALAEOZOIC	PERMIAN ? DEVONIAN ?	BURRAMUNDI CONGLOMERATE	D/Pc	Boulder, cobble and pebble conglomerate
		HART DOLERITE	Edh	Green black, medium to coarse-grained dolerite
	UPPER PROTEROZOIC	CARSON VOLCANICS	Ekc	Green black basalt, amygdaloidal basalt, minor sandstone and siltstone
		KING LEOPOLD SANDSTONE	Ekl	White, medium to coarse-grained quartz sandstone, pebble conglomerate
		VALENTINE SILTSTONE	Pbn	Purple grey and brown, fissile, fully laminated shale and siltstone
		O'DONNELL FORMATION	Ppn2	Olive green to fawn micaceous silty shale, coarse quartz sandstone base
		LOWER PROTEROZOIC (UNDIFFERENTIATED)	LAMBOO COMPLEX	
	VIOLET VALLEY GRANITE		Pbv	Equigranular, medium to coarse-grained tonalite
	BOW RIVER GRANITE		Pbo+	Porphyritic granite, coarse-grained granite, granodiorite, aplite
		HALLS CREEK GROUP		
	OLYMPIO FORMATION	Pho	Quartz greywacke, feldspathic greywacke, siltstone, shale, carbonaceous siltstone	

SYMBOLS

	Geological boundary position approximate
	Fault
	Anticline
	Syncline
	Dip and strike of strata
	Trial line of dam site

SCALE OF MILES

1 3/4 1/2 1/4 0 1 2

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

MACDONALD GORGE DAM SITE

MARGARET RIVER

GEOLOGICAL PLAN

To accompany report by F.R.Gordon

laden gravels of the Ord River are not considered deleterious for use in concrete, it would be presumptuous to condemn the Margaret River gravels.

Dimension stone is readily obtainable from the massive beds of the King Leopold Sandstone.

INVESTIGATION PROGRAMME

An extensive investigation programme will be necessary to bring the Macdonald Gorge dam site from the reconnaissance stage through the feasibility stage to the commencement of design.

(1) Survey. It is recommended that the gorge area be surveyed and mapped by phototheodolite.

(2) Geological mapping is intimately bound up with the mapping of the gorge walls by phototheodolite. A scale of 50 feet to the inch is suggested for all work in the vicinity of the dam site.

(3) Probing by Gemco drill, at 10 foot centres, of the possible foundation area in the river bed, is considered necessary.

(4) On the results of the geological mapping and the bedrock profile as revealed by drilling, a diamond drilling programme can be designed. It will necessarily be extensive.

(5) Sources of construction material should be confirmed or investigated.

On the basis of this programme the type of dam may be selected and the final centre line established.

CONCLUSIONS

1. Although the dam site at Macdonald Gorge has several of the attributes of an excellent location for a dam, the geological structure of the foundation rocks is complex because of intensive faulting and drag folding.

2. The dam site on the Margaret River may be compared with the Dimond Gorge dam site on the Fitzroy River which has also been investi-

gated in the reconnaissance stage. Because of its simpler geological structure, the Dimond Gorge dam would be a much more economic proposition to investigate and construct.

3. An extensive programme of investigation has been outlined for the Macdonald Gorge site. The 'unknowns' are far too numerous and weighty to allow a firm choice of type of dam or centre line at this stage.

4. Further investigation of the possible spillway area at Jenney's Glen will be necessary.

5. It is recommended that detailed surveying of the gorge should be done by phototheodolite. Other similar sites such as Dimond Gorge could be included in this programme.

6. The dam site has obvious merit in the small cross section of the gorge that will need to be dammed. There is a reasonably large upstream storage basin, and the site itself is geographically the closest of the main dam sites to the proposed irrigation areas.

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REVIEW OF A QUARRYING OPERATION AT MERREDIN, STANDARD GAUGE RAIL PROJECT

by F. R. Gordon

INTRODUCTION

The Standard Gauge Railway between Northam and Kalgoorlie traverses part of the great inland plateau. The rock series with the exception of some laterite is probably of Precambrian age, and represents highly folded ancient sediments, pyroclastics, lava flows, and basic intrusives, which have been invaded by granitic magmas. The folded remnants of the intruded rocks form a slight topographic relief, generally as north-northwesterly directed ridges. Most of these low rounded ridges are of greenstone, while the shrub covered country and sandplain overlie areas of granite gneiss. The most conspicuous topographic features of the area are numerous large bare granite masses known as 'rocks' and are regarded as bosses of granite intruded into the gneiss complex.

Between Northam and Southern Cross these rocks are practically the only source of ballast (Gordon, 1964).

BALLAST REQUIREMENTS

The physical requirements for stone used for ballast have been established through empirical observations, and little is known concerning the exact relationship of the specification tests employed and conditions in the rail bed. The

desired properties have been detailed in connection with previous contract sections (Gordon, 1964, 1965). In summary the rock

1. must be particularly resistant to impact
2. must have a high abrasion resistance
3. must not break down under traffic, but must not be too strong for efficient crushing
4. must have good mechanical interlock
5. must not deteriorate rapidly because of weathering. The basic properties of a rock that influence its usefulness include resistance to weathering, hardness, toughness, cleavage, density, composition, porosity, and structure.

The shape and size of the ballast pieces as produced from the treatment plant are also important. The usual tests to determine the suitability of a stone for ballast are those for soundness, resistance to abrasion, specific gravity, particle shape and fractures, soft particles, and gradation. However, a specification for ballast usually only specifies a grading and a maximum loss in a Los Angeles abrasion test, and beyond a general correlation between low L.A. loss and sound performance as a ballast, little is known of the ultimate performance of rock closely specified by L.A. results.

A particular source of ballast must be further evaluated in terms of its potential as a working quarry.

1. The deposit should be close, say within 2 miles, of existing or proposed railway lines.
2. The extent and depth must be assessed in order to give a probable yield, which must be considerably more than the ballast quantity.
3. The physical properties of the rock must be evaluated with regard to wastage, excessive fines, ease of breakage by explosives, and by crushing plant.
4. There must be easy access and the possibility of a good plant layout.

SITE SELECTION AND TESTING

The contractors proposed to work only from an abandoned Australian Blue Metals—Railway quarry $1\frac{1}{2}$ miles south of the town of Merredin (Plate 15). This quarry had not been considered in the reconnaissance survey, and the consultants to the Western Australian Government Railways, Maunsell & Partners, were not convinced that it would supply ballast capable of meeting the specification. Further tests were initiated jointly by the contractor and the consultants with the aid of the Mines Department. The rock from the abandoned quarry was compared geologically with a much finer-grained granite, theoretically preferable, that came from an outcrop near the Merredin Rifle Range. The latter had been favourably commented upon in the reconnaissance report. Both field and petrological examinations showed that granulation of large quartz grains in the coarse-grained granite was responsible for excessive breakage in the quarry and in L.A. tests. In the finer-grained rock the breakage was partially controlled by the feldspar component which was in a matrix and not concentrated in large match-box-shaped laths.

Further surveys were made of the abandoned quarry and of the existing A.B.M. quarry, $2\frac{1}{2}$ miles north of Merredin. In both places the quarry floors were covered with a thick mantle of sand, and there were large piles of reject fines close to the crusher site. The rock in the abandoned quarry was coarser in grain size than in the working quarry. Samples from old stock piles and from current production runs showed L.A. losses of 43 to 54. Both quarries were at the point of maximum face height working into the hill, and thus further work in both would result in an increase in the proportion of weathered rock from sheeted areas near the surface. In the abandoned quarry from $1/3$ rd to $1/5$ th of the face consisted of weathered rock. Undoubtedly this was the reason for the Railway Commission relinquishing the lease. Several piles of oversize rocks in the quarry were sampled and tested by the contractor giving an L.A. loss of 22, but this low figure was not considered representative of the quarry material.

These considerations favoured a shift of emphasis to the Rifle Range site, 2 miles east of Merredin, and $\frac{1}{2}$ mile north of the Standard Gauge Railway line. The outcrop, oval in shape, is elongated in a northeasterly direction; the major axis is 2,600 yards and the minor axis 600 yards. The rock is a fine to medium-grained granite, with coarse pegmatitic and porphyritic segregations, with lenses of fine-grained basic rock. No joint sets are apparent apart from sheet joints which are well developed. The geology of the outcrop is obscured by surface weathering and a thin skin of limonite weathering. There is a certain amount of loose rock from the remnants of sheet jointed seams and to the west the outcrop is obscured by high-level sand. Some small depressions on the rock surface are occupied by clay and sand, and these are often the result of deeper weathering because of the incidence of joints or of a more schistose rock type.

In order to further investigate the site, and at the request of the consultants, five diamond drillholes were put down by the Mines Department at sites jointly agreed upon by the consultants, the contractor, and the Mines Department. No site supervision of the drilling was

exercised by the Geological Survey, but the cores on arrival in Perth were logged geologically and were photographed. The following subdivisions were employed:

1. granite, fine-grained, and aplite
2. granite, medium-grained
3. granite, coarse-grained
4. pegmatite
5. basic lenses.

It was found in practice that there was considerable overlap between the divisions, in particular, medium and coarse-grained types often co-existed in alternating bands up to 1 inch thick.

The outstanding feature of the physical condition of the cores was the almost complete lack of joints other than sheet joints parallel to the ground surface. Chemical weathering was governed by the sheet joints and in general the top 5 feet of core was stained with limonite. Over this depth, the sheet joints had an incidence of one every foot, whereas for the remainder of the hole the incidence became progressively less. The average distance between sheet joints for the complete hole was 3 feet 6 inches. The length of each stick of core was recorded on the logs, as this was an index of the cohesion and strength of the rock, and the comparatively long core pieces recovered also showed the effective sheet joint spacing. The only information available from the driller indicated 'easy drilling' for all holes.

Apart from fairly wide variations in the grain sizes, the rock types also showed considerable changes in each hole. However the boundaries were not structural weaknesses and the fine-grained basic lenses especially were considered advantageous.

The cores were split, which meant breaking firstly into pieces of less than 4 inches. One half of the split sample was retained in core boxes for record purposes. The other portion was divided into the same classes as shown on the logs, but every alternate piece of core was placed in a bulk sample. This bulk sample which constituted one quarter of the total core, was crushed and given an L.A. test, as were any of the class samples of sufficient size to make up a test. The smaller sized class samples for various bores were grouped together to make test samples. Table 1 gives details of the various test results. It is notable that all the samples except the pegmatite gave acceptable test results. However there seems to be little particular virtue in an L.A. of 39.5 as compared with a figure of 40.8; the difference can barely be called significant.

Table 1
LOS ANGELES ABRASION TEST RESULTS

Location	Length	Class of Sample	Grain Size %			L.A. Result
			Fine	Medium	Coarse	
DH33	49	Composite $\frac{1}{2}$ core	43	40	13	35.0
DH32	50	Composite $\frac{1}{2}$ core	42	26	10	38.5
DH31	30	Composite $\frac{1}{2}$ core	17	68	15	35.0
DH30	30	Composite $\frac{1}{2}$ core	16	66	17	39.5
DH31, 32, 33	....	Pegmatite	....	....	....	40.8
DH30, 31, 32	....	Medium-coarse	....	....	....	38.0
Average of $\frac{1}{2}$ core samples						37.8

Apart from the pegmatite result, there is little significant correlation between grain size and Los Angeles abrasion loss from these figures. The other obvious cause of weakening of the rock fabric is breakdown by physical and chemical weathering because of the incidence of sheet joints. In order to evaluate this fully, the core for the top 5 to 10 feet of each hole would have to be discarded before analysis.

From the cores, the following average composition of the quarry rock has been calculated :

	%
fine-grained granite....	28
medium-grained granite	41
coarse-grained granite	11
pegmatite	4
basic lenses	16
	100

At the conclusion of the testing programme there was a general agreement that the Rifle Range quarry offered the best prospects of obtaining stone to conform to the specification. In spite of the wide variations of rock type, the reasonably good L.A. test results, the predominance of medium and fine-grained classes of rock, and the restriction of weathering to the top five of 50 feet, were decisive. It was considered that an L.A. of about 40 would be obtained on actual working.

PLANT AND OPERATION

Crushing Plant

The flow sheet for the quarry is detailed in Plate 16. The layout is conventional and efficient under normal circumstances. The primary, a jaw crusher (36 inches x 42 inches), is set for a 6 inch opening and is fed at $\frac{3}{4}$ choke. There are two secondary cone crushers, Symons and TY, set at 1 $\frac{1}{2}$ inches, and the product is then conveyed to vibrating screens. The +2 inch rock is returned to the Symons cone crusher, and this fraction is about 10 to 15 % of discharge from the cones. There are two screens of 2 $\frac{1}{4}$ inches and 2 inches in the upper screen, and $\frac{3}{4}$ inch, $\frac{1}{2}$ inch and $\frac{3}{8}$ inch in the lower screen. The ballast product, -2 inches + $\frac{3}{8}$ inch is conveyed to the stock pile, the - $\frac{3}{8}$ inch is conveyed to the reject pile, and these fines make up to 30% of the input.

QUARRY APPRAISAL

Quarry

The thickness of the layer of weathered rock has decreased as the height of the face increased, as the quarry moved into the granite hill. With the face height at 20 feet, from 10 to 15 feet of sheeted, weathered rock was exposed. At the present face height of 50 feet, about 5 to 8 feet of rock has been affected by weathering. There are two areas of deeper weathering, and in both cases vertical jointing is associated with minor shearing. These areas can be readily followed on the ground surface as depressions in the rock. On the basis that the strongest rock is topographically most prominent, it appears desirable that the quarry face should follow the highest part of the rock ridge which is exposed continuously. However, nothing is known of the nature of the rock hidden under a sand cover to the west which may be indicative of a change of rock type, and as the 'rock' outcrops are generally asymmetric having a steeper face on the west side, quarrying in this direction is not recommended.

It is doubtful that an expensive quarrying operation in the removal of the top 5 feet of weathered rock would have improved the product significantly, as it is of interest to note that the L.A. losses have been fairly consistent regardless of the extent of weathered rock found in the working face at the time.

Examination of the rock pile shows that the blast hole layout is efficient, producing a reasonable balance between oversize and rock acceptable by the primary crusher. It is considered that the sand lying on the quarry floor has been produced immediately adjacent to the blasthole, rather than from general breakdown from grinding of rocks moving during blasting. There is a zone of shattered rock surrounding each blasthole, with granulation to sand size for 6 inches, and general shattering and breakage for 1 to 3 feet. This means that blasting destroys 13% of the rock in the mass of each paddock fired. Not all of this amount is left as fines on the

quarry floor : much of the outer shattered zone will be loaded and processed. If we assume one quarter of the shattered zone produces sand left in the quarry, then about 10% of the throughput is already in a form to produce reject fines. As the total waste is about 30%, crushing and movement in the plant must subsequently produce 20% fines.

Granulation of the rock round the blasthole is indicative of localization of intense shock waves caused by a high explosive. A slow-acting explosive would not normally produce such shattering, but it may not produce adequate rock breakage either. It is possible that the hole diameter is too small for the type of explosive in use on this particular quarry rock and this is a matter on which further study may be warranted.

It is considered that further investigation should be done on the nature of the breakdown of the quartz grains during blasting and crushing. At present, a piece of rock is processed by (1) blasting from the face, (2) loading and dumping, (3) passage through a jaw crusher, (4) passage through a cone crusher, and (5) 10 to 15% has a further pass through a cone crusher. It is possible that progressive comminution affects the crystal fabric of the rock, and after repeated assaults the quartz grains finally give way. Alternatively this breakdown could be effective from the very beginning of quarrying, and in fact is an inherent rock weakness. In addition to the initial petrological examination further petrological examination has been commenced to determine the state of the quartz grains in rock of the following categories :

1. fresh unbroken quarry rock
2. rock blasted from the face
3. rock that has passed through the jaw crusher
4. rock that has passed the TY cone
5. rock returned from the Symons cone
6. screened ballast (+ $\frac{1}{4}$, -2 inch)
7. reject fines from stock pile
8. shattered rock adjacent to blast hole.

This enquiry may be of value to contractors in any future quarry work in similar rock between Northam and Kalgoorlie as it may indicate that a change of crusher type and a reduction in the number of steps in the crushing circuit would minimise the production of excessive reject fines.

Much of the quarry run material is tabular in shape ; this is a consequence of the sheet joints that appear to have a spacing of from 2 to 4 feet in the sub-surface zone. The incidence seems to be higher than was apparent from the drillholes and it is suspected that a certain amount of opening up has occurred from blasting vibrations, and also possibly from rebound or stress relief on the removal of adjacent rock. The fact that sheet joint spacing is 2 feet in the side walls and 5 feet in the main face appears to be a consequence of the shape of the rock outcrop.

A noteworthy feature is that the rocks left for secondary blasting are almost entirely of homogeneous fine-grained granite.

Cracking, where developed in the face or on the sides of blocks, is quite irregular and the breaks appear to take a preferred path through quartz segregations rather than a direct path. This suggests the action of a rather slow-acting shock wave from the explosion, as distinguished from the fast-acting, intense shock that is apparently confined to the area round the drillhole.

Crushing plant

Abrasive wear of the plant is considerable, and loader tracks, the secondary crusher wearing surfaces, and jaws of the primary all need repair before their normal span. This is caused by the abrasive action of the broken quartz grains, and this could be partly remedied by removal of fines from the circuit. The obvious solution would be to place a vibrating grizzly ahead of the primary crusher and to take the fines direct to the secondary. Another, but possibly less effective, scheme

would be the use of a vibrating screen in front of the cone crushers with the rejection of $\frac{3}{4}$ inch fines, or a separation of + and -2 inch material.

At one time notable layering of the product stockpile was apparent and there were horizontal zones of fines, smaller than the specification limits. This was related to the initial crushing and also to some extent by the movement in the pile by rubber tyred loaders pushing the product about with an action akin to auto-genous grinding. This stone was re-screened to remove the excessive fines. Also the rubber tyred loaders were taken off the pile and were required to work from the sides, though it is noted that the segregation in a conical pile is automatic. Satisfactory grading of the product can be achieved by working the plant from the sides of the stockpile so that re-mixing occurs during loading.

The fines contained in the reject pile may have a future value as cement sand and for roadworks, though screening costs may make it uneconomical because local supplies are being met by A.B.M.

Results achieved

The results achieved, counted in terms of obtaining acceptable L.A. test results, have been marginal. Prior to the development of a full face, the proportion of sheeted and weathered rock in the throughput was high, and a similar situation would develop if the quarry face was advanced into lower ground. This fact then has meant a gradual improvement because of a higher proportion of good rock.

Because concern was felt as to the available quantity of rock, the quarry floor was dropped 5 feet. Although creating a drainage problem, this increased the quantity of rock available and decreased the proportion of weathered rock.

The recent recognition of vertically jointed and weathered granite in one area of the quarry has meant that selective mining has been possible, and this has assisted in raising the class of stone delivered to the crusher, although it is of interest that the average L.A. results remained practically unchanged.

The layout of the exploratory diamond drill-holes was confined to areas where the full quarry face was to be developed and no holes were drilled in the entry and development section, where the face was less than 30 feet high, so that the weathering depths measured from the drillholes were far less than the thickness of sheeted and weathered rock found lower on the slopes.

In the initial opening of the quarry a considerable proportion of the stone was used in establishing all-weather haul roads and a ramp with turning area to the primary crusher. In this phase, rock as passed through the plant was screened again due to excessive fines in the stockpile.

The L.A. test results obtained from core samples, while representative of the rock types, did not show the full effect of the quarrying and crushing operation. The cores were split, crushed, and screened for the test, whereas quarry rock is blasted from the face, and reduced 2 or 3 times before reaching the desired size. The test results were not misleading as an allowance must be made for the differences in treatment. The average L.A. value obtained from the quarry throughout its working life has been 43.2 with little variation on this value. This means that the exploratory average of 37.8 has to be increased by about 5% or 6% in order to correlate the laboratory test results with tests made on production runs.

It has taken some time for the quarry routine to settle down, and for the present blasting pattern to be evolved. It is not considered that much improvement would be achieved in this regard; possibly some slowing in the speed of the explosion could give less pulverization of face rock or possibly this could be achieved by altering the size of drillhole.

In the crushing plant experiment has been necessary to get the most effect from the crushing machines. In general it has been found that

improved results were achieved by reducing the opening of the primary crusher and increasing the opening of the secondary. The screens have also been adjusted, and an improvement has resulted. The fact that a wrong shape of plate was found on the jaws of the primary crusher did not assist the contractor in maximum production and has contributed to the waste fines in the reject pile.

It would be fair comment to say that the quarry was never highly regarded, it simply was considered the best available source of rock in the area.

CONCLUSIONS AND RECOMMENDATIONS

The experience of investigation and working the quarry may be applicable to the investigation and working of other quarries of similar material.

1. The preliminary investigations at the quarry site were valid in that the site is still considered the best available. Under optimum operating conditions the quarry produces ballast barely meeting the L.A. loss requirement of the specification.

2. A figure of about 5% or 6% has to be added to the L.A. results obtained from borehole material to bring them to figures from production runs. Under normal conditions it appears that the L.A. of samples blasted from the weathered outcrop may give an indication of the L.A. value expected from the production stockpile by decreasing the value by about 2% or 3%.

3. The early results obtained from the quarry were not good. Blasthole pattern, the size of crusher openings, and screen sizes are all important variables that did not achieve optimum working efficiency until after a few month's production.

4. The high ratio of weathered to unweathered rock that exists on the lower slopes of the granite 'rocks' was not discernible from the limited number of drillholes, which, to obtain maximum information, were drilled in positions of maximum face height.

5. A quarry face of 15 to 20 feet was developed before the operation of the crusher, and the stone was used for various construction purposes. The inherent defects in the quartz have still not been fully assessed and even an increase in height of the quarry face has not resulted in better L.A. figures.

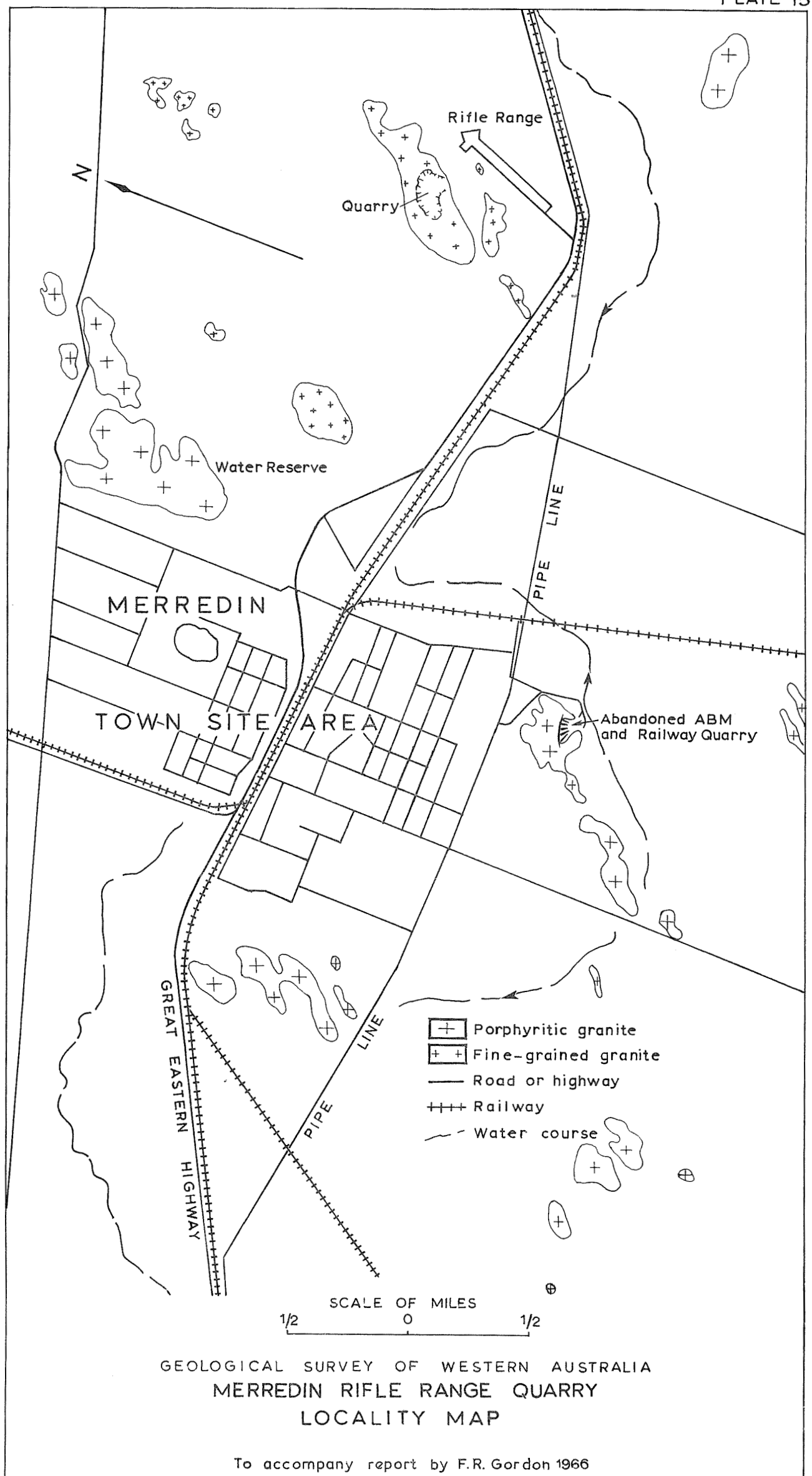
6. The height of the face of the working quarry will decrease as work proceeds southeasterly down the spine of the outcrop, and it is considered that a further cut into the quarry floor should be considered, in order to maintain the present ratio between weathered and unweathered rock.

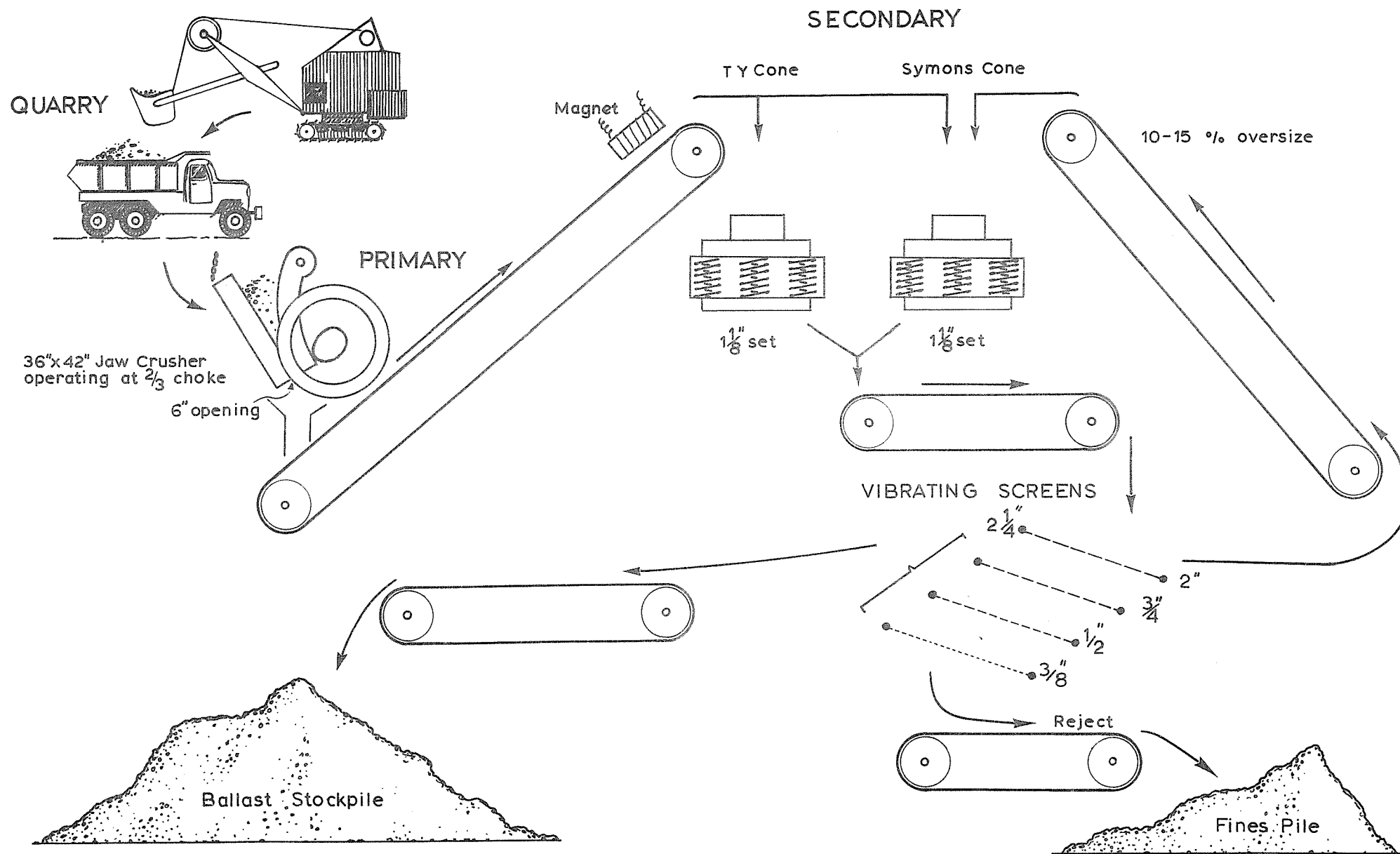
7. For any granite quarry in the area between Northam and Kalgoorlie, one of the prime considerations should be to secure a working face at least 50 feet high, by going below ground level if possible. Work in side hill locations should be avoided and development concentrated in the topographically highest part of the 'rock,' if this does not seriously affect the quantity of stone available and make the operation expensive.

8. Provision of a vibrating grizzly in front of the primary crusher, and the provision of shaking screens before the secondary cone crushers, could possibly reduce abrasion of moving parts by removing a large proportion of quartz grit from the feed.

9. Experimentation by the contractor in a variation of the type of explosive or in the sequence of firing a blast may reduce the amount of fines produced and may be worth following up, although this may also increase the amount of secondary blasting required.

10. Petrological work has been initiated to discover the nature of the breakdown of the quartz grains. At present it is suspected that breakdown is not a cumulative process but occurs when coarse-grained crystal masses are





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MERREDIN RIFLE RANGE QUARRY
FLOW SHEET

oriented to give a favourable path for fracturing or cracking at any of the various stages of the production process.

11. There is undoubtedly scope for a lot of research on the investigation of quarry sites.

Perhaps a longer tender period should be allowed, for the tenderers to make a more thorough investigation of this important and costly aspect of the contract.

Diamond drilling is one of the most useful tools and possibly large size cores could be obtained for L.A. tests that would enable 2 or 3 passes through a crushing circuit, but diamond drill bits producing core in excess of 3½ inches diameter are not normally available.

12. In the quarry operation the following items have been altered or adjusted: (i) the proportion of weathered rock has decreased; (ii) the screen size has been changed to allow a wider grading; (iii) the convexity of the crusher jaws has been varied; (iv) the opening of the primary has been decreased and the opening of the secondary increased; (v) the spacing, layout, and loading of the blastholes has been altered.

All these variables have been altered in a manner which should have given a better L.A. result, but this has not eventuated. Either some of the variables worked in the wrong direction, or an unknown factor such as rock type has adversely influenced results.

13. It is possible that blasting has an effect on the quarry rock akin to moderate weathering.

14. The problem of accurate prediction of L.A. results from initial investigations may have to await further advances in rock mechanics. Uniaxial compression tests may be of use as there is certainly a correlation between compressive strength and drillability and ease of drilling is surely an index of the toughness and cohesion of a rock. Conversely measurement of speed of drilling could be of value, especially if a body of information is built up. The Rifle Range quarry granite drills at 2.05 feet per hour.

15. For the granite 'rocks,' the size of an outcrop and its resistance to weathering are two factors that determine the height. The topography tends to reflect the character of the underlying rock, a smooth surface indicating a homogenous composition whereas depressions indicate variety.

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ASPECTS OF STABILITY OF ROCK CUTS NEAR KELLERBERRIN, STANDARD GAUGE RAIL PROJECT

by F. R. Gordon

INTRODUCTION

The relatively high granite hills to the west of Kellerberrin have necessitated a considerable deviation of the Standard Gauge Railway from the existing line, in order to maintain ruling grade and to minimize rock excavation. The final location involved two rock cuttings which have been completed; the track has been laid and ballasted and the line is in full use.

The cutting known as K4 is approximately 5 miles southwest of Kellerberrin and extends from K4 miles 62 chains to K5 miles 24 chains with a maximum depth of cut of 40 feet at K5 miles 14 chains. The more easterly cutting, known as K8, extends from K7 miles 59 chains to K8 miles 23 chains with a maximum depth of cut of 30 feet at K7 miles 77 chains.

Because a softer basic lens was encountered in the predominant granite of the K8 cutting, the cuttings were briefly examined geologically during excavation, as it was feared that the batter angle of 60° would have to be adjusted. At the completion of excavation the two cuttings were examined in the company of Mr. G. Preston, Senior Resident Engineer for the consultants, Maunsell and Partners. The purpose was to define any areas or blocks liable to rock fall or sliding, and all suspect areas were numbered with red paint to allow ready identification, if and when remedial works were instituted.

GEOLOGY

Rock types

The area was examined by geological reconnaissance during the preliminary studies for the location of the Kellerberrin Deviation (Gordon, 1963).

The cuttings are situated about half way down a broad, gently sloping, southerly facing hill slope, and rock is very close to the surface.

In cutting K4, granite gneiss is remarkably uniform throughout, but the rock can be divided into a number of zones, distinguished by the

amount of physical or chemical weathering that has been dominant. The rock is a light-grey, weakly banded granite gneiss with biotite segregations from 1 to 2 feet apart.

The rock is divided by several major sheet joints roughly parallel to the ground surface and these have controlled weathering by limiting the movement of water. The various types of rock resulting from chemical weathering applicable to the area are shown in Table 1.

Table 1
WEATHERING OF GRANITE GNEISS,
KELLERBERRIN AREA

Completely weathered	Completely altered to a sandy clay, disintegrates in water.
Highly weathered	Intensely weathered, with recognizable rock structure, can be broken in the hand.
Moderately weathered	Considerably weathered but core pieces cannot be broken in the hand.
Slightly weathered	Rock is limonite-stained throughout, feldspars are cloudy.
Limonite stained joints	Joint faces coated, granite blocks between joints are unweathered.
Fresh rock	Unweathered joint coatings may be of clay, chlorite, pyrite.

In the cutting at K8 there are considerable variations in both the rock types and the degree of weathering. There are three main types of granite: (1) an equigranular light-grey granite with occasional large basic lenses (0 to 9½ chains); (2) a light-grey foliated granite gneiss, with a foliation dip of about 70° to the west, which in places considerably distorted (9½ chains to 24.2 chains); (3) a medium to coarse-grained porphyritic granite, light-grey in colour, that occurs from 24.2 chains to the end of the cutting. Three dolerite dykes traverse the cutting, all of which strike 240°, almost at right angles across the cutting, and dip at 80° to the east: (i) a dyke 1 foot wide on the left hand side (LHS) at 24.3 chains thins to 6 inches wide on the right hand side (RHS); (ii) a 2-foot 2-inch wide dyke is located at 15.7 chains on the LHS; (iii) an 8-inch wide dyke is found at 14.4 chains on the LHS.

There is a large basic body between 8½ and 9½ chains with irregular margins and intrusions of pegmatite and big masses of vein quartz. A definite foliation, which strikes across the cut and dips at 30° to the west can be seen in places. A major pegmatite dyke extends from 9·25 to 9·55 chains (i.e. about 21 feet wide) and contains large basic inclusions. Quartz and feldspar make up the bulk of the rock, but biotite and magnetite segregations are common.

Geomechanical data

Faulting and folding are not of importance in the mechanical configuration of the two cuttings, nor does the type of rock appear to affect the inherent stability.

Jointing is the dominant structural feature, controlling the stability of individual blocks of rock, and indirectly influencing the stability of rock and debris masses by controlling water movement which accelerates weathering.

The most important joints are the sheet joints which are mostly parallel to the existing ground surface. Although they are not as continuous as the joints developed in steeper topography, the joints have allowed weathering to develop on either side of the opening, and 9-inch wide seams of completely decomposed granite (as a sandy kaolin clay) are common. As is usual in this type of joint, the incidence is greatest near the ground surface and the potentially unstable areas are usually concentrated in the top 10 feet of the cutting.

Most of the stability problems are posed by large individual blocks of rock that are lying on the sheet joint clay seam lying in the dip into the cut on the highest (north) wall. Another common type of instability has resulted from overhangs developing where blocks of relatively fresh rock have resisted blasting while the sheet joint clay seam and the slightly to moderately weathered rock underneath has been removed (Plate 17).

The second most numerous type of stability problem involves individual blocks of rock that are separated by normal jointing or are standing out of the walls, and have a steep-dipping exfoliation joint at the rear. The number of these joints in cutting K4 is unusual, and it is almost certain that the technique of pre-splitting, used exclusively in this cutting, is responsible for the cracking and joint formation. Exfoliation joints of this type are developed parallel to the face of the excavation, that is, parallel to the initial slot, and are considered a post-excavation relaxation feature, analogous to the rebound mechanism of large scale sheet joints. What is surprising is a large number so close to ground surface, and the cause is considered to be the intensity of the explosive effort used to form the primary slot, followed by general excavation.

Overshooting the toe of the batter to give an over-steep face is usually achieved by faulty excavation methods. Overloading of blast holes, or underloading followed by trimming, are the

normal causes. However, examination in the cuttings near Kellerberrin has shown that certain aspects of oversteep batter toes is as much a problem of design as of excavation method. The cutting of a vertically walled ditch at the foot of the batter inevitably results in a reduction of effective strength of the rock. If on completion of the excavation the toe is slightly full, which would be a reasonable condition to avoid shattering from the rose of joints resulting from blasting (Gordon, 1966), then excavation of the ditch would further accentuate the condition at the toe (Figure 8).

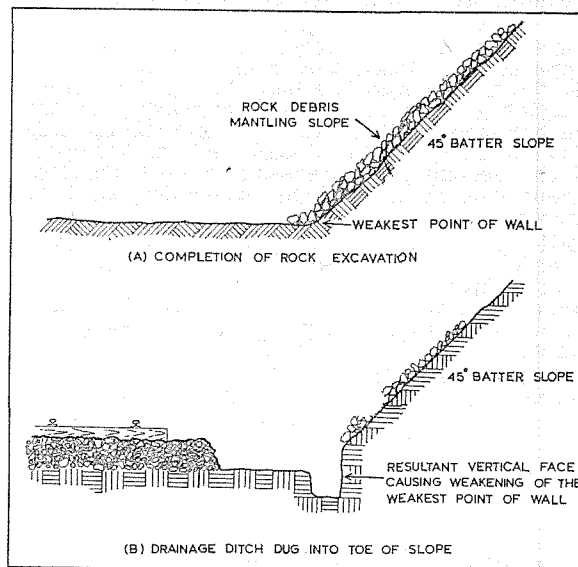


FIGURE 8: KELLERBERRIN ROCK CUTTINGS; SECTIONS ACROSS CUTTINGS IN WEATHERED ROCK AREAS

The effect of battering the weathered rock back to 45° (in this case) is completely nullified.

Of minor importance in the two cuttings are the more conventional types of block instability. These include intersection of main joint planes, overshot batter toe giving oversteep faces, shattered rock, and clay seams other than in sheet joints.

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GEOLOGICAL INVESTIGATION OF MOOCHALABRA CREEK DAM SITE

by J. D. Wyatt

SUMMARY

To improve the Wyndham water supply, the Public Works Department intends to dam Moolchalabra Creek, a tributary of the King River.

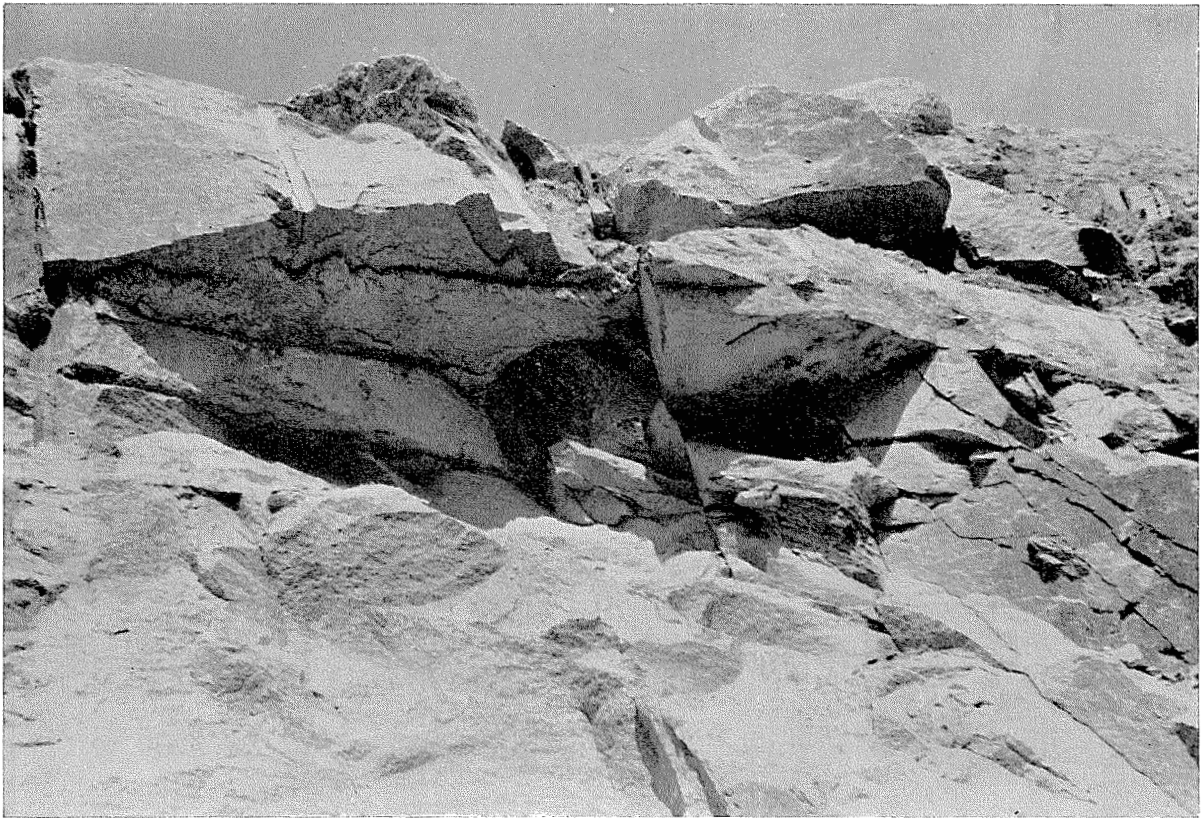
Detailed mapping and five diamond drillholes were used in the investigation of a trial centre line. The dam is to be constructed of rockfill with an impervious clay core, and these materials will be obtained close to the dam site.

The embankment is expected to rise 60 feet above the present creek bed, to an R.L. of 106 feet. To cope with the wet season flooding, a spillway will be excavated on the left bank of the creek.

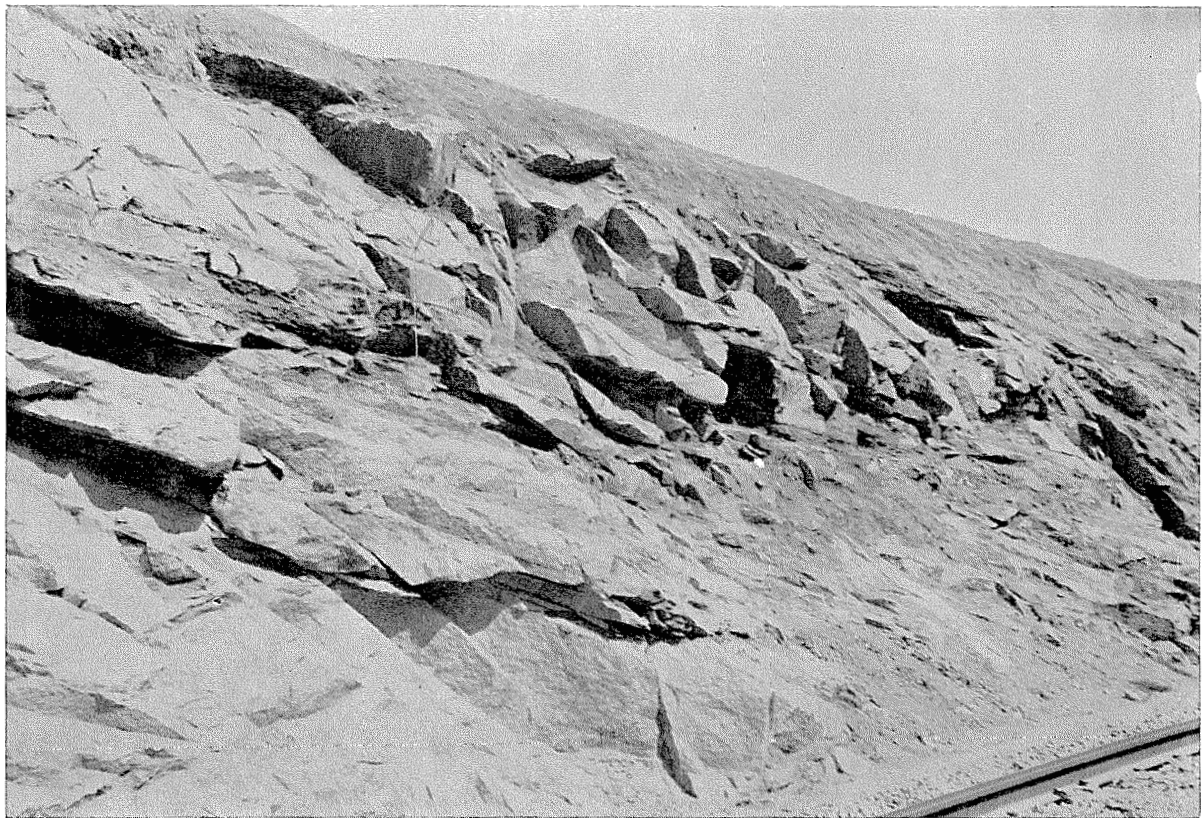
The foundations of the proposed dam and spillway will be composed of a closely jointed and well bedded sandstone containing thin siltstone interbeds. Jointing is mainly restricted to two major sets, one striking north and the other east.

Three major faults were mapped just upstream from the proposed site and one of these may prove to be a troublesome leakage path from the reservoir.

Important disadvantages of the site include a steep cliff forming the right abutment, two faults upstream from the trial centre line, and the permeability of the abutments.



A—Overhangs caused by the presence of sheet joints channelling blasting. A weathered clay seam on a sheet joint 6 inches thick is seen immediately under the main overhang ; F 1155.



B—Joints produced by pre-splitting technique ; F 1156.

INTRODUCTION

A dam to supply water to Wyndham is proposed for a site on Moochalabra Creek, a tributary of the King River. The site is 15 miles south of the town.

Access from Wyndham is by way of the Great Northern Highway to the 8 mile peg, thence 14 miles along an all-weather gravel road to the mouth of Moochalabra Creek. From this point to the proposed dam site the final 1.3 miles along the creek bed can be negotiated only by 4-wheel drive vehicles.

This report sets out the results of plane table geological mapping on a scale of 1 inch to 50 feet, and includes diamond drilling information.

Regional geology of the area is covered in a report of the Bureau of Mineral Resources (Plumb and Veevers, 1965). In 1965 a short visit to the site was made by F. R. Gordon and his recommendations were used as a basis for the more detailed mapping and diamond drilling investigations completed later in 1966 (Gordon, 1966).

GEOLOGICAL SETTING

TOPOGRAPHY AND DRAINAGE

The topography is rugged as a result of the deep dissection of the Kimberley Plateau. To the west of the proposed dam site the plateau is separated by a fault scarp from the tidal flats of the Cambridge Gulf Lowlands.

The area is drained by short, intermittent, but actively eroding streams. The drainage is dendritic, except in the northwestern part of the plateau where most of the creeks flow either west or northwest off the elevated land down to the tidal flats.

Shortly before joining the King River, the north-westerly flowing Moochalabra Creek swings sharply south around a low spur, which is opposed on the right bank of the creek by an almost sheer cliff face rising some 150 feet above the river bed. This is the site of the proposed dam and spillway, through which a trial centre line, B₁-B₃, has been laid out.

Downstream from the pegged centre line, Moochalabra Creek flows parallel to the King River, but in an opposite direction, and is separated from it by a steep, narrow ridge. About one mile further downstream the valley takes a right angled swing to the west to join the King River, as a series of poorly defined channels flowing across a small tidal flat.

At the proposed dam site the valley is asymmetric having a steep right abutment and a flat (6°) left abutment.

Several permanent pools occur along the river channel, both upstream and downstream from the pegged centre line, and these are invariably located at the base of the steep cliff sections. The pools have almost certainly resulted from an increase in the rate of erosion, where the river has impinged on the outer side of a bend. Such a pool occurs on the right side of the river bed at the proposed dam site.

ROCK TYPES

Unconsolidated sediments in the river channel overlie a silty sandstone (the Pentecost Sandstone of Plumb and Veevers, 1965), which has been intruded by a number of quartz veins.

On the western side of the saddle centred about 400N 100W, a small outcrop of sandstone with sandy shale interbeds has been mapped (Plate 18).

Alluvium

The bed of Moochalabra Creek is covered with alluvium about 10 feet thick. It is poorly sorted and the composition ranges from large blocks of sandstone (10 feet x 8 feet x 2 feet), down to fine-grained silty sand. The most frequent sizes encountered are fragments 9 inches and 12 inches square.

The upper 2 feet of the alluvium usually consists of a layer of rounded boulders, cobbles, and pebbles, in places overlain by sand which has been partly stabilized by vegetation.

Pentecost Sandstone

This is the dominant rock type exposed at the dam site. It is a fine to medium-grained rock, containing fine-grained silty interbeds. Ripple marks and current bedding are common.

The bedding dip is usually west at between 5° to 15° and the strike N25°E (Figure 9). The thickness of the beds varies with the grain size. The more silty sandstones are generally thinly-bedded with partings every 3 inches to 6 inches, whereas the coarser-grained blocky sandstones have major beds up to 5 feet thick, but with discontinuous partings only 12 inches to 24 inches apart.

In some of the steeper sections of the right abutment cliff face, along trial centre line B₁-B₃, the thin-bedded, silty sandstones have been eroded back into the cliff as much as 10 feet to leave overhangs.

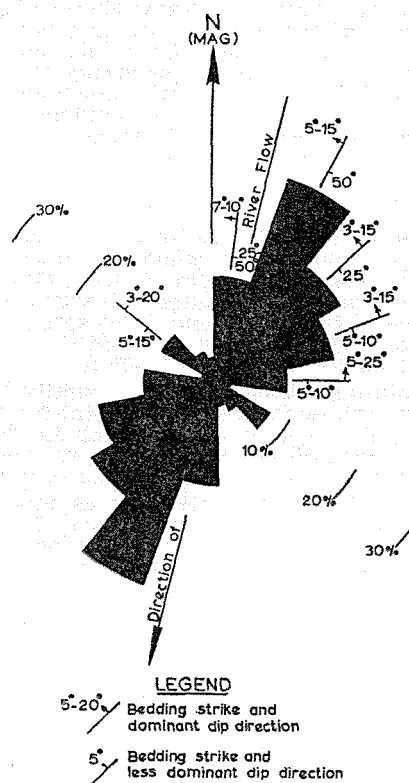


FIGURE 9: BEDDING STRIKE ROSETTE FROM 103 READINGS IN PENTECOST SANDSTONE, MOOCHALABRA CREEK

Mendena Formation

An exposure of silty sandstone with purple shale beds occurs at 000N 400W on the western side of Fault No. 1. The bedding dip and strike is variable because of the proximity of Fault No. 1. On the basis of lithology and position with regard to the Pentecost Sandstone, the rocks are considered to belong to the Mendena Formation.

Quartz veins

Quartz veins are common near the proposed dam site. One of these was traced continuously over a distance of 1,000 feet and intermittently for a further 700 feet. The veins occur as single and multiple intrusions, usually along the north-trending joint system, and are commonly between 6 and 12 inches wide. All are steeply dipping and some show slicken-sides which indicate movement east-side-north, or east-block-down.

FAULTING

There are three main faults in the area covered by the detailed investigations, the largest (Fault No. 1) forming the western boundary to the mapping.

Fault No. 1 forms a steep scarp just east of the main access track from Wyndham to the King River Pumping Station; it strikes north and probably has a steep dip. It is not expected that this fault will have any effect on the construction of the proposed rockfill dam.

Fault No. 2 strikes N26°E with a vertical dip and passes along the eastern side of the topographic saddle. It appears to have been formed contemporaneously with Fault No. 1.

In the vicinity of 550N 120E, Fault No. 2 has a cemented fault breccia zone which ranges between 2 and 15 feet in width. It is difficult to trace in a downstream direction, but as it was not intersected in drillhole No. 1, it is probable that Fault No. 2 has been offset south-block-east by movement along Fault No. 3, although the direction and amount of movement is not precisely known.

Fault No. 3 located about 150N 000E, has a strike of N65°E and a near vertical dip. Water tests carried out in drillhole 4, which passed through this fault zone, show the fault to be a potential leakage path for water stored in the reservoir. The distance from one side of the saddle to the other along the strike of the fault is about 700 feet. The fault movement is unknown, but from topographic evidence appears to be south-block-east. No indication of this fault is apparent on the left side of the river.

JOINTING

A total of 280 joint readings were taken from every major outcrop of sandstone in the area of the dam site. The joint rosette (Figure 10) prepared from these readings clearly shows the existence of two prominent joint sets:

North strike, dipping 70°W—55°E
East strike, dipping 80°N—75°S

The joints striking north are usually less frequent than those striking east. Joint frequencies range from one joint every 1/4 inch in the thin-bedded finer-grained sandstones to one joint every 60 inches in the thick-bedded sandstones.

The jointing planes are open as much as 12 inches and are usually iron-stained. Most joint surfaces are free from clay decomposition products, but many are filled with thin quartz veinlets.

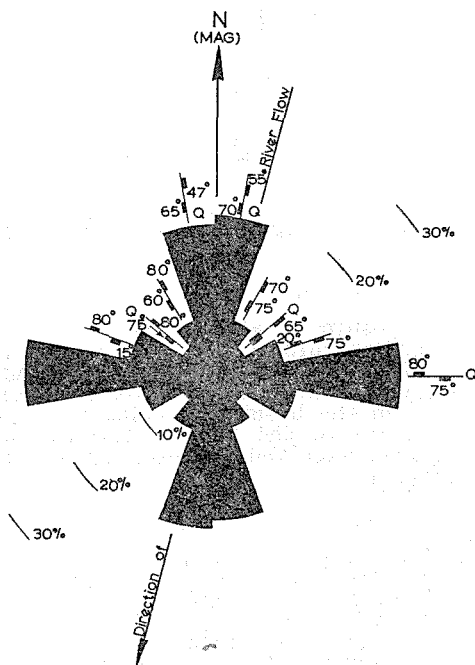


FIGURE 10. JOINT ROSETTE FROM 286 READINGS IN PENTECOST SANDSTONE, MOOCHALBRA CREEK

FOLDING

Folding is restricted to one northeasterly trending anticline bounded to the east, west, and south, by Faults Nos. 1, 2, and 3 respectively, and a number of small flexures located on the

right bank of Moochalabra Creek, upstream from the trial centreline.

Anticlinal folding has caused separation between the major bedding planes of the Pentecost Sandstone, together with the formation of numerous closely spaced tension cracks, which usually do not continue through more than one bed.

SUBSURFACE INVESTIGATIONS

PITS

Two bulldozer pits were excavated in the bed of Moochalabra Creek just downstream from trial centre line B₁-B₂ (Plate 19). Both pits exposed bedrock between 8 and 12 feet below the river bed. The river alluvium in the walls of these excavations was composed of boulders, cobbles, pebbles, and about 30% sand.

DIAMOND DRILLING

Drillhole 1 was drilled from the bottom of one of the bulldozed pits, beneath the river to a point some 30 feet beyond the vertical cliff forming the right abutment.

It was expected that the breccia zone of Fault No. 2 would be intersected, but instead only a few small clay-filled shears were noted. Most of the drill core was composed of a relatively massive pink and white sandstone, in places highly silicified.

Water testing of this hole showed that between 8 feet and 108 feet drill depth, water losses ranged from 8 to 40 lugeons with varying water pressures. Below 108 feet water losses fell to less than 1 lugeon.

Drillhole 2 was located on the left abutment and drilled vertically to a depth of 54 feet 7 inches.

Core losses of 3 feet 6 inches occurred in the initial 6 feet of drilling, and an examination of the hole showed that this loss was a result of deep weathering of some of the sandstone horizons. Throughout the length of the hole these highly weathered zones, as well as thin-bedded silty partings are common.

Water pressure tests carried out between 8 feet and 45 feet showed losses of between 15 to 40 lugeons. Below 45 feet losses dropped to less than 1 lugeon.

Drillhole 3 was located about the centre of the proposed spillway site, and drilled vertically to a depth of 35 feet.

The core was broken and in places thin-bedded, but the sandstone was generally more sound than that intersected in drillhole 2.

Water pressure testing between 8 feet and 25 feet showed a loss of 17 lugeons, but from 25 feet to 35 feet water losses increased to 30 lugeons.

Drillhole 4 was located on the topographic saddle separating Moochalabra Creek from the King River, and was designed to investigate Fault No. 3 and the right abutment of the proposed dam at river bed level.

The fault was intersected as a 14 feet wide zone of intermittent brecciation and silicification, between 91 feet and 112 feet 6 inches drill depth.

Water pressure testing between 8 feet and 112 feet showed losses of up to 18 lugeons. Past the fault zone water losses dropped to 1.5 lugeons.

Drillhole 5 was designed to investigate the right abutment; it was drilled from the top of the steep cliff face and laid out to intersect with drillhole 1.

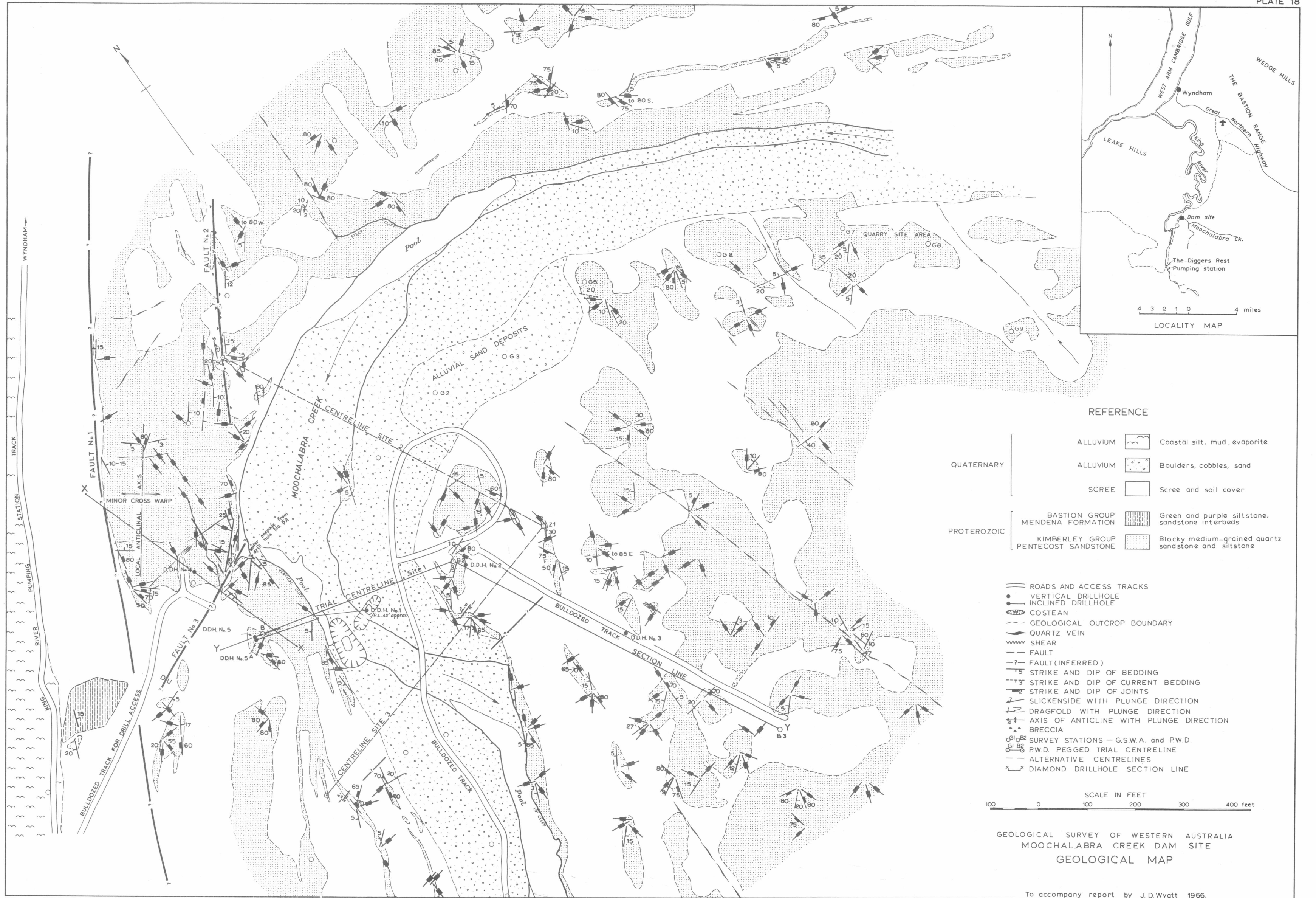
At a depth of 108 feet 3 inches, two diamond drill bits were lost down the hole and it was abandoned.

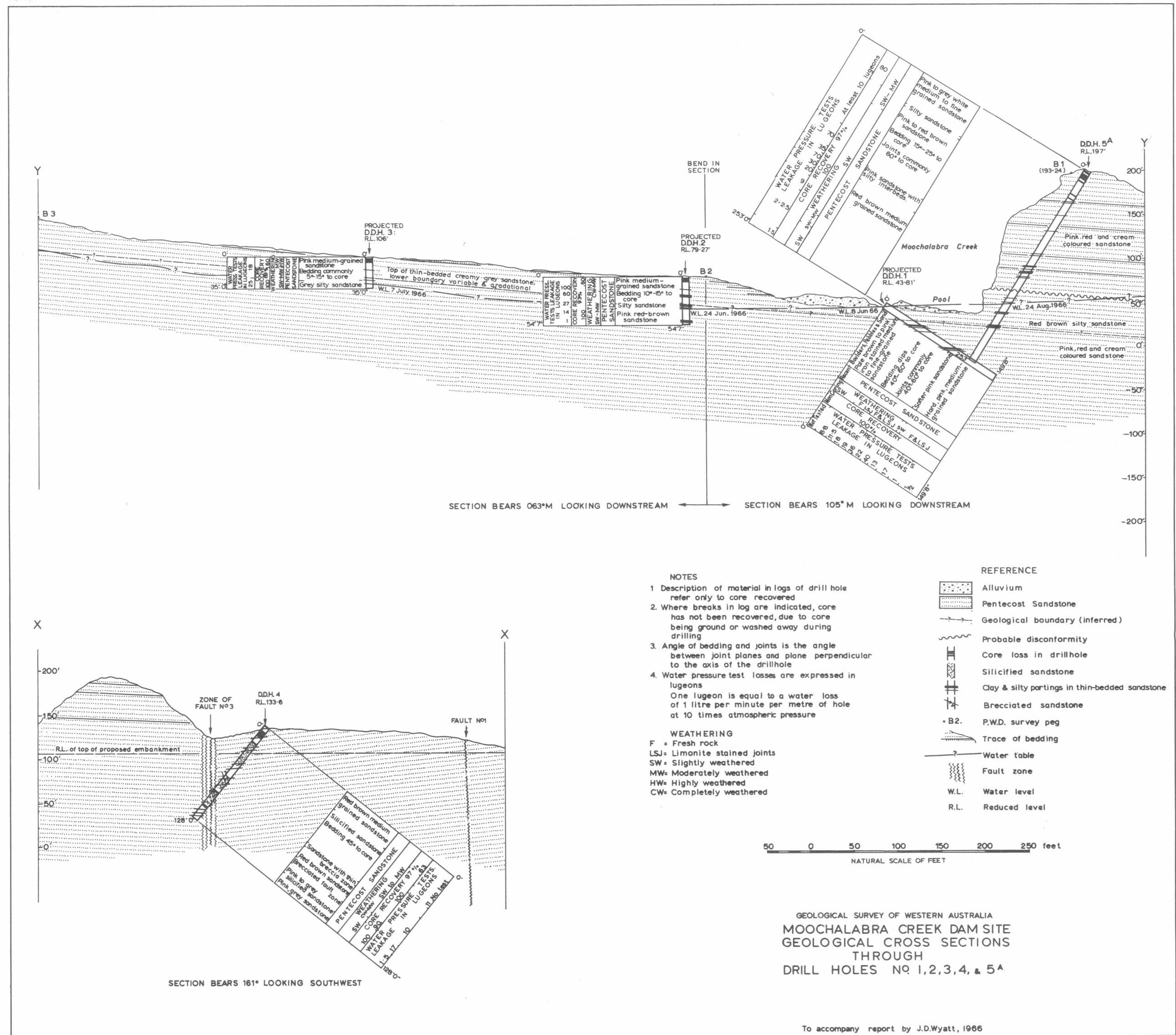
The hole was surveyed for dip at 100 feet but there was no measurable deviation.

Drillhole 5A was put down after hole 5 was abandoned. The results down to 100 feet were similar.

Throughout drilling, water could be seen issuing from numerous joint, bedding, and fault planes, as far away as 180 feet from the collar of the hole.

Water pressure testing between 20 feet and 100 feet drill depth, showed a loss of about 15 lugeons, with the pump at maximum output. The maximum possible loss was probably much greater.





Between 100 feet and 150 feet, tests were made at regular 10 or 20 feet intervals and with the pump on maximum output and water pressures of between 20 to 50 pounds per square inch, the losses were as high as 40 lugeons.

From 150 feet to 170 feet, the water losses dropped to 25 lugeons and from 170 feet to the end of the hole the losses dropped to a minimum of 2 lugeons.

The hole was surveyed for dip at 130 feet and 220 feet, and these results showed a flattening of about 1° for every 100 feet of drilling.

SITE APPRAISAL

DAM SITE

The geological features which are considered disadvantageous at the proposed trial centre line are as follows:

1. The presence of two faults upstream from the proposed centre line, one of which (Fault No. 3) may form a leakage path through the topographic saddle separating Moochalabra Creek from the King River.

2. The open nature of the jointing and bedding planes, which in places has caused the deep weathering of the sandstone and in turn has been followed by the erosional removal of broken rock as far back as 20 feet into the cliff face.

The permeability of the sandstone by way of these fractures will make it difficult to achieve a watertight bond between the abutment and the impervious clay core.

3. The steepness and height of the cliff face forming the right abutment. As the top of the proposed dam is expected to be around RL 106 feet and as the cliff rises to RL 200, this means that a steep cliff face will rise about 100 feet above the embankment. With an unknown thickness of loose scree on the upper slopes, this would constitute a considerable hazard during construction.

Two other sites, Nos. 2 and 3 (Plate 18), were selected as possible alternatives. Neither has been investigated by drilling and it is likely that the foundation conditions will be very similar to site No. 1.

One advantage of site No. 2, is that it is located upstream from the original trial centre line and will therefore avoid the two faults on the right bank of Moochalabra Creek. Site No. 3, located downstream from site No. 1 will not have a steep cliff face on the right abutment.

SPILLWAY SITE

A site for the proposed spillway has been tentatively chosen on the spur forming part of the left bank of Moochalabra Creek. The same location with minor alterations as to direction and depth of the cut, will be common to all three proposed dam sites.

Because of the gentle slope (6°) of this side of the river valley, and the presence of several broad bedding terraces, excavation of the proposed spillway channel will be simplified.

The rock type is jointed sandstone, with fine-grained silty sandstone interbeds. Drilling indicates that the upper 10 feet of rock will contain several weathered horizons. This material will either have to be removed during construction or protected from future erosion when the spillway is in use.

CONSTRUCTION MATERIALS

ROCKFILL

Abundant rockfill will be available from the Pentecost Sandstone and a quarry site has been selected in this rock unit on the left bank of the river, centred on 350N 1400E (Plate 18).

The site consists of a number of river terraces, formed by erosion of flat bedding plane surfaces. The lowest terrace is about 15 to 20 feet above the bed of Moochalabra Creek, and the next about 20 feet higher.

Excavation of the rock, from Moochalabra Creek south, will enable advantage to be taken of the natural face formed along the left bank of the river.

As quarrying continues to the second terrace a 40-foot high working face will be formed. If

the dam is built in one year, no problems will arise when the river is in flood, sometime between December and April.

Some scree occurs as talus slopes between the terraces. The size of the blocks is between 12 inches x 12 inches x 18 inches up to 72 inches x 30 inches x 18 inches.

FILTER ZONE MATERIAL

Sufficient suitable filter zone material will be available from the bed of Moochalabra Creek, although it will need washing and screening.

IMPERVIOUS BORROW

The search for impervious clay borrow was concentrated along both sides of the access track between the dam site and King River Pumping Station. Elsewhere, random samples were taken of likely material for distances of up to 16 miles from the dam site.

Little of the material sampled by the auger drilling was suitable, most of the samples being either silty sand or sticky black mud.

One area, west of the King River Pumping Station was drilled late in 1966. Laboratory tests completed to date suggest that this area will be a source of suitable impervious borrow.

CONCLUSIONS

The rock types at the proposed dam site are alluvium in the river channel overlying a sandstone with silty interbeds and a silty-sandstone with shale interbeds. The beds dip generally west at between 5° and 15° and strike N25°E. Crossbedding and ripple marking are common.

There are two dominant, steeply dipping joint sets striking north and east.

Three large faults were mapped, one of which, Fault No. 3, is known to be important as a possible leakage path from the reservoir.

Folding is restricted to one northeasterly trending anticline centred on 400N 050W, and some small flexures in the sandstones cropping out in the steep cliffs on the right bank of the river.

Diamond drilling was restricted to give holes put down along a proposed trial centre line, and drilling revealed that:

1. Frequent jointing and major open bedding planes are responsible for high water losses of up to 40 lugeons being recorded during water pressure testing.

2. The sandstone is in places deeply weathered usually along the bedding, down to at least 10 or 15 feet below the ground surface. This weathering is selective and may only involve one or two horizons of sandstone.

One trial centre line for the proposed dam was investigated by detailed mapping and diamond drilling, and the main disadvantages of this site appear to be:

1. the excessive permeability of the abutments, especially the right abutment

2. the steep cliff face forming the right abutment

3. the presence of large faults upstream from the proposed dam site which may affect the water tightness of the proposed reservoir.

Two other tentative sites were selected, upstream and downstream from the original trial centre line B₁-B₃.

The possible advantage of site No. 2 is its position upstream from the two faults, whilst the advantage of site No. 3 is that it does not have a steep cliff face forming the right abutment. Neither of these two alternatives appears to have any advantages in the foundations.

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- Gordon, F. R., 1966, Geological reconnaissance at Moochalabra Creek dam site: West. Australia Geol. Survey Rec. 1966/8 (unpublished).
- Plumb, K. A., and Veevers, J. J., 1965, Explanatory notes on the Cambridge Gulf 1:250,000 Geological Sheet SD/52-14, Western Australia: Australia Bur. Mineral Resources Rec. 1965/174 (unpublished).

HYDROGEOLOGICAL FEATURES OF THE GASCOYNE RIVER, WEST OF THE KENNEDY RANGE

by J. L. Baxter

ABSTRACT

A reconnaissance of the Gascoyne River, to determine the feasibility of transporting water in the channel from the proposed dam site at Kennedy Range to Carnarvon, has shown that there are three main areas from which water will be lost. These are the Birdrong Formation and two abandoned channels of the river.

INTRODUCTION

A dam to supply the Carnarvon irrigation area is proposed for a site on the Gascoyne River in the southern end of the Kennedy Range, 92 miles east of Carnarvon.

The present water supply for Carnarvon is obtained from the alluvial deposits of the river, but the supply of water is limited. Recharge of these sands is dependent on flows of the river, and these flows are intermittent and sometimes quite small. The amount of water pumped from the river in 1964-65 was 1,004 million gallons and in 1965-66 was 1,321 million gallons.

To avoid the expense of a pipeline from the dam to Carnarvon it has been proposed by the Public Works Department that the water be transported in the existing river channel by releases to keep the river sands saturated. A reconnaissance survey was carried out as part of the initial investigation to determine the feasibility of this scheme. A geological sketch map of the area is shown on Plate 20.

PHYSIOGRAPHY AND CLIMATE

The Gascoyne River flows west through the southern end of the Kennedy Range and across broad flood plains to Rocky Pool. Although the main channel continues west, there are numerous distributary streams forming anabranches which may flow at times of river flooding. The Gascoyne River is mature throughout its course west of the Kennedy Range. The river to Fishy Pool, 17 miles west of the dam site, has a gradient of approximately 1 in 880 and flows over basin sediments. It is up to half a mile wide and in places is braided. From Fishy Pool to Rocky Pool the river flows across old flood plains, where the channel is confined between low banks and has a gradient of approximately 1 in 1,000. From Rocky Pool to Carnarvon the river flows through a recent delta in which the gradient is approximately 1 in 1,800.

There are six physiographic subdivisions through which the river flows.

The *Kennedy Range*, the southern end of which has been breached by the river, forms the abutments for the proposed dam site and rises to about 500 feet above the surrounding plain.

The *Mooka surface*, a billy surface about 2 miles wide, is formed along the western margin of the Kennedy Range. It supports little vegetation.

Low rises occur as rocky knolls in the sand dunes and deltaic deposits. There is a line of these ridges northeast of Rocky Pool.

The *sand dunes* cover an area between the Mooka surface and the old river plain. The dunes are between 30 and 80 feet high.

The *old river plain* extends northwest from Fishy Pool and extends southwest to the coast.

It is a flat area with sand rises up to 15 feet high. The area appears to be an old delta of the Gascoyne River.

The *river delta* extends from Rocky Pool to the coast. The dissection of the unconsolidated flood plain deposits by the anabranches is typical of such deltaic areas.

The average rainfall over the Gascoyne River drainage area is 7 inches, the average evaporation is 99 inches. The average maximum temperature in summer is 101°F and the minimum is 71°F. The average maximum temperature in winter is 72°F and the minimum is 46°F.

HYDROLOGICAL AREAS

There are three areas of importance in the hydrology of the Gascoyne River west of the Kennedy Range: the Cretaceous sequence which crops out to a point 17 miles downstream from the proposed dam site; the old river plain and river delta physiographic areas of the Gascoyne River which are developed west of the Cretaceous sequence and extend to the coast; and the sand dune unit which lies north and south of the river between the Cretaceous sequence and the river delta.

The Cretaceous sequence

The Cretaceous sequence is composed of a sandstone, shale, and radiolarite. The sandstone is the Birdrong Formation which is the best aquifer in the Carnarvon Basin. It must be considered an important intake source where it crops out in the bed of the Gascoyne River.

The Windalia Radiolarite commonly has a siliceous capping of either billy or opaline material. This surface is usually fractured. The unit is only slightly porous.

The shale, which does not crop out in the bed of the river, is approximately 30 feet thick and weathers to a clay. This unit is relatively impermeable.

The Birdrong Formation crops out from about 3 miles downstream of the proposed dam site to Fishy Pool, a distance of 14 miles. The sandstone is extremely porous and pools form over this unit only where there is a clay layer in the river bed. At Carnarvon the Birdrong Formation produces artesian water from a depth of 1,300 to 1,500 feet.

The salinity of the water in the sub-artesian Highway Bore, which draws from the top of the Birdrong Formation, is 4,000 ppm. The salinity of the water recovered from Brickhouse 4 artesian bore at a depth of 1,500 feet is 3,245 ppm.

The old river plain and river delta

The old river plain and delta of the Gascoyne River extend from Fishy Pool, 17 miles west of the proposed dam site, to the coast. They can be divided into three distinct groups.

The *present river channel* contains sands of variable thickness acting as reservoirs for water. The salinity of the water is variable from 400 ppm to 2,000 ppm, and all the stations situated on the river use either a river well or a spear to obtain water for domestic purposes. At Carnarvon the water in the river sands is used to irrigate the broad-acre crops grown there.

The *old river channels* are now marked by clay-pans and small sand rises. The old channels leave the river at Fishy Pool, Doorawarra, and Rocky Pool. The channel north of Fishy Pool contains a good supply of stock quality water with salinity ranging between 1,800 ppm and 5,000 ppm. This channel is being tapped by at least seven bores. The channel south from Doorawarra Homestead contains an almost unlimited supply of water with 400 to 3,000 ppm salinity. The water levels in this channel indicate that there is flow away from the river at a gradient of approximately 1 in 900. The depth to the old river sands is about 60 feet. The channels north and south of Rocky Pool contain an unlimited supply of highly saline water.

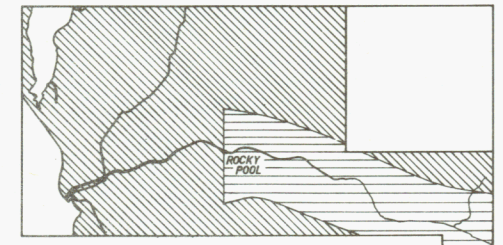
The *flood plains* between the old channels of the Gascoyne River consist of partly consolidated deltaic sediments. The water in these deposits is more saline than that obtained from the old channels. The salinities range between 1,500 ppm and 7,000 ppm, and generally the supply is poorer.

GEOLOGY OF THE GASCOYNE RIVER WEST OF THE KENNEDY RANGE

REFERENCE

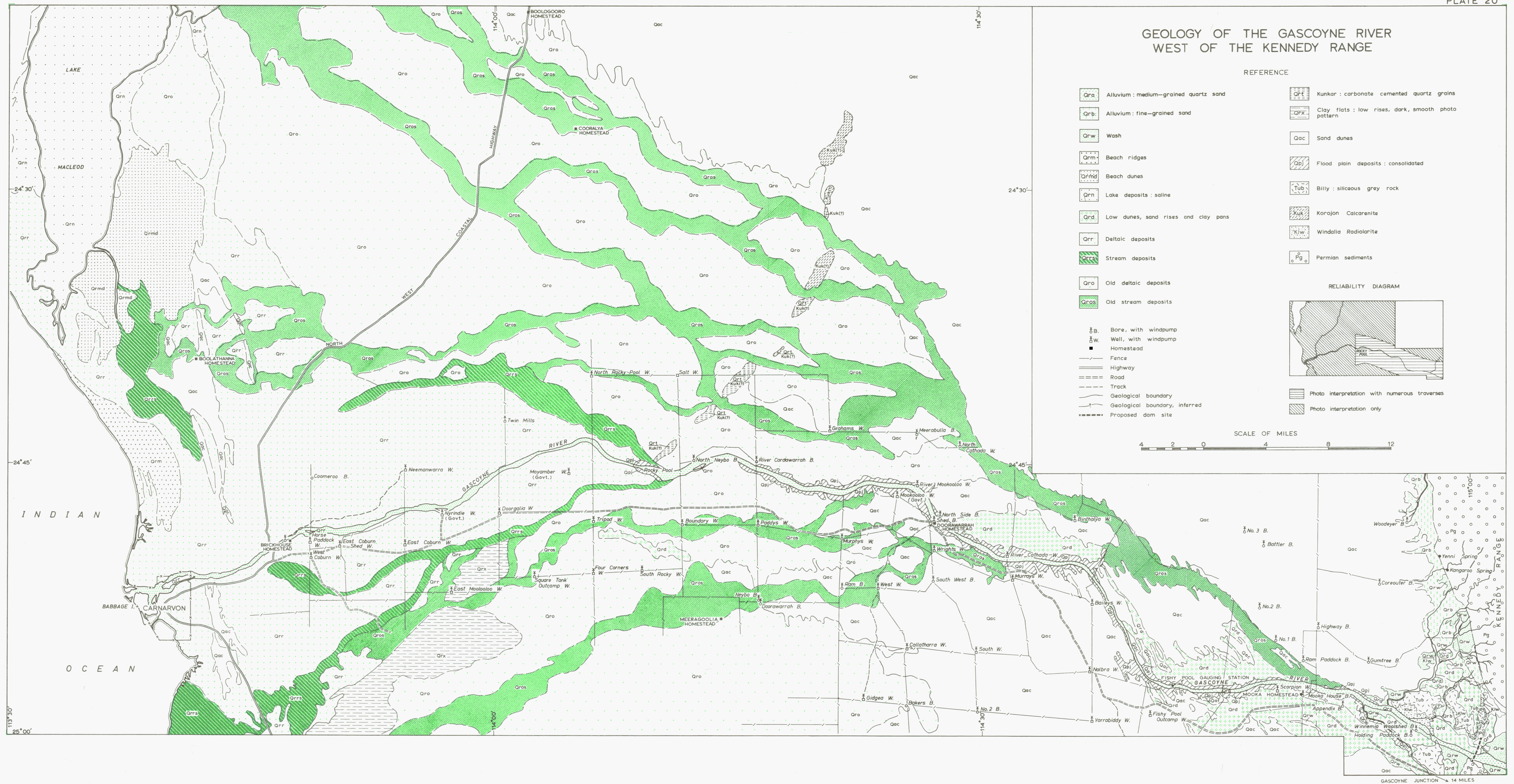
- | | | | |
|--|---------------------------------------|---|--|
|  Qra | Alluvium : medium-grained quartz sand |  Qpf | Kunkar : carbonate cemented quartz grains |
|  Qrb | Alluvium : fine-grained sand |  Qfx | Clay flats : low rises, dark, smooth photo pattern |
|  Qrw | Wash |  Qac | Sand dunes |
|  Qrm | Beach ridges |  Qpj | Flood plain deposits : consolidated |
|  Qrmd | Beach dunes |  Tub | Billy : siliceous grey rock |
|  Qrn | Lake deposits : saline |  Kux | Korojon Calcarenite |
|  Qrd | Low dunes, sand rises and clay pans |  Klw | Windalla Radiolarite |
|  Qrr | Deltaic deposits |  Pg | Permian sediments |
|  Qrs | Stream deposits | | |

RELIABILITY DIAGRAM



- 8.B. Bore, with windpump
 8.W. Well, with windpump
 ■ Homestead
 — / — Fence
 === Highway
 == == Road
 --- Track
 ~~~~~ Geological boundary  
 ~~~~~ Geological boundary, inferred  
 - - - - - Proposed dam site
-
- The map shows a landscape with various features. A legend on the left defines the symbols used. On the right, a map shows the study area with a 'PROPOSED DAM SITE' indicated by a dashed line. The map is divided into two main sections: the left section is labeled 'Photo interpretation with numerous traverses' and the right section is labeled 'Photo interpretation only'. The right section also shows a 'BACKY FISH' area.

SCALE OF MILES



The sand dunes

The sand dunes cover an area which is not affected by the river. The country beneath the dunes contains only small quantities of potable water. The dunes themselves contain small supplies of water of good quality, but these are insufficient to meet stock requirements.

APPRAISAL OF WATER LOSS

The two main areas of intake into which water will be lost from the river are the Birdrong Formation and the old river channels. The Birdrong Formation will take a considerable quantity of water along the 14-mile stretch in which it is exposed to the Gascoyne River bed. The old river channels which leave the river from Fishy Pool and Rocky Pool will take a certain amount of water, but it is expected that most will be taken by the channel which leaves the river east of Doorawarra.

RECOMMENDATIONS AND CONCLUSIONS

1. The course of the Gascoyne River west of the Kennedy Range has many areas from which

water would be lost while flowing from the dam site to Carnarvon.

2. These areas must be tested by measurements over a considerable period of time and during all stages of the river flow from drought to flood conditions. Tests will include flow testing, measurement of the variation of water level and salinity in the bores at present in the old channels, and drilling in the Birdrong Formation at the intake areas along the channel.

3. The potential of the old river channels as sources for water supplies to stations is high. These channels contain large quantities of water suitable for stock and some water suitable for domestic purposes.

4. The possibility of a low head dam at Rocky Pool, as originally proposed by the Public Works Department, should be reviewed. The possibility of discharging water from the dam into the channels to the north and south from Rocky Pool would provide some measure of flood control on the river, and possibly extend the irrigation area along these channels. The dam site at Rocky Pool should provide sufficient water for the immediate projected needs of the Carnarvon irrigation area.

THE SEARCH FOR OIL IN WESTERN AUSTRALIA IN 1966

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

INTRODUCTION

The principal development in the search for oil during 1966 was the announcement by West Australian Petroleum Pty. Ltd. that Barrow Island would be developed as Western Australia's first commercial oilfield, and that production would commence during 1967. This success has come to the company after 15 years of continuous exploration, and more than 60 years after the first exploratory well for oil was drilled in the State.

The amount of drilling carried out in 1966 was similar to that in 1965. A total of 25 test wells, 4 stratigraphic wells, and 5 structure wells were drilled during the year, and another test well was still drilling on December 31st. In addition 5 development wells were put down on Barrow Island and these were awaiting testing at the end of the year. Of the test wells, 11 were completed as potential producers: 5 oil wells, 1 oil and gas well, 3 gas wells, and 2 gas and condensate wells. Two more were suspended pending completion as producing wells. By comparison, during 1965 there were 26 test wells and 10 stratigraphic wells completed, and of the test wells 20 were potential producers.

Geophysical exploration declined during 1966 compared with the previous year. Seismic operations decreased from 93 party months in 1965 to 72 in 1966, and gravity surveys fell from 14 party months to 5½. Aeromagnetic surveys totalling some 2,700 line miles were flown in 1966 compared with 44,000 line miles the previous year. Field geological surveys amounted to 9 geologist months in 1966 compared with 16 in 1965.

OIL HOLDINGS

The positions of permits to explore and licenses to prospect in Western Australia at the end of 1966 are shown on Plate 21. Details of each concession current at the end of the year are as follows:

OIL HOLDINGS IN WESTERN AUSTRALIA ON 31st DECEMBER, 1966

Permits to Explore

| No. | Name of Holder | Area in Square Miles | Date of Expiry of Current Tenure |
|------|--|----------------------|----------------------------------|
| 27H | West Australian Petroleum Pty. Ltd. | 34,650 | 31/12/66 (renewal applied for) |
| 28H | do. do. do. | 30,750 | do. |
| 30H | do. do. do. | 140,200 | do. |
| 106H | Westralian Oil Limited | 11,800 | 28/9/67 |
| 127H | Alliance Oil Development Australia N.L. | 13,800 | 28/3/67 |
| 134H | Exoil Pty. Ltd. and Hunt Petroleum Corporation | 12,600 | 31/3/67 |
| 135H | do. do. do. | 12,000 | 31/3/67 |
| 136H | do. do. do. | 12,450 | 31/3/67 |
| 151H | Beach-General Exploration Pty. Ltd. | 14,200 | 7/2/68 |
| 152H | do. do. do. | 11,650 | 7/2/68 |
| 153H | do. do. do. | 13,050 | 7/2/68 |
| 172H | Alliance Petroleum Australia N.L. | 6,150 | 30/3/67 |
| 173H | do. do. do. | 12,250 | 30/3/67 |
| 174H | do. do. do. | 6,100 | 30/3/67 |
| 175H | do. do. do. | 6,050 | 30/3/67 |
| 177H | do. do. do. | 6,050 | 30/3/67 |
| 193H | Hawkestone Oil Co. Ltd., BP Petroleum Development Australia Pty. Ltd. | 2,750 | 5/2/67 |
| 205H | Alliance Petroleum Australia N.L. | 16,700 | 17/9/67 |
| 213H | Woodside (Lakes Entrance) Oil Co. N.L., B.O.C. of Aust. Ltd., Shell Development (Aust.) Pty. Ltd. | 104,000 | 20/6/67 |
| 217H | West Australian Petroleum Pty. Ltd. | 17,600 | 30/5/67 |
| 221H | Australian Aquitaine Petroleum Pty. Limited, Arco. Ltd. | 44,000 | 28/7/67 |
| 225H | West Australian Petroleum Pty. Limited | 8,000 | 20/7/67 |
| 226H | do. do. do. | 34,700 | 6/4/67 |
| 227H | do. do. do. | 11,400 | 6/4/67 |
| 228H | do. do. do. | 2,900 | 13/5/67 |
| 232H | Victorian Oil No Liability | 3,000 | 20/6/67 |
| 233H | West Australian Petroleum Pty. Ltd. | 6,800 | 10/2/67 |
| 235H | Canadian Superior Oil (Aust.) Pty. Ltd. | 19,400 | 21/1/67 |
| 236H | Abrolhos Oil No Liability, BP Petroleum Development Australia Pty. Ltd. | 2,600 | 3/2/67 |
| 238H | B.O.C. of Australia Ltd., Shell Development (Aust.) Pty. Ltd., Woodside (Lakes Entrance) Oil Coy. N.L. | 1,260 | 9/1/68 |
| 240H | Coastal Petroleum N.L. | 11,850 | 14/6/68 |
| 241H | do. do. do. | 11,850 | 14/6/68 |
| 242H | do. do. do. | 11,850 | 14/6/68 |
| 243H | do. do. do. | 11,850 | 14/6/68 |
| 251H | West Australian Petroleum Pty. Ltd. | 4,228 | 29/6/68 |
| 253H | Westralian Oil Limited | 5,200 | 28/12/68 |
| 254H | Tenneco Australia Inc. | 12,100 | Appl. pending |
| 256H | Continental Oil Company of Australia Ltd., Australian Sun Oil Company | 12,850 | do. |
| 257H | do. do. do. | 12,850 | do. |

Licenses to Prospect

| No. | Name of Holder | Area in Square Miles | Date of Expiry of Current Tenure |
|------|--|--------------------------------|-------------------------------------|
| 96H | West Australian Petroleum Pty. Limited | 100.00 | 18/3/67 |
| 97H | do. | 191.396 | 26/7/67 |
| 99H | do. | 190.458 | 4/12/67 |
| 101H | do. | 193.02 | 17/12/67 |
| 102H | do. | 195.551 | 13/1/67 |
| 103H | do. | 200.00 | 20/5/67 |
| 104H | do. | 197.867 | 7/6/67 |
| 105H | do. | 196.032 | 14/8/67 |
| 106H | do. | 200.00 | 11/9/67 |
| 107H | do. | 200.00 | 25/2/67 |
| 108H | do. | 200 (excluding Lyndon Loc. 42) | 17/1/67 |
| 109H | do. | 200.00 | 22/2/67 |
| 111H | do. | 150.00 | 4/6/67 |
| 113H | do. | 200.00 | 10/5/66 (to be converted to leases) |
| 114H | Alliance Oil Development Aust. N.L. | 67.00 | 27/10/67 |
| 115H | West Australian Petroleum Pty. Limited | 200.00 | 5/5/67 |
| 117H | do. | 200.00 | 10/9/67 |
| 118H | do. | 117.687 | 29/9/67 |
| 119H | do. | 109.032 | 12/1/67 |
| 120H | Westralian Oil Limited | 195.984 | 30/11/67 |
| 121H | Associated Freney Oil Fields N.L. | 120.00 | 11/7/67 |
| 122H | do. | 113.418 | 11/7/67 |
| 123H | do. | 113.232 | 11/7/67 |
| 124H | do. | 112.528 | 20/4/67 |
| 125H | do. | 112.477 | 20/4/67 |
| 126H | West Australian Petroleum Pty. Limited | 200.00 | 8/2/67 |
| 127H | do. | 200.00 | 17/1/67 |
| 128H | do. | 182.00 | 8/3/67 |
| 129H | do. | 200.00 | 8/3/67 |
| 130H | do. | 189.929 | 28/3/67 |
| 132H | do. | 200.001 | 13/5/67 |
| 133H | do. | 200.001 | 13/5/67 |
| 135H | do. | 106.197 | 17/5/67 |
| 136H | do. | 190.765 | 17/5/67 |
| 137H | do. | 8.830 | 17/5/67 |
| 138H | do. | 196.224 | 17/5/67 |
| 139H | do. | 189.684 | 17/5/67 |
| 140H | do. | 198.750 | 17/5/67 |
| 141H | do. | 188.941 | 17/5/67 |
| 142H | do. | 193.350 | 17/5/67 |
| 143H | do. | 198.133 | 17/5/67 |
| 144H | do. | 193.104 | 17/5/67 |
| 145H | do. | 187.411 | 17/5/67 |
| 146H | do. | 187.032 | 17/5/67 |
| 147H | do. | 188.953 | 17/5/67 |
| 148H | do. | 200.00 | 9/6/67 |
| 149H | do. | 200.00 | 14/7/67 |
| 150H | do. | 200.00 | 18/10/67 |
| 151H | do. | 194.367 | 5/7/67 |
| 152H | do. | 192.00 | 18/10/67 |
| 153H | do. | 196.00 | 18/10/67 |
| 154H | Beach-General Exploration Pty. Ltd. | 160.20 | 18/12/67 |
| 155H | West Australian Petroleum Pty. Ltd. | 193.75 | 18/10/67 |
| 156H | do. | 189.269 | 18/10/67 |
| 157H | do. | 188.973 | 15/2/68 |
| 158H | do. | 196.00 | 20/3/68 |
| 159H | do. | 196.00 | 20/3/68 |
| 160H | do. | 195.871 | 20/3/68 |
| 161H | do. | 196.129 | 20/3/68 |
| 162H | do. | 196.00 | 20/3/68 |
| 163H | do. | 200.00 | 20/3/68 |
| 164H | do. | 199.997 | 20/3/68 |
| 165H | do. | 200.00 | 20/3/68 |
| 166H | do. | 133.841 | 13/3/68 |
| 167H | do. | 160.520 | 13/3/68 |
| 168H | do. | 186.473 | 13/3/68 |
| 169H | do. | 200.00 | 20/3/68 |
| 171H | do. | 190 provisional | 14/4/68 |
| 172H | do. | 199.697 | 21/6/68 |
| 173H | do. | 190 provisional | 10/8/68 |
| 174H | do. | 190 provisional | 29/7/68 |
| 175H | do. | 200.00 | 11/8/68 |
| 176H | do. | 188.968 | 27/9/68 |
| 177H | do. | 200 provisional | 20/12/68 |
| 178H | do. | 200 provisional | Appl. pending |
| 179H | do. | 197 provisional | Appl. pending |
| 180H | do. | 195 provisional | Appl. pending |
| 181H | do. | 200.00 | Appl. pending |
| 182H | do. | 200.00 | Appl. pending |

DRILLING

The positions of wells drilled for petroleum exploration in Western Australia to the end of 1966 are shown on Plates 22 to 25. 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 (Dongara Nos. 1-3, Gingin No. 2, Mt. Adams No. 1, and Sue No. 1) during the year, and another (Erregulla No. 1) was still being tested on 31st December. A single stratigraphic well (Preston No. 1) was drilled during 1965.

The three wells at Dongara were all completed as potential gas producers. Dongara No. 1 was located near the crest of an anticlinal structure delineated by seismic methods. The gas reservoir in this well is the 'Basal Triassic Sandstone', which also contained oil and gas at Yardarino. It underlies the Kockatea Shale and was encountered in Dongara No. 1 between 5,482 feet and 5,516 feet. Testing of this unit yielded dry gas flows of up to 10.3 mmcf/day (on a 1/4-inch choke).

Dongara No. 2 was drilled three-quarters of a mile west-northwest of No. 1, and was also completed in the 'Basal Triassic Sandstone'. Testing yielded up to 9.1 mmcf/day of dry gas (on a 1/4-inch choke). The third well was sited three-quarters of a mile east-southeast of No. 1. It yielded flows of 3.24 mmcf/day (on a 1/4-inch choke) from the 'Basal Triassic Sandstone', and 1.95 mmcf/day (on a 1/4-inch choke) from the Irwin River Coal Measures, in which formation the well was completed as a potential producer.

There has been no further drilling at Dongara since the No. 3 well was completed in September 1966. None of the wells have penetrated the petroleum water interface, and it appears that a significant gas field is present. It is possible that an oil column is developed on the flanks of the structure, though oil was not recovered in any of the three wells drilled to date.

Gingin No. 1 was completed as a gas and condensate well in 1965, production being obtained from the Lower Jurassic Cockleshell Gully Formation. Gingin No. 2 was then drilled 2 miles south and 1 mile east of No. 1 to determine the extent of the field. The well was completed as a potential producing gas and condensate well in January 1966. An initial flow of 3.92 mmcf/day of gas with 270 bbl/day of condensate was obtained from the interval 13,962 to 14,704 feet, but this fell rapidly with prolonged testing. Production testing of Gingin No. 1 continued during the year, but no decision has been made on the possible economic development of the field.

A small amount of oil was recovered from the Erregulla No. 1 well in the Cockleshell Gully Formation. Swabbing of the interval 10,413 to 10,435 feet for 3 1/2 hours yielded 22 1/2 barrels of oil. Testing of the well was still in progress at the end of the year.

Further details of the wells drilled in Permit 27H during the year are as follows:

Dongara No. 1

Type: Test well.
License to Prospect: 111H.
Latitude and Longitude: 29° 15' 07" S., 114° 59' 14" E.
Elevation: Ground level 148 feet, derrick floor 161 feet.
Commenced: 30th March, 1966.
Rig released: 2nd July, 1966.
Total depth: 7,080 feet.
Bottomed in: Lower Permian.
Status: Gas well, completed over the interval 5,482 to 5,495 feet in the 'Basal Triassic Sandstone'. Production of 10.3 mmcf/day on a 1/4-inch choke, 3.14 mmcf/day on a 1/4-inch choke.

Dongara No. 2

Type: Test well.
License to Prospect: 111H.
Latitude and Longitude: 29° 14' 54" S., 114° 58' 29" E.
Elevation: Ground level 74 feet, rotary table 87 feet.
Commenced: 31st July, 1966.
Rig released: 12th August, 1966.
Total depth: 5,725 feet.
Bottomed in: Lower Permian.
Status: Gas well, completed over the interval 5,515 to 5,527 feet in the 'Basal Triassic Sandstone'. Production of 9.1 mmcf/day on a 1/4-inch choke, 2.8 mmcf/day on a 1/4-inch choke.

Dongara No. 3

Type: Test well.
License to Prospect: 111H.
Latitude and Longitude: 29° 15' 28" S., 114° 59' 59" E.
Elevation: Ground level 91 feet, rotary table 104 feet.
Commenced: 2nd September, 1966.
Rig released: 18th September, 1966.
Total depth: 5,822 feet.
Bottomed in: Lower Permian.
Status: Gas well, completed over the interval 5,490 to 5,502 feet in the Irwin River Coal Measures. Production of 1.95 mmcf/day on a $\frac{1}{4}$ - inch choke.

Erregulla No. 1

Type: Test well.
License to Prospect: 175H.
Latitude and Longitude: 29° 22' 28" S., 115° 23' 45" E.
Elevation: Ground level 763 feet, rotary table 779 feet.
Commenced: 3rd September, 1966.
Total depth: 13,925 feet.
Status: Testing on 31st December. 22½ barrels of oil obtained in 3½ hours by swabbing the interval 10,413 to 10,435 feet in the Cockleshell Gully Formation.

Gingin No. 2

Type: Test well.
License to Prospect: 115H.
Latitude and Longitude: 31° 10' 18" S., 115° 50' 35" E.
Elevation: Ground level 856 feet, rotary table 872 feet.
Commenced: 25th July, 1965.
Rig released: 18th January, 1966.
Total depth: 14,704 feet.
Bottomed in: Lower Jurassic.
Status: Gas and condensate well, completed over the intervals 14,011 to 14,110, 14,150 to 14,210, 14,270 to 14,380, and 14,540 to 14,640 feet in the Cockleshell Gully Formation. Testing of the interval 13,962 to 14,704 feet produced up to 270 barrels/day of oil and 3.92 mmcf/day of gas.

Mt. Adams No. 1

Type: Test well.
License to Prospect: 171H.
Latitude and Longitude: 29° 24' 25" S., 115° 10' 00" E.
Elevation: Ground level 282 feet, rotary table 298 feet.
Commenced: 26th March, 1966.
Rig released: 24th May, 1966.
Total depth: 12,438 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Preston No. 1

Type: Stratigraphic well.
Latitude and Longitude: 32° 56' 53" S., 115° 42' 33" E.
Elevation: Ground level 20 feet, rotary table 25 feet.
Commenced: 26th August, 1966.
Rig released: 18th September, 1966.
Total depth: 2,511 feet.
Bottomed in: Lower Jurassic.
Status: Dry, plugged, and abandoned.

Sue No. 1

Type: Test well.
License to Prospect: 152H.
Latitude and Longitude: 34° 03' 54" S., 115° 19' 04" E.
Elevation: Ground level 269 feet, rotary table 282 feet.
Commenced: 31st January, 1966.
Rig released: 8th March, 1966.
Total depth: 10,097 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

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 2 test wells (Glenroy No. 1 and Onslow No. 1), 5 structure wells (Merlinleigh Nos. 1-5),

and 2 stratigraphic wells (Long Island No. 1 and Tortoise Island No. 1) on this permit in 1966, and another test well, Kennedy Range No. 1, was still drilling at the end of the year. Onslow No. 1 yielded a small flow of gas from a Lower Cretaceous sand, but was abandoned. The other wells were dry. Details of the wells are as follows:

Glenroy No. 1

Type: Test well.
License to Prospect: 174H.
Latitude and Longitude: 21° 49' 05" S., 114° 52' 28" E.
Elevation: Ground level 10 feet, rotary table 15 feet.
Commenced: 19th October, 1966.
Rig released: 29th October, 1966.
Total depth: 2,127 feet.
Bottomed in: Lower Cretaceous.
Status: Dry, plugged, and abandoned.

Kennedy Range No. 1

Type: Test well.
License to Prospect: 153H.
Latitude and Longitude: 24° 29' 45" S., 114° 59' 27" E.
Elevation: Ground level 968 feet, kelly bushing 980 feet.
Commenced: 1st December, 1966.
Status: Drilling ahead at 5,694 feet on 31st December, 1966.

Long Island No. 1

Type: Stratigraphic well.
License to Prospect: 165H.
Latitude and Longitude: 21° 37' 10" S., 114° 41' 10" E.
Elevation: Ground level 16 feet, rotary table 30 feet.
Commenced: 21st September, 1966.
Rig released: 3rd November, 1966.
Total depth: 7,081 feet.
Bottomed in: Middle Triassic.
Status: Dry, plugged, and abandoned.

Merlinleigh No. 1

Type: Structure well.
Latitude and Longitude: 24° 29' 48" S., 114° 59' 15" E.
Elevation: Ground level 953 feet, rotary table 958 feet.
Commenced: 18th May, 1966.
Rig released: 26th May, 1966.
Total depth: 1,000 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Merlinleigh No. 2

Type: Structure well.
Latitude and Longitude: 24° 28' 45" S., 114° 59' 27" E.
Elevation: Ground level 961 feet, rotary table 966 feet.
Commenced: 30th May, 1966.
Rig released: 15th June, 1966.
Total depth: 1,003 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Merlinleigh No. 3

Type: Structure well.
Latitude and Longitude: 24° 29' 08" S., 114° 59' 53" E.
Elevation: Ground level 964 feet, rotary table 969 feet.
Commenced: 30th June, 1966.
Rig released: 6th July, 1966.
Total depth: 545 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Merlinleigh No. 4

Type: Structure well.
Latitude and Longitude: 24° 29' 08" S., 114° 58' 57" E.
Elevation: Ground level 950 feet, rotary table 955 feet.
Commenced: 6th July, 1966.
Rig released: 10th July, 1966.
Total depth: 445 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Merlinleigh No. 5

Type: Structure well.
Latitude and Longitude: 24° 28' 27" S., 114° 59' 07" E.
Elevation: Ground level 952 feet, rotary table 957 feet.
Commenced: 14th July, 1966.
Rig released: 18th July, 1966.
Total depth: 575 feet.
Bottomed in: Lower Permian.
Status: Dry, plugged, and abandoned.

Onslow No. 1

Type: Test well.
License to Prospect: 174H.
Latitude and Longitude: 21° 45' 56" S., 114° 52' 17" E.
Elevation: Ground level 0 feet, rotary table 16 feet.
Commenced: 1st September, 1966.
Rig released: 14th November 1966.
Total depth: 9,835 feet.
Bottomed in: Permian.
Status: A drill stem test of the interval 1,724 to 1,728 feet in the 'Basal Cretaceous Sandstone' yielded 100 to 200 mcf/day of gas and 150 to 160 barrels/day of water. Plugged and abandoned.

Tortoise Island No. 1

Type: Stratigraphic.
License to Prospect: 173H.
Latitude and Longitude: 21° 35' 08" S., 114° 51' 11" E.
Elevation: Ground level 16 feet, rotary table 30 feet.
Commenced: 14th November, 1966.
Rig released: 26th December, 1966.
Total depth: 7,000 feet.
Bottomed in: Jurassic.
Status: Dry, plugged, and abandoned.

PERMIT TO EXPLORE 30H

Permit to Explore 30H covers part of the Canning Basin and is held by West Australian Petroleum Pty. Ltd. The company drilled a single well, Kidson No 1, in the permit area during 1966. Details are as follows:

Kidson No. 1

Type: Test well.
License to Prospect: 155H.
Latitude and Longitude: 22° 37' 00" S., 125° 00' 27" E.
Elevation: Ground level 1,165 feet, rotary table 1,181 feet.
Commenced: 21st November, 1965.
Rig released: 20th July, 1966.
Total depth: 14,539 feet.
Bottomed in: Lower Ordovician.
Status: Dry, plugged, and abandoned.

PERMIT TO EXPLORE 147H

Permit to Explore 147H was held by Hunt Oil Co. and Placid Oil Co. in the Officer Basin. A single well, Yowalga No. 2, was drilled on this permit during the year. This hole encountered Proterozoic rocks at shallow depth, and as a result the companies decided to withdraw from exploration in this State, and relinquished the concessions they had held. Details of the well are as follows:

Yowalga No. 2

Type: Test well.
License to Prospect: 170H.
Latitude and Longitude: 26° 10' 12" S., 125° 58' 00" E.
Elevation: Ground level 1,550 feet, kelly bushing 1,563 feet.
Commenced: 1st March, 1966.
Rig released: 24th March, 1966.
Total depth: 3,246 feet.
Bottomed in: Upper Proterozoic.
Status: Dry, plugged, and abandoned.

PERMIT TO EXPLORE 151H

Permit to Explore 151H is held by Beach-General Exploration Pty. Ltd. in the eastern Canning Basin. The permit is farmed out to Australian Aquitaine Petroleum Pty. Ltd., and the company completed one stratigraphic well, Point Moody No. 1, during the year. Details are as follows:

Pt. Moody No. 1

Type: Stratigraphic well.
License to Prospect: 154H.
Latitude and Longitude: 21° 15' 34" S., 127° 48' 22" E.
Elevation: Ground level 1,387 feet, rotary table 1,400 feet.
Commenced: 2nd October, 1965.
Rig released: 14th January, 1966.
Total depth: 8,009 feet.
Bottomed in: Upper Carboniferous.
Status: Minor gas shows. Plugged and abandoned.

PERMIT TO EXPLORE 217H

Permit to Explore 217H covers the northern end of the Carnarvon Basin and is held by West Australian Petroleum Pty. Ltd. The company drilled 10 test wells (Barrow Nos. 19-28) and 5 development wells on Barrow Island during the year. The development wells and Barrow Nos. 27 and 28 were suspended at the end of the year, pending completion as producing wells. Of the others all except Barrow No. 25 (which was dry) were completed as producers.

It was announced in May, 1966, that West Australian Petroleum Pty. Ltd. would proceed with the commercial development of the Barrow Island oilfield. Production would commence in May, 1967 at a rate of about 9,000 barrels per day, and this was expected to rise to about 20,000 barrels per day in two years.

A total of 6 producing reservoirs have now been established on Barrow Island; the Windalia sands at about 2,000 feet (oil and gas), the Neocomian sands at about 5,500 feet (gas and condensate), and four Jurassic sands at about 6,200 feet, 6,600 feet, 6,700 feet, and 6,870 feet respectively (oil and gas). Of these the Windalia is the most extensive, and production will be mainly from this reservoir, although the Jurassic sands will also contribute. The Windalia field covers some 24,700 acres with an average productive sand interval of 44 feet. It is estimated that 240 wells, on 80-acre spacing, will be required to develop this field. The primary recovery percentage from the Windalia sands is expected to be low as they have very low permeabilities, and commonly require fracturing. The company initially estimated that the primary recovery from the Windalia would amount to at least 85,000,000 barrels, but subsequently it was announced that this figure had been increased to 114,000,000 barrels. The company will also experiment with secondary recovery methods to determine whether the economic recovery can be increased.

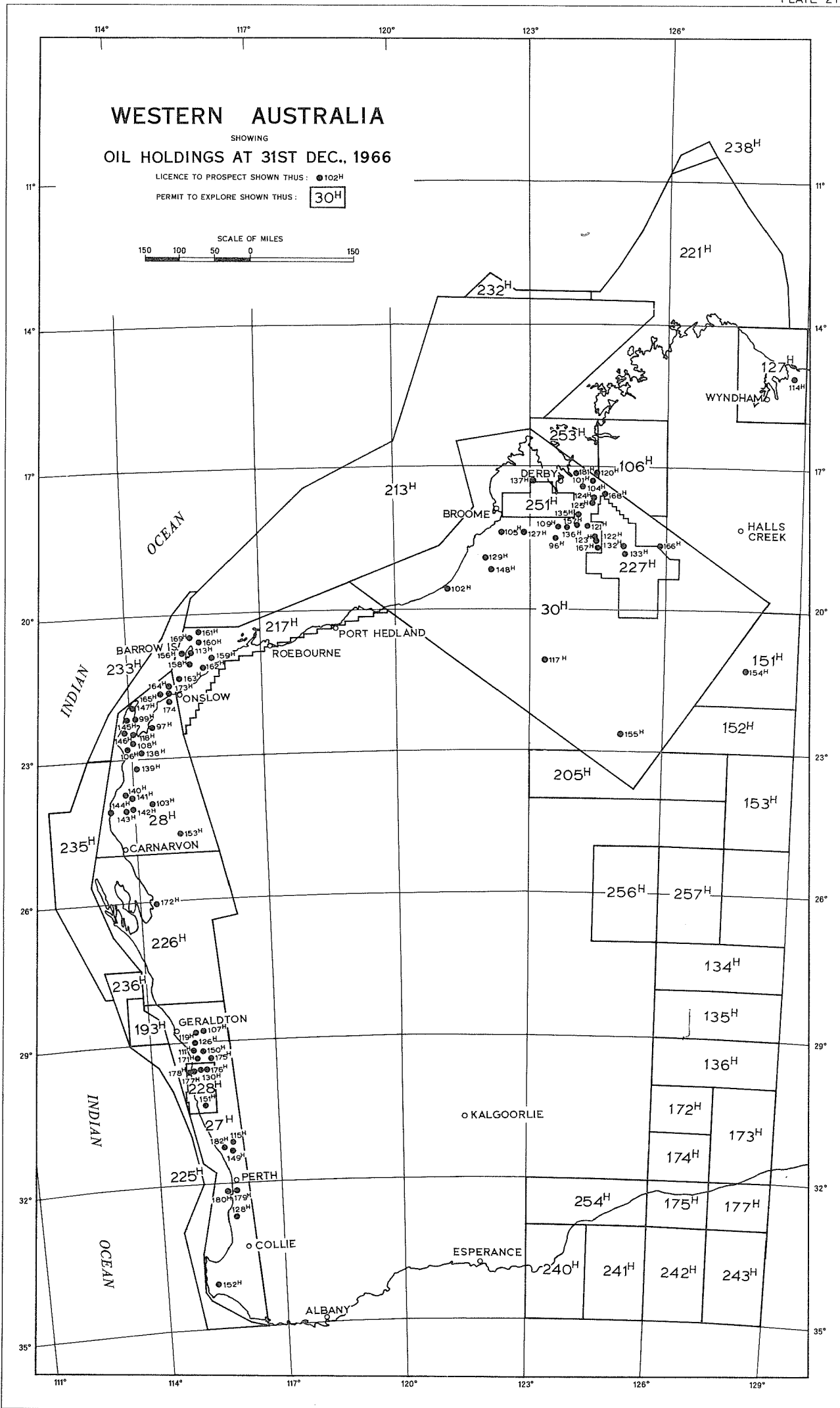
Details of wells drilled during 1966 are as follows:

Barrow No. 19

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 47' 13" S., 115° 22' 30" E.
Elevation: Ground level 130 feet, rotary table 141 feet.
Commenced: 2nd January, 1966.
Rig released: 10th January, 1966.
Total depth: 2,459 feet.
Bottomed in: Lower Cretaceous.
Status: Oil well, completed over the intervals 2,252 to 2,260 feet, and 2,266 to 2,284 feet in the Windalia Radiolarite.

Barrow No. 20

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 47' 37" S., 115° 24' 51" E.
Elevation: Ground level 109 feet, rotary table 120 feet.
Commenced: 12th January, 1966.
Rig released: 20th January, 1966.
Total depth: 2,465 feet.
Bottomed in: Lower Cretaceous.
Status: Oil well, completed over the intervals 2,334 to 2,326 feet, 2,320 to 2,310 feet, 2,304 to 2,298 feet, 2,280 to 2,266 feet, 2,260 to 2,244 feet and 2,238 to 2,230 feet in the Windalia Radiolarite.



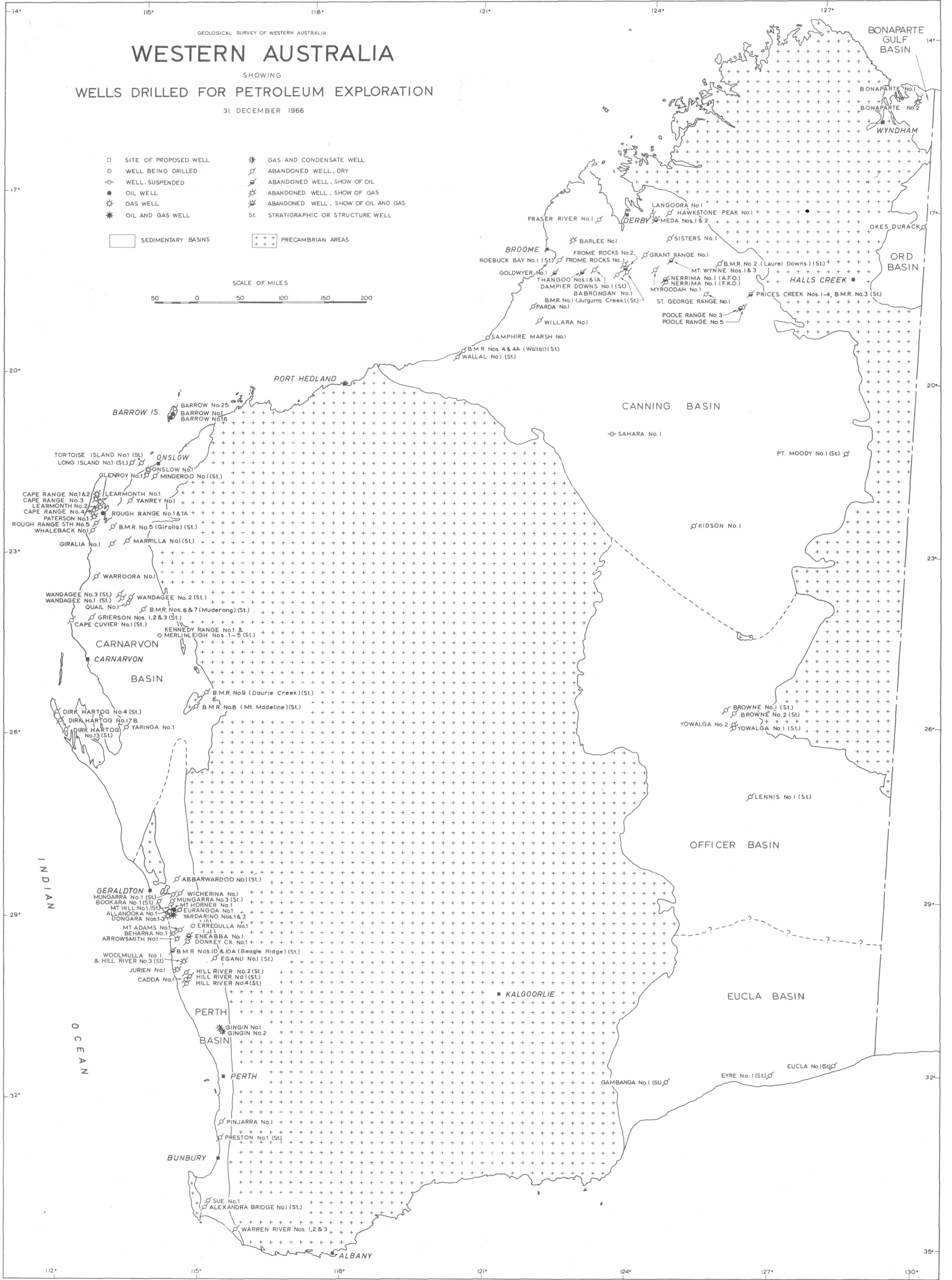
WESTERN AUSTRALIA

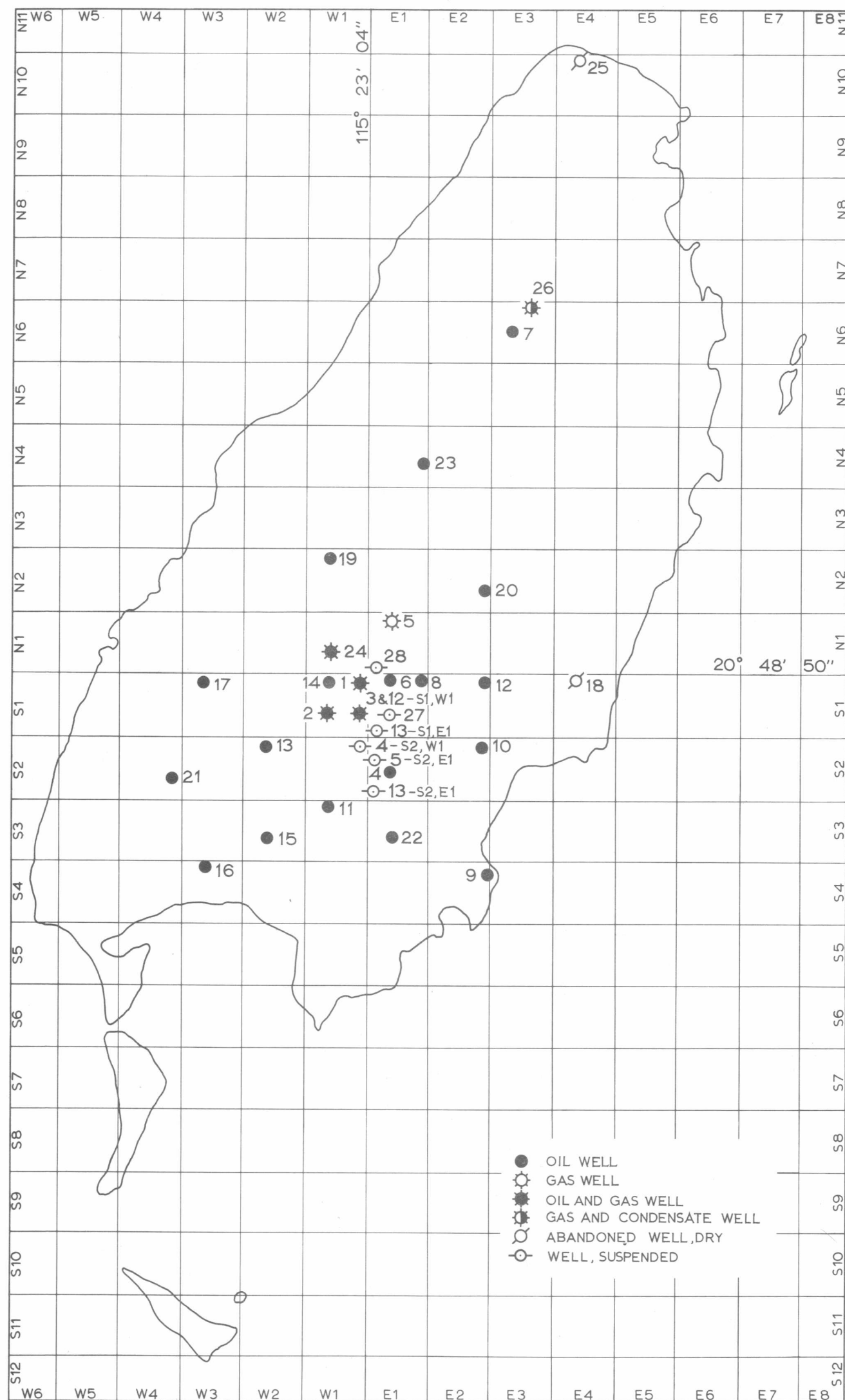
SHOWING
WELLS DRILLED FOR PETROLEUM EXPLORATION
31 DECEMBER 1966

- | | |
|-------------------------|---------------------------------------|
| ○ SITE OF PROPOSED WELL | ✱ GAS AND CONDENSATE WELL |
| ○ WELL BEING DRILLED | ✱ ABANDONED WELL, DRY |
| ○ WELL, SUSPENDED | ✱ ABANDONED WELL, SHOW OF OIL |
| ● OIL WELL | ✱ ABANDONED WELL, SHOW OF GAS |
| ✱ GAS WELL | ✱ ABANDONED WELL, SHOW OF OIL AND GAS |
| ✱ OIL AND GAS WELL | St. STRATIGRAPHIC OR STRUCTURE WELL |

SEDIMENTARY BASINS

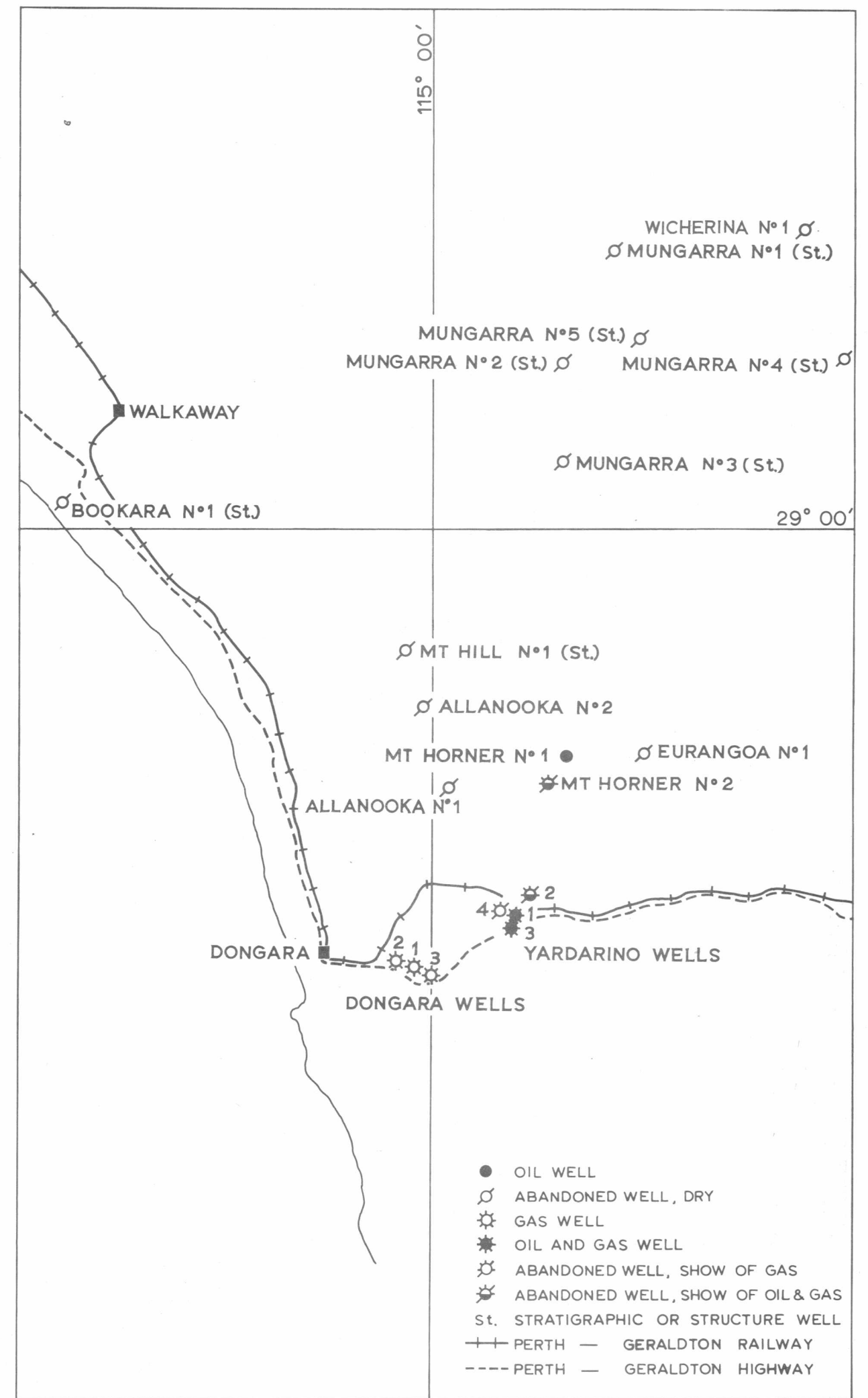
PRECAMBRIAN AREAS





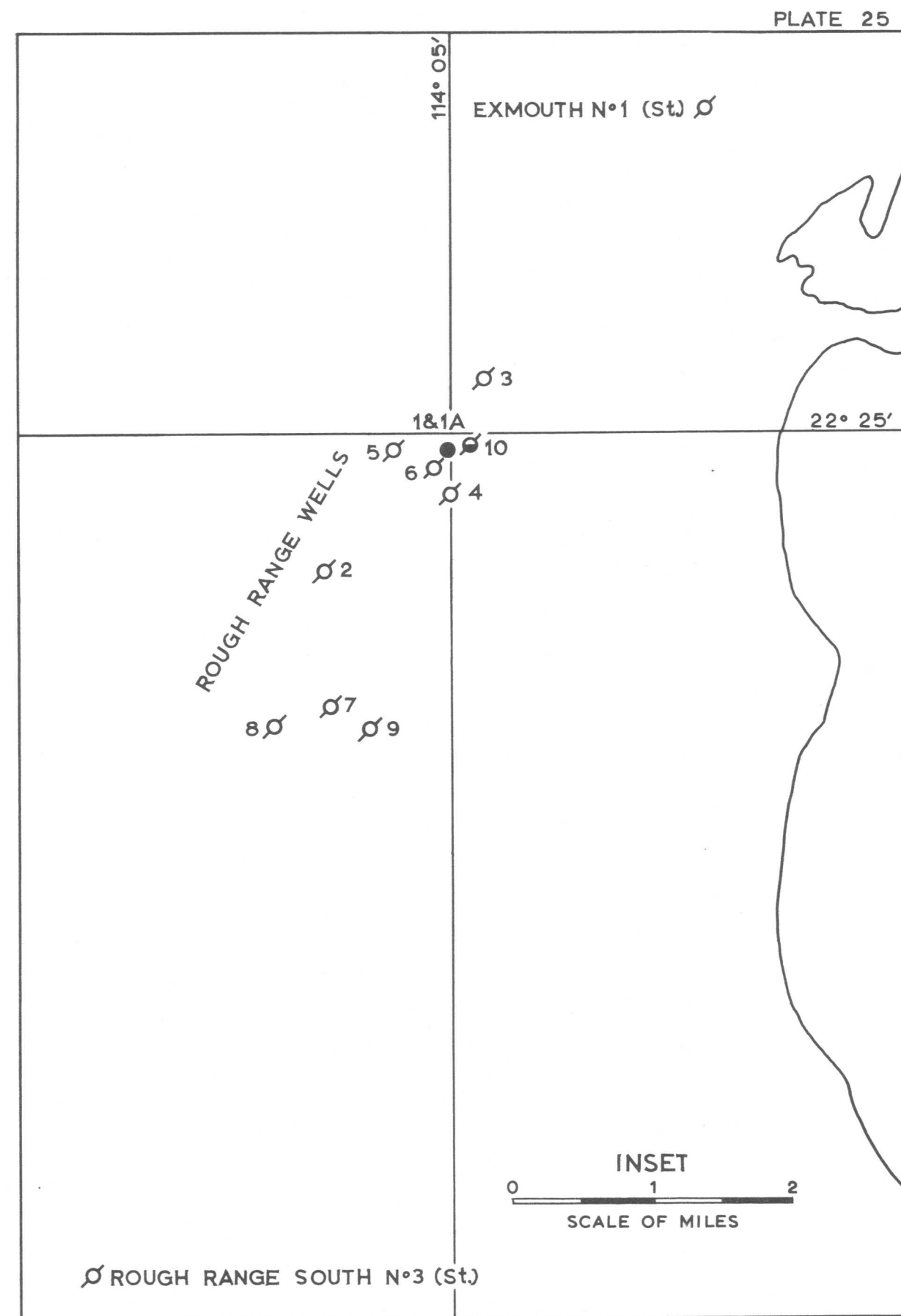
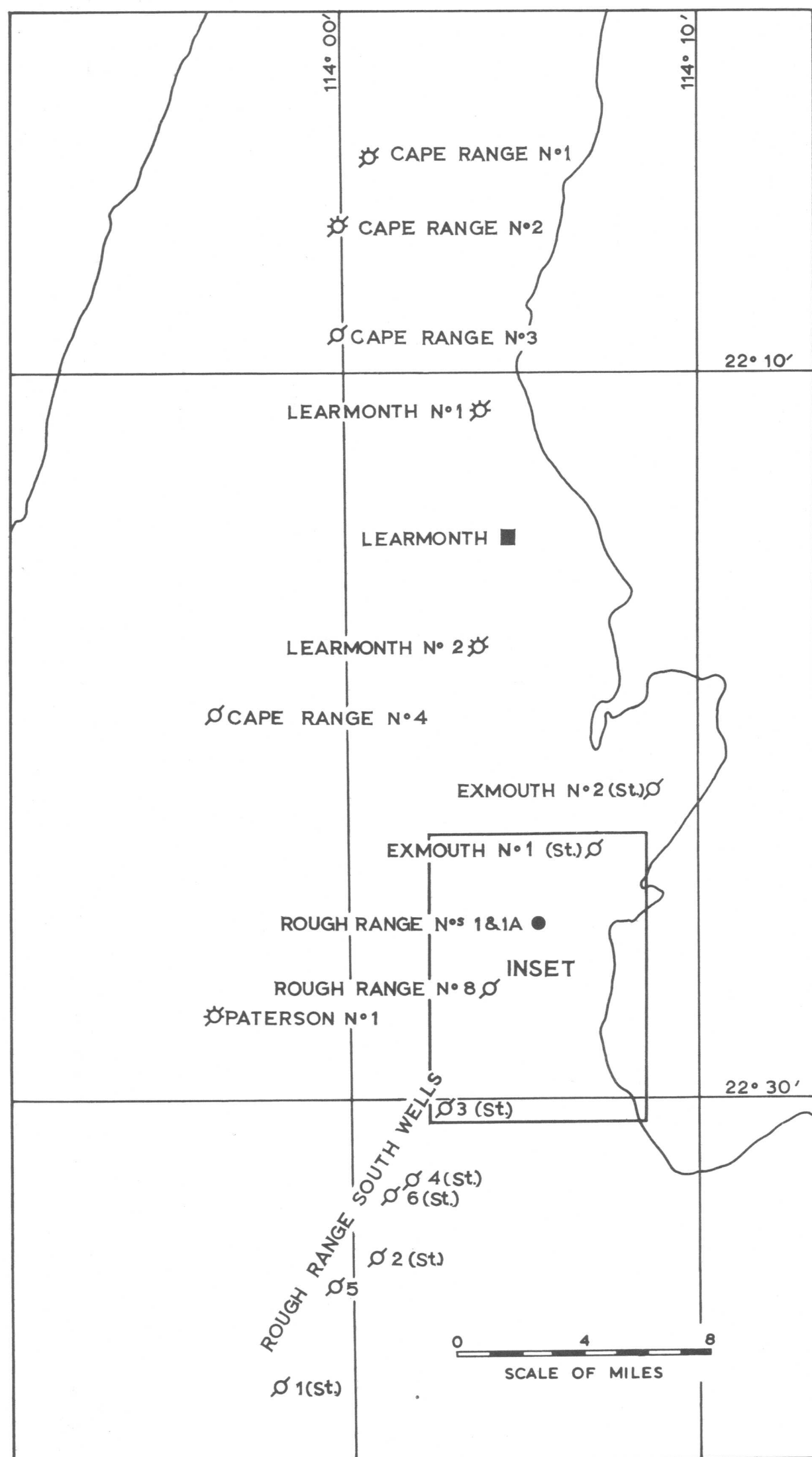
BARROW ISLAND
SHOWING WELLS DRILLED FOR PETROLEUM

1 0 1 2 3
SCALE OF MILES



DONGARA AREA
SHOWING WELLS DRILLED FOR PETROLEUM

0 4 8
SCALE OF MILES



- OIL WELL
- ABANDONED WELL, DRY
- ⊗ ABANDONED WELL, SHOW OF OIL
- ⊗ ABANDONED WELL, SHOW OF GAS
- St. STRATIGRAPHIC OR STRUCTURE WELL

CAPE RANGE - ROUGH RANGE AREA
SHOWING WELLS DRILLED FOR PETROLEUM

Barrow No. 21

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 50' 17" S., 115° 25' 11" E.
Elevation: Ground level 95 feet, rotary table 106 feet.
Commenced: 22nd January, 1966.
Rig released: 30th January, 1966.
Total depth: 2,435 feet.
Bottomed in: Lower Cretaceous.
Status: Oil well, completed over the intervals 2,258 to 2,284 feet, and 2,318 to 2,325 feet in the Windalia Radiolarite.

Barrow No. 22

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 51' 09" S., 115° 23' 27" E.
Elevation: Ground level 50 feet, rotary table 61 feet.
Commenced: 2nd February, 1966.
Rig released: 12th February, 1966.
Total depth: 2,709 feet.
Bottomed in: Lower Cretaceous.
Status: Oil well, completed over the intervals 2,489 to 2,501 feet, and 2,532 to 2,538 feet in the Windalia Radiolarite.

Barrow No. 23

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 45' 55" S., 115° 23' 53" E.
Elevation: Ground level 189 feet, rotary table 200 feet.
Commenced: 15th February, 1966.
Rig released: 21st February, 1966.
Total depth: 2,580 feet.
Bottomed in: Lower Cretaceous.
Status: Oil well, completed over the interval 2,362 to 2,381 feet in the Windalia Radiolarite.

Barrow No. 24

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 48' 30" S., 115° 22' 30" E.
Elevation: Ground level 169 feet, rotary table 180 feet.
Commenced: 24th February, 1966.
Rig released: 1st April, 1966.
Total depth: 7,349 feet.
Bottomed in: Upper Jurassic.
Status: Oil and gas well, completed over the interval 6,218 to 6,222 feet in Jurassic sediments.

Barrow No. 25

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 40' 17" S., 115° 26' 19" E.
Elevation: Ground level 53 feet, rotary table 64 feet.
Commenced: 12th April, 1966.
Rig released: 17th May, 1966.
Total depth: 8,314 feet.
Bottomed in: Upper Jurassic.
Status: Dry, plugged and abandoned.

Barrow No. 26

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 43' 41" S., 115° 25' 32" E.
Elevation: Ground level 171 feet, rotary table 183 feet.
Commenced: 21st May, 1966.
Rig released: 3rd July, 1966.
Total depth: 7,875 feet.
Bottomed in: Upper Jurassic.
Status: Gas and condensate well, completed over the interval 5,550 to 5,555 feet in Lower Cretaceous sandstone.

Barrow No. 27

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 49' 24" S., 115° 23' 28" E.

Elevation: Ground level 217 feet, rotary table 228 feet.
Commenced: 5th July, 1966.
Rig released: 22nd July, 1966.
Total depth: 7,304 feet.
Bottomed in: Upper Jurassic.
Status: Suspended awaiting completion as a producing well.

Barrow No. 28

Type: Test well.
License to Prospect: 113H.
Latitude and Longitude: 20° 48' 45" S., 115° 23' 12" E.
Elevation: Ground level 188 feet, rotary table 199 feet.
Total depth: 7,000 feet.
Commenced: 5th August, 1966.
Rig released: 25th August, 1966.
Bottomed in: Upper Jurassic.
Status: Suspended, awaiting completion as a producing well.

Barrow 12-S1, W1

Type: Development well.
License to Prospect: 113H.
Location: Twin well with Barrow No. 3.
Elevation: Ground level 150 feet, rotary table 161 feet.
Commenced: 4th December, 1966.
Rig released: 8th December, 1966.
Total depth: 2,361 feet.
Bottomed in: Lower Cretaceous.
Status: Suspended, awaiting testing.

Barrow 13-S1, E1

Type: Development well.
License to Prospect: 113H.
Location: 20 chains south and 20 chains east of Barrow No. 3.
Elevation: Ground level 167 feet, rotary table 178 feet.
Commenced: 9th December, 1966.
Rig released: 13th December, 1966.
Total depth: 2,354 feet.
Bottomed in: Lower Cretaceous.
Status: Suspended, awaiting testing.

Barrow 4-S2, W1

Type: Development well.
License to Prospect: 113H.
Location: 40 chains south of Barrow No. 3.
Elevation: Ground level 185 feet, rotary table 195 feet.
Commenced: 14th December, 1966.
Rig released: 17th December, 1966.
Total depth: 2,300 feet.
Bottomed in: Lower Cretaceous.
Status: Suspended, awaiting testing.

Barrow 5-S2, E1

Type: Development well.
License to Prospect: 113H.
Location: 60 chains south and 20 chains east of Barrow No. 3.
Elevation: Ground level 141 feet, rotary table 151 feet.
Commenced: 18th December, 1966.
Rig released: 22nd December, 1966.
Total depth: 2,290 feet.
Bottomed in: Lower Cretaceous.
Status: Suspended, awaiting testing.

Barrow 13-S2, E1

Type: Development well.
License to Prospect: 113H.
Location: 100 chains south and 20 chains east of Barrow No. 3.
Elevation: Ground level 85 feet, rotary table 96 feet.
Commenced: 22nd December, 1966.
Rig released: 1st January, 1967.
Total depth: 2,198 feet.
Bottomed in: Lower Cretaceous.
Status: Suspended, awaiting testing.

PERMIT TO EXPLORE 226H

Permit to Explore 226H is held by West Australian Petroleum Pty. Ltd. and is farmed out to Continental Oil Company of Australia Ltd. and Australian Sun Oil Company Ltd. It covers the southern part of the Carnarvon Basin. One test well, Yaringa No. 1, was drilled in the permit area in 1966. Details are as follows:

Yaringa No. 1

Type: Test well.
License to Prospect: 172H.
Latitude and Longitude: 26° 03' 58" S., 114° 21' 35" E.
Elevation: Ground level 70 feet, kelly bushing 88 feet.
Commenced: 2nd July, 1966.
Rig released: 18th August, 1966.
Total depth: 7,508 feet.
Bottomed in: ?Ordovician.
Status: Dry, plugged, and abandoned.

PERMIT TO EXPLORE 227H

Permit to Explore 227H is held by West Australian Petroleum Pty. Ltd. and is farmed out to Continental Oil Company of Australia Ltd. and Australian Sun Oil Company Ltd. One test well, St. George Range No. 1, was drilled in this permit area during 1966. Details are as follows:

St. George Range No. 1

Type: Test Well.
License to Prospect: 132H.
Latitude and Longitude: 18° 41' 30" S., 125° 08' 11" E.
Elevation: Ground level 566 feet, kelly bushing 584 feet.
Commenced: 16th September, 1965.
Rig released: 15th May, 1966.
Total depth: 14,553 feet.
Bottomed in: Lower 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. Two wells, Beharra No. 1 and Donkey Creek No. 1, were drilled in the permit area during 1966. Details are as follows:

Beharra No. 1

Type: Test well.
License to Prospect: 177H.
Latitude and Longitude: 29° 29' 10" S., 115° 00' 45" E.
Elevation: Ground level 74 feet, kelly bushing 95 feet.
Commenced: 28th November, 1966.
Rig released: 16th December, 1966.
Total depth: 6,744 feet.
Bottomed in: Precambrian.
Status: Dry, plugged, and abandoned.

Donkey Creek No. 1

Type: Test well.
License to Prospect: 176H.
Latitude and Longitude: 29° 37' 35" S., 115° 17' 25" E.
Elevation: Ground level 350 feet, kelly bushing 365 feet.
Commenced: 30th August, 1966.
Rig released: 21st October, 1966.
Total depth: 12,640 feet.
Bottomed in: Lower Triassic.
Status: Dry, plugged, and abandoned.

GEOFYSICAL OPERATIONS

Seismic

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

| Company | Permit | Basin | Party Months |
|--|--------|----------------|---------------|
| West Australian Petroleum Pty. Ltd. | 27H | Perth | 24.42 (land) |
| do. | 28H | Carnarvon | 1.9 (marine) |
| do. | 30H | Canning | 5.81 (land) |
| do. | 217H | Carnarvon | 0.31 (marine) |
| do. | 225H | Perth | 8.65 (land) |
| Gewerkschaft Elwerath | 251H | Canning | 5.30 (marine) |
| Continental Oil Co. of Australia Ltd. | 226H | Carnarvon | 0.10 (marine) |
| do. | 227H | Canning | 5.0 (land) |
| Arco Ltd. and Anacapa Corp. | 127H | Bonaparte Gulf | 1.32 (land) |
| do. | 221H | do. | 0.65 (land) |
| B.O.C. of Australia Ltd. | 213H | Canning | 2.0 (marine) |
| French Petroleum Co. (Aust.) Pty. Ltd. | 228H | Perth | 7.0 (marine) |
| BP Petroleum Development Aust. Pty. Ltd. | 193H | Perth | 0.57 (marine) |
| Canadian Superior Oil (Aust.) Pty. Ltd. | 235H | Carnarvon | 5.5 (land) |
| | 236H | | 0.5 (marine) |
| | | | 2.5 (marine) |

Gravity

A gravity survey was carried out during the year in the Perth Basin, on Permit to Explore 228H, for French Petroleum Company (Aust.) Pty. Ltd. This amounted to 5.5 party months.

Magnetic

West Australian Petroleum Pty. Ltd. conducted an aeromagnetic survey over 2,665 line miles on Permit to Explore 30H in the Canning Basin. A ground magnetic survey totalling 390 line miles was carried out by Gewerkschaft Elwerath on Permit to Explore 251H in the Canning Basin.

GEOLOGICAL OPERATIONS

Field geological studies were carried out by oil exploration companies in the Carnarvon, Canning, and Officer Basins. They were distributed as follows:

| Company | Permit | Basin | Geologist Months |
|-------------------------------------|--------|-------------------|------------------|
| West Australian Petroleum Pty. Ltd. | 30H | Canning | 3 |
| Gewerkschaft Elwerath | 251H | Canning | 4 |
| French Petroleum (Aust.) Pty. Ltd. | .... | Canning & Officer | 2 |

Photogeological work was conducted by Coastal Petroleum N. L. over Permits to Explore 172H-177H (1.7 geologist months), and an airborne Profile Recording Survey was carried out over Permits to Explore 151H and 152H by Australian Aquitaine Petroleum Pty. Ltd. (party of 6 for 4 months). The Geological Survey of Western Australia continued its mapping programme in the Eucla Basin (6 geologist months) and Perth Basin (3.5 geologist months).

A LATE PRECAMBRIAN BELT OF VULCANICITY IN CENTRAL AUSTRALIA

by R. C. Horwitz and J. L. Daniels

ABSTRACT

In central Australia crystalline rocks occur between the Amadeus, Eucla, and Officer basins. These rocks are part of a Precambrian complex referred to in South Australia as the Musgrave-Mann Complex. The complex is part of a tectonic unit which has been referred to as the Pitjantara Shield and the Musgrave Block.

These crystalline rocks have been mapped in Western Australia on parts of the Cooper, Scott, and Talbot 1:250,000 Sheet areas by the Geological Survey of Western Australia, and mapped on the Rawlinson Sheet area by the Bureau of Mineral Resources.

The present stage of mapping allows a better understanding of the distribution and chronology of volcanic rocks of the region and corre-

lations can be suggested with their possible equivalent in other areas. The occurrences define a belt with vulcanicity closely related to a belt with contemporaneous evaporite beds, leading to diapirism. These all define a palaeogeographic trend in Australia for the upper Middle Proterozoic.

CENTRAL AUSTRALIA

A sequence of interbanded basic, acid, and intermediate volcanic flows has been recognised in the Talbot, Cooper, Scott, and Rawlinson Sheet areas of Western Australia and in the Bloods Range Sheet area of the Northern Territory. Their continuity, by structural repetition, has been established in the Scott and Cooper Sheet areas (Horwitz and others, 1967). In the Scott, Rawlinson (W.A.), and Bloods Range (N.T.) Sheet areas, their continuity has also been established by structural repetition. Forman and Hancock (1964) refer to the lavas as the Mount Harris Basalt, but the unit is known to include acid flows. The consanguinity of these volcanic rocks with those of the Talbot Sheet is recognised by comparison of sequences and by results of age determinations.

On the Cooper Sheet, the base of this mixed volcanic sequence is not exposed because it is masked by the intrusion of granite and gabbro-granophyre sheets and these rocks are folded in sympathy (Horwitz and others, 1967). A sequence of basalts, not intruded by granite, and a basal conglomerate rest unconformably on the eroded core of an anticline which involves the mixed volcanic suite and both sheets of plutonic rocks. The sequence of mixed volcanic rocks (at Tollu & Skirmish Hill), intruded by granite and overlain unconformably (at McDougall Bluff) by basalts, is thus similar to the sequence described on the Talbot Sheet in the Warburton Range (Horwitz and Sofoulis, 1963). The large porphyry bodies formerly considered to be intrusive are now known to be volcanic flows, at least in part.

Acidic volcanic rocks, in the mixed volcanic suite, have been dated by W. Compston at the Australian National University. Samples from the Tollu area, on the Cooper Sheet, and from the Warburton area, on the Talbot Sheet, indicate an age of the order of 1,100 m.y. (Compston pers. comm. 1965).

Thomson (1966), in a review on the age of the metamorphic rocks of the region, rightly suggested that the Mount Harris Basalt and the volcanic rocks of Skirmish Hill could be cogenetic but his reference to the "Skirmish Hill Area (W.A.)" is ambiguous. The basal conglomerate, referred to in his table (p. 223) for the Skirmish Hill area (Cooper Sheet) probably applies to the younger set of basalts of McDougall Bluff, and, because of an unfortunate selection of descriptions for different parts of the sequence from different authors, in the Warburton Range area (Talbot Sheet) this author's table wrongly implies that basic dykes are older than the basic volcanic rocks above the unconformity.

The basal contact of the mixed flows is, however, exposed in the northern part of the crystalline complex, where the plutonic sheets that intrude the volcanic assemblage do not persist as large bodies. On the Scott Sheet, in the Giles Creek region, the Mount Harris Basalt rests unconformably on a basement of rapakivi-like granite (a granite packed with large feldspar ovoids, but not known to carry oligoclase-rimmed potash feldspars. This is the rock referred to as pyterlite by Eskola, 1963). The relationship is locally obscured by the younger granite which contains large phenocrysts of feldspar, some rounded and others euhedral. The presence of an unconformity at this stratigraphic position in this general area, although already recognised by Forman, was later rejected (Forman and Hancock, 1964), probably because of the similarity in a porphyritic facies between the pyterlite, the younger granite, and some of the coarsely porphyritic flows in the mixed volcanic suite.

On the northern side of this Musgrave Block, Forman and Hancock show that the crystalline complex containing the Mount Harris Basalt is overlain unconformably by the Dean Quartzite followed by the Pinyinna Beds which these authors equate with the Heavitree Quartzite and Bitter Springs Limestone (Joklik, 1955) respectively. These are overlain by the Areyonga Formation (Prichard and Quinlan, 1962), or its equivalents, which contain glacial beds, recognised as part of the Sturtian Series by Mawson (1957). There is no record of defined volcanic flows in the Bitter Springs Limestone though volcanic tuffs have been recognised (Webb, 1959).

On the Talbot Sheet, boulder beds that overlie unconformably the younger basalt have been equated with the glacials of the Sturtian Series of the Adelaide System (Horwitz, 1966). These are younger than the basic dykes in the region, a relationship already established to the east on the Alberga Sheet (S.A.) by Coats (1963).

Little or no sediment is interstratified with the mixed volcanic rocks on the Cooper Sheet. On the Scott Sheet (in the Giles Creek area, Kathleen Range, and Dean Range) phyllitic siltstone and sandstone occur, interstratified with lava flows. These mixed flows are interlayered with dolomite and chert in the Warburton Range on the Talbot Sheet (Sofoulis, 1962). On the northern part of the Cooper Sheet, the two plutonic sheets, intrusive into this volcanic sequence, have their maximum development and it is possible that these are aspects of related igneous activity (Horwitz and others, 1967; Daniels, 1967).

It is concluded that mixed acid and basic lavas were extruded within a fairly well defined area in the Musgrave Block. It is part of an igneous complex forming the youngest crystalline basement to the Upper Proterozoic glacial deposits which are so well developed in parts of the Adelaide System.

CORRELATIONS WITH OTHER REGIONS

Walpole and others (1965) tentatively correlated the Mount Harris Basalt with volcanic rocks known to be older than 1,400 m.y., from the northern part of the Northern Territory. They also correlated them with unnamed volcanic rocks on the northwestern edge of the Amadeus Basin. The first correlation conflicts with recent age determinations and is discarded. The second correlation is believed to apply to rocks described by Wells and others (1961) on the northeastern part of the MacDonald Sheet, which lies north of the Scott Sheet. These authors describe, amongst other rock types, porphyritic dacite and rhyolite associated with shale, siltstone, sandstone, and chert in the region below the Heavitree Quartzite equivalents. There is, to our knowledge, no other record of vulcanicity older than the Heavitree Quartzite and ranging to the order of 1,100 m.y. on the northern edge of the Amadeus Basin, towards the east.

Correlations have been suggested for the volcanic rocks of the Musgrave Block with those of the Pilbara-Murchison general area of Proterozoic rocks. Thomson (1966) has proposed correlations with units of the Mt. Bruce Super-group, but these are contradicted by comparison with age determinations in Leggo and others (1965). The correlation with rocks of this area had been proposed previously, in a general way, by Sofoulis (1962) and appears to apply to a grouping of rocks that overlie the Archaean, south and west of Lake Carnegie in the Kingston Sheet area where four bands of rhyolite have been recognised, interlayered with sediment and possible tuffs. According to W. R. Jones (pers. comm. 1966) possible acidic lavas occur in the Edmund Sheet area in the Kiangi Creek Formation, a part of the Bangemall Group (Daniels, 1966).

Volcanic rocks have been recognised in the general area north of Wiluna, on the Glengarry, Peak Hill, and Nabberu Sheets and in the Billeranga Hills on the Perenjori Sheet, north of Perth, where thin lava flows have been identified. There are references to possible tuffs but no reference to defined flows in parts of the Precambrian between longitude 124° and the west coast, in rock

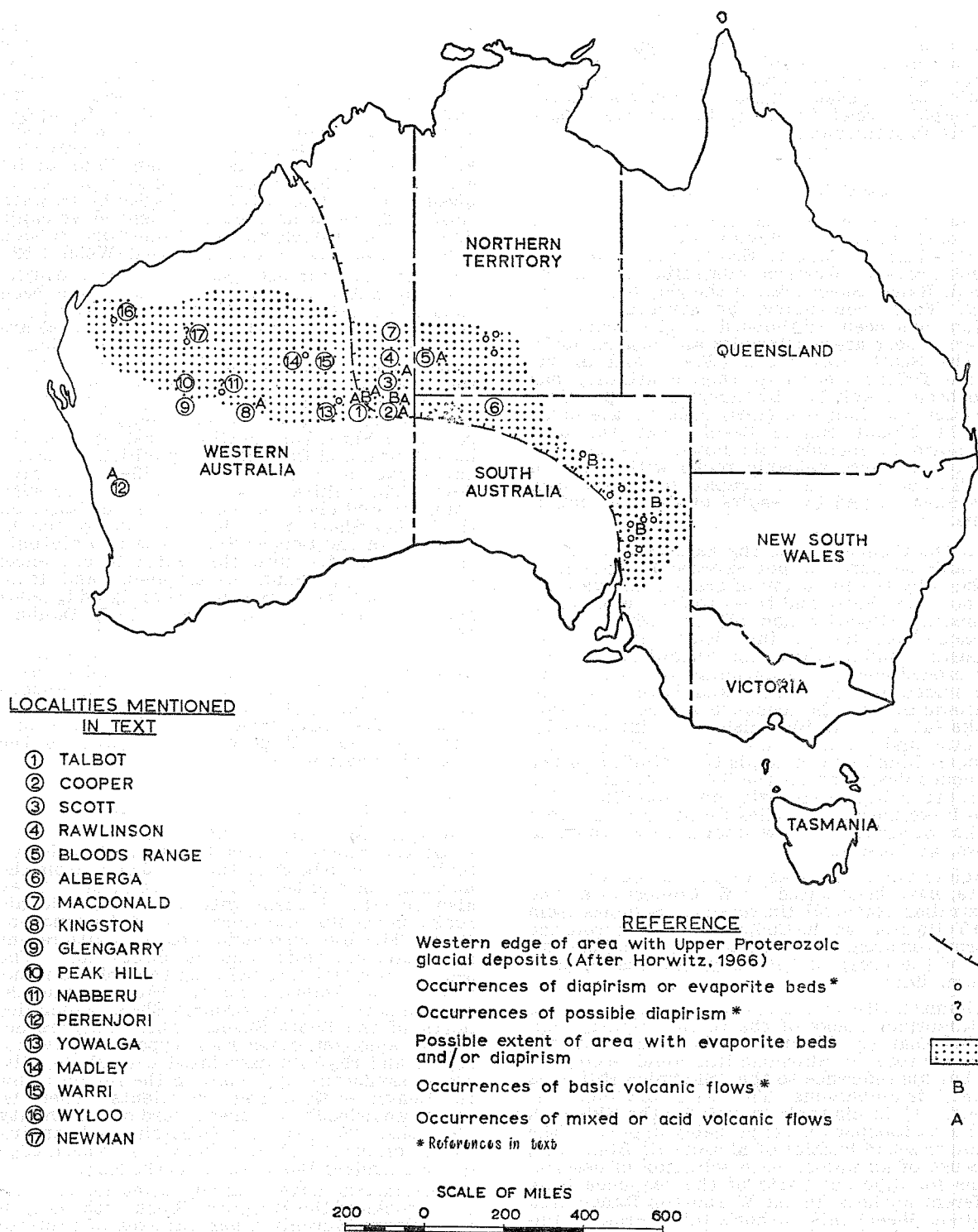


FIGURE 11
DISTRIBUTION IN AUSTRALIA OF LATE MIDDLE PROTEROZOIC
VULCANICITY AND EVAPORITE BEDS

sequences that have been recognised to equate possibly with those of the Musgrave Block. These areas are depicted in the 1966 edition of the Geological Map of Western Australia.

There is no record of volcanicity of comparable age in the Kimberley region of Western Australia.

On the Yowalga Sheet, 50 miles west of the last outcrops on the Talbot Sheet, basalts were intersected in depth in association with red-beds and evaporite deposits and were assigned to the late Precambrian.

Let us consider both sequences of flows in the Musgrave Block as a whole and include vulcanism that would range from 1,200 m.y. to the base of the late Precambrian glacial deposits. The occurrences of volcanic flows, here included in

this grouping (Figure 11), suggests that they are in an east-west trending belt. It is tempting to extend this belt eastwards to include some of the volcanic rocks of the northern and central Flinders Range of South Australia, all now included in the Willouran Series (Crawford, 1963). These volcanic rocks appear in piercement folds as well as in the layered sequence. Both the diapirism and the lava flows are a feature of the central and northern Flinders Range; no defined flows are recorded from the southern part of the Range.

The Willouran Series has been dated by Compston and others (1966) with a preferred age of about 1,400 m.y. but these authors leave open the possibility of the Willouran Series including rocks as young as 900 m.y.

If our correlation is adopted, there is sympathy in distribution and trend between volcanic flows and evaporite beds, believed to be indicative of a palaeogeographic zone marginal to a continent. These are plotted in Figure 11 from the data available in literature (Coats, 1965; Cook, 1966; Wells, 1963).

In the North-West Division of Western Australia, diapirism has been noted in the Bagemall Group near Mt. Florry on the Wyloo Sheet (Daniels, 1966). Previously un-recorded field observations suggests diapirism in the Newman and Nabberu Sheets.

The upper part of the Adelaide System has a general northwesterly trend in its distribution which is believed to be controlled by an old shore line (Horwitz, 1966).

The Adelaide System, as redefined (Thomson and others, 1964), is believed to be a complex grouping, at the intersection of separate units in the Precambrian. From evidence in Western Australia on age determinations carried out by W. Compston, a part of the Adelaide System can be assigned to the upper part of the Middle Proterozoic.

It is concluded that the upper Middle Proterozoic in Australia is controlled by an east-west palaeogeography, while the palaeogeography of the Upper Proterozoic runs north-south across Australia.

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A ZONE OF ARCHAEOAN CONGLOMERATES IN THE EASTERN GOLDFIELDS, WESTERN AUSTRALIA

by R. C. Horwitz, M. J. B. Kriewaldt, I. R. Williams and J. J. G. Doepel

ABSTRACT

Archaean conglomerates in the Eastern Goldfields of Western Australia lie in a zone that is oblique to the main fold axes and extends from Southern Cross and Norseman to north of Laverton. It is considered to reflect an Archaean chain of volcanic islands. In this zone oligomictic conglomerates are associated with flows and sills of felsic rocks. By contrast polymictic conglomerates are not associated with eruptive rocks.

INTRODUCTION

Archaean conglomerates in the Eastern Goldfields of Western Australia occur in a zone trending northeasterly through Kalgoorlie, and are believed to reflect the Archaean geography (Figure 12). Both oligomictic and polymictic conglomerates are found and are described in Western Australian Geological Survey Bulletins (Nos. 21, 42, 47, 56, 66, 71, 73, 79, 84, 97, 103, and 114) and annual reports (for 1947, 1960, 1961, and 1963). Age determinations by A. Turek, of the

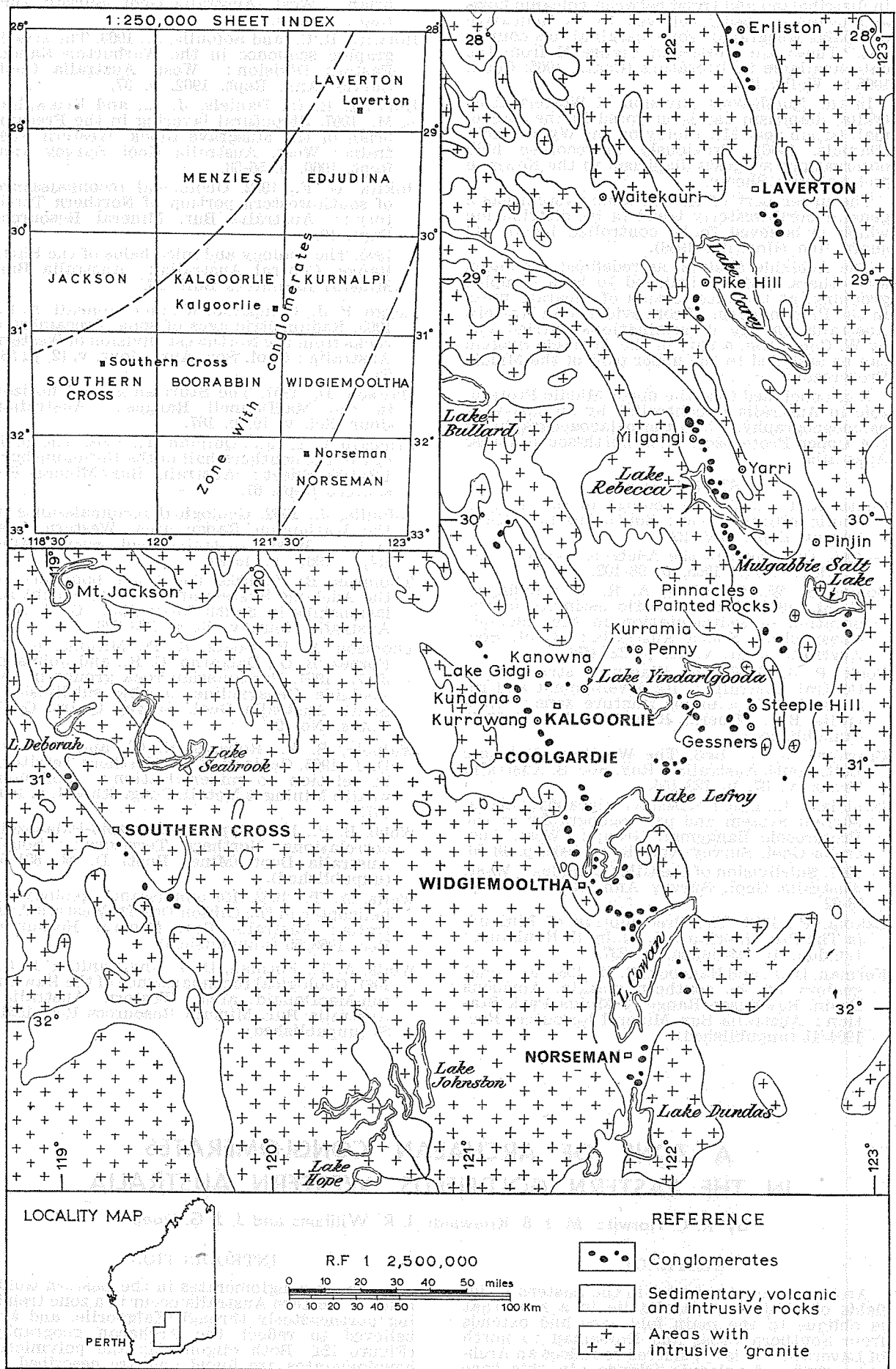


FIGURE 12 ARCHAEO CONGLOMERATES IN THE EASTERN GOLDFIELDS OF WESTERN AUSTRALIA.

Australian National University, confirm an Archaean age. Other conglomerates at Mount Jackson and in the Woodline Beds are Proterozoic.

POLYMICTIC CONGLOMERATES

The polymictic conglomerates are typified by the conglomerates at Kurrawang. They occur as lenses within beds of metamorphosed greywacke. The most abundant clasts are chert and jaspilite, fine-grained felsic rocks with porphyritic texture, quartz, and quartzite. Rock types that have been recorded from the clasts in the Kurrawang area are shown in Table I.

Table 1

ROCKS RECORDED FROM CONGLOMERATES AT KURRAWANG

| | |
|---|-----------------------------|
| Jasperoid and hematite-bearing quartz, black chert, quartz, quartzite, quartz- and feldspar-porphyrines, felsite, granite, etc. | G.S.W.A. Bull. 42. |
| Hematite-jasper, liver-coloured quartzite, and quartz- and albite-porphyrines. | Thomson, 1913. |
| Quartz, quartzite (?), jasperoid rock (often banded), and albite-porphyry. | Maclaren and Thomson, 1913. |
| Aplite, pegmatite, quartz-porphyry and feldspar-porphyry, granitic pebbles. | Maclaren and Thomson, 1913. |
| Limestone, porphyry, quartzite, granite, and almost pure magnetite. | Chewings, 1896. |
| Acid porphyry, felsitic intermediate porphyry, hornblende porphyry, fine-grained aggregate of mica and feldspar. | G.S.W.A. Bull. 56. |
| Quartzite, granite, gneissic rock, etc. | Larcombe, 1912. |
| Porphyry, slate, schist, quartz, etc. | Larcombe, 1912. |

It is noteworthy that clasts of granite are very rare in the polymictic conglomerates, although they have been recognized by several workers. We agree with Maclaren and Thomson that the paucity of granite clasts probably means that there were no large areas of granite exposed in the distributive province during sedimentation. It is possible that the granite clasts were eroded from small bodies which were composed mainly of fine-grained rocks of felsic composition.

Most of the clasts are pebble sized although at many localities cobbles predominate and there are several occurrences containing boulders. They are set in a matrix of cleaved and metamorphosed greywacke, similar to that of the surrounding beds. In many areas, the clasts are deformed and stretched parallel to the cleavage planes, and where the clasts are closely packed together, they are moulded around each other. Before deformation, many of the clasts were apparently rounded. During metamorphism, biotite and chlorite have grown in the matrix and in some of the clasts.

OLIGOMICTIC CONGLOMERATES

In contrast to the polymictic conglomerates are the oligomictic conglomerates in which practically all the clasts are of a rock type that has been called 'porphyry'. These clasts all have a porphyritic texture and belong to a felsic suite with rock types ranging from rhyolite to dacite and, less commonly, to andesite. Many of these conglomerates directly overlie large bodies of porphyry. In some deposits, the fragments of porphyry are almost entirely angular and these are better termed breccias. Clasts in the oligomictic conglomerates range from pebble size to boulder size, some of the boulders being over 12 feet long. In some, the elements are packed together closely; in others they are scattered in a greywacke matrix. Close resemblances between the clastic albite and the albite phenocrysts of the porphyry clasts have been recognized by Trendall who also noted that many of the darker coloured fragments, which had been called basalt in hand specimen, are porphyry with a metamorphic biotite.

DISTRIBUTION

Conglomerates are widespread in the area of the Widgiemooltha Sheet and their significance has been discussed by Horwitz and Sofoulis (1965). Among their conclusions are:

1. There are two sequences separated by an unconformity.
2. The upper sequence rests on rhyolite flows or on large 'porphyry' sills.
3. There are no large 'porphyry' sills or rhyolites in the upper sequence.
4. The conglomerates are restricted to the upper sequence.
5. The clasts of the conglomerates were eroded from rocks of both the lower and upper sequences.
6. An area of more rapid subsidence to the east of Lake Lefroy lacks conglomerates and is fringed by 'highs' oriented west of north and northeast.

Subsequent mapping in the area of the Kalgoorlie and Kurnalpi Sheets indicated that the conglomerates are not present west and north-west of Coolgardie but that they extend to the northeast to Yarri and beyond. In the south of the Kurnalpi Sheet area these conglomerates pass laterally into a succession of metamorphosed greywacke and schist. As a simplification, it can be said that the conglomerates in this region are present at two separate horizons. The lower horizon, which occurs at Lake Rebecca south of Pinjin, is characterized mainly by felsic lavas. The lavas are overlain by and interfinger with conglomerates of the oligomictic, 'porphyry,' type. The higher and more widespread horizon is recognized by the association in some places of greywacke and polymictic conglomerates and in others of oligomictic conglomerates and flows and sills of felsic rocks.

ORIGIN

Several different theories of origin have been proposed for the conglomerates. After Honman's work at Mt. Jackson and south of Kalgoorlie, the conglomerate at Kurrawang was generally thought to be a basal conglomerate lying unconformably on older rocks. The earlier opinion that the conglomerate beds were part of the Archaean succession was later revived, and it has been confirmed by all subsequent work. Most of the conglomerates away from Kurrawang are thought to be part of the main sedimentary succession. It is pointed out by McLaren and Thomson that the beds at Kurrawang have been 'claimed by glaciologists as products of ice action', but that they considered them to be riverine deposits. A glacial origin was also suggested by Mawson (1949) for the conglomerates at Kanowna.

The oligomictic conglomerates were attributed by Gibson to brecciation by shearing before final crystallization of an intrusive igneous rock. This concept is comparable to that of Trendall's, who considers that 'it is possible that such greywackes may be the ultimate detrital product of bulk flow of porphyry with or without admixed terrigenous detritus'.

Maitland pointed out that there are 'conglomerates of undoubtedly sedimentary origin at Kanowna', and this is how they were described by Blatchford and Jutson.

An outcrop was described by Honman as 'massive porphyry containing rounded and angular inclusions of porphyry in a porphyritic ground mass' and he considered that 'the massive porphyry bands have been derived almost *in situ* by subcrustal fusion from rocks similar to the metamorphic schists adjoining'. Almost fifty years later, the idea that the conglomerates are changed into porphyries became popular. This viewpoint is reported by Sofoulis. The idea that these conglomerates have been 'porphyritized' was not favoured by Trendall. We have not recognized any 'porphyroids' with porphyroblastic feldspars, although G. J. H. McCall and W. R. O'Beirne of the University of Western Australia inform us that they have evidence supporting 'porphyritization' near Widgiemooltha. A porphyry, now known to be unconformably overlain by a conglomerate to the east of Coolgardie, was attributed by McMath to granitization of the conglomerate.

CONCLUSIONS

The Archaean succession containing the conglomerates consists of greywacke beds interfingering with mafic and felsic extrusive rocks and intruded by concordant and discordant bodies of ultramafic, mafic, and felsic rocks (including granite). There is more than one horizon with conglomerates. Where polymictic conglomerates are common, there are no felsic rocks in the nearby and immediately underlying rocks. On the other hand, oligomictic conglomerates are invariably closely associated with flows and sills of felsic rocks. The oligomictic conglomerates have their provenance in these felsic rocks. The zone of conglomerates extends for at least 300 miles from Southern Cross and Norseman to north of Laverton, and where best developed is about 100 miles across. The zone was a 'positive' area throughout the formation of the upper part of the Archaean sequence. Emergence of areas within this zone is indicated by conglomerate and breccia, unconformities, basalt with vesicles, and rhyolite agglomerate. The geography of the time can be pictured as a chain of volcanic islands which was oriented northeast. This palaeogeographic trend is oblique to that of the main fold axes in the region.

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STRUCTURAL LAYERING IN THE PRECAMBRIAN OF THE MUSGRAVE BLOCK, WESTERN AUSTRALIA

by R. C. Horwitz, J. L. Daniels, and M. J. B. Kriewaldt

ABSTRACT

Near the Western Australian border, between latitudes 25° and 27° S., sedimentary rocks and volcanic flows, dated at about 1,100 m.y., unconformably overlie porphyry, granulite, rapakivi (pyterlite) granite, and a granite gneiss sheet. At rock unit contacts, the sequence is also intruded by another granite sheet and by the Giles Complex which includes four main gabbro sheets.

Prior to the intrusion of the Giles Complex, there were at least two periods of tectonism with metamorphism, including one older and another younger than the unconformity. Near the W.A. border, north of latitude 25° 30' the Giles Complex is absent and the granites are greatly reduced. A complex sequence of events resulted in a layered structure which was folded before the end of the Precambrian on axes trending west-northwest, and with recumbent folds in the north. The Giles Discontinuity, regarded as a zone of transcurrent faulting, transects the fold area diagonally from the northeast. The sequence is followed by basalt at MacDougall Bluff and by dolerite dykes, which are considered to pre-date late Proterozoic glacial rocks elsewhere. The Giles Complex is considered to be late Proterozoic, although part could be older than this.

INTRODUCTION

The assemblage of Precambrian plutonic, metasedimentary, sedimentary, and volcanic rocks that straddles the 26th parallel near the Western Australian border and extends into the southwest of the Northern Territory and the northwest of South Australia, has been called both the Pitjintara Shield (Chewings, 1935; Ellis, 1937) and the Musgrave Block (Hills, 1965; Thomson, 1966).

These rocks form a basement to the late Precambrian and Phanerozoic rocks of the southern part of the Amadeus Basin (see Horwitz and Daniels, 1967), and contain the Giles Complex,

named by Sprigg and Wilson (1959). This complex is composed of a number of plutons of basic rocks with associated ultrabasic and acid rocks.

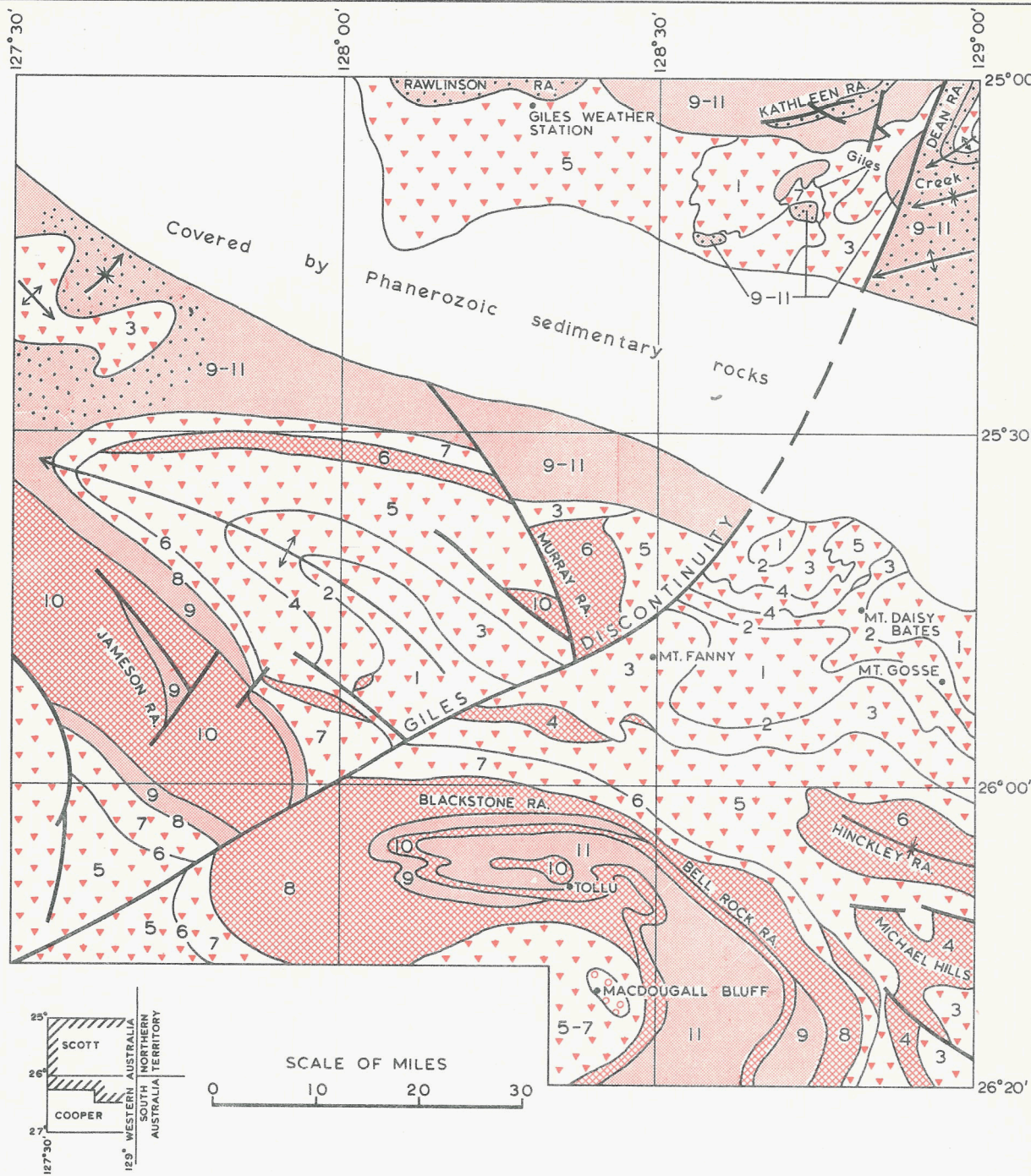
Mapping of the Scott and Cooper 1:250,000 Sheet areas, which cover a portion of the Western Australian part of the Musgrave Block, has revealed several features. The block is composed of at least two unconformable sequences, both intruded in parts by granite. The Giles Complex is not a single sheet, disrupted by folding and shearing, but several intrusions, each with its own characteristics (Daniels, 1967). There are several granites, two of which occur in sheets. The different sheets of the Giles Complex, and the granites, have intruded certain horizons: the most favourable horizons are usually the contacts, or deduced contacts, of the different country rock units. These plutonic sheets are confined to the southern part of the area, although the sheets of granite extend further north than the sheets of the Giles Complex. Dolerite dykes which cut all other units of the Musgrave Block, are also restricted to the south, having the same regional distribution as the sheets of the Giles Complex. The distribution of igneous rocks defines an igneous province.

STRUCTURAL LAYERING

The recognition of the different sheets of the Giles Complex, of the various granites in the region, and of the stratigraphy of the host rocks has led to the recognition of a folded structural layering of rocks in this part of the Musgrave Block.

This layering is most clearly seen between the Michael Hills and Bell Rock Range where the structural succession is:

- Top. Acidic and basic volcanic rocks
- Gabbro
- Porphyritic granite
- Gabbro
- Granulite
- Gabbro
- Granite gneiss



REFERENCE

| | |
|--|--|
| | Conglomerate and basalt |
| | Unconformity |
| | Giles Complex (gabbro, ultrabasic rocks, and granophyre) |
| | Sedimentary rocks |
| | Acidic and basic volcanic rocks |
| | Unconformity |
| | Granite gneiss |
| | Rapakivi granite (pyterlite) |
| | Porphyry, granulite, and gneiss |
| | Fault |
| | Syncline |
| | Anticline |
| | Porphyritic granite (age uncertain, see text) |

STRUCTURAL LAYERING

| | | |
|--------|--|--|
| Top | | |
| 11 | | Sedimentary rocks |
| | | Acidic and basic volcanic rocks |
| 10 | | Jameson Range Gabbro level |
| 9 | | Sedimentary rocks, acidic and basic volcanic rocks |
| 8 | | Blackstone Range Gabbro level |
| 7 | | Porphyritic granite |
| 6 | | Hinckley Range Gabbro level |
| 5 | | Porphyry, granulite, and gneiss |
| 4 | | Michael Hills Gabbro level |
| 3 | | Granite gneiss |
| 2 | | Thin discontinuous gabbro level |
| 1 | | Rapakivi granite (pyterlite) |
| Bottom | | |

INTERPRETATION OF THE MUSGRAVE BLOCK IN WESTERN AUSTRALIA

The volcanic rocks, at the top of this succession, are an assemblage of separate acidic and basic volcanic flows. In the Jameson Range region the volcanic rocks are regionally metamorphosed and a gabbro is developed some distance above their base.

Between Hinckley Range and Mt. Gosse, a poorly developed, discontinuous gabbro horizon is present in the basal part of the granite gneiss; the underlying granite is a rapakivi (pyterlite, see Horwitz and Daniels, 1967).

Combining these sequences with other local sequences and using the names of the gabbro levels given by Daniels (1967) the following structural layering is obtained:

- Top. 11. Acidic and basic volcanic rocks
 10. Jameson Range Gabbro level
 9. Acidic and basic volcanic rocks
 8. Blackstone Range Gabbro level
 7. Porphyritic granite level
 6. Hinckley Range Gabbro level
 5. Granulite, gneiss and porphyry
 4. Michael Hills Gabbro level
 3. Granite gneiss level
 2. Thin discontinuous gabbro level
 1. Rapakivi granite

CHRONOLOGY

Within the zone containing igneous sheets, gabbro is not developed along the total length of each contact but forms localized lens-shaped bodies up to 21,000 feet thick (Jameson Range Gabbro) and 68 miles long (Blackstone Range Gabbro). In the south end of the Bell Rock Range, no volcanic rocks separate the Blackstone Range Gabbro (level 8) from the Jameson Range Gabbro (level 10). The latter, which is in some areas a granophyre, is rich in xenoliths of the volcanic rocks. Within the zone containing igneous sheets, the granite sheets of levels 3 and 7 are present throughout.

The structural succession is not in chronological sequence. The units of the different levels, separated by gabbro intrusions, are usually of a single rock type, as set out in the table; however, the granite gneiss contains rafts of granulite and the main granulite (level 5) contains pods of granite gneiss.

In the northern part of the Scott Sheet area, in the Kathleen Range, volcanic flows are overlain by a thick succession of sandstones and phyllites. There, and throughout the region north of Giles Creek, these acidic and basic volcanic flows rest unconformably on the rapakivi granite, and south of the Giles Creek, pods of porphyritic granite have intruded the contact.

At Giles Weather Station a porphyry several thousand feet thick separates the rapakivi granite from the unconformity; and in the general locality of Mt. Daisy Bates and Mt. Gosse, granite gneiss occurs between the rapakivi granite and a metamorphosed and sheared porphyry which can be traced into granulite at Mt. Fanny. The porphyry of the Giles region is thus equated with the granulite and gneiss (level 5) and the granite gneiss is thus believed to have intruded at the contact between levels 1 and 5. It is thought that the rapakivi granite is intrusive into the porphyry. In the Murray Range, an outlier of acidic and basic volcanic rocks rests on eroded granite gneiss.

The relative age of the gabbro sheets is discussed by Daniels (1967) who considers that they are genetically related. Their relationship to the porphyritic granite has been observed south of the Hinckley Range where it is intruded and assimilated by gabbro.

There have been at least two periods of metamorphism including one older and another younger than the unconformity.

The following chronological order of events in the region is proposed:

A. the oldest rocks are the porphyry and granulites of level 5

B. intrusion of rapakivi granite (level 1)

C. regional metamorphism more intense towards the south

D. intrusion of granite (gneiss of level 3)

E. erosion, followed by volcanic flows and deposition of sediments (levels 9 and 11)

F. regional metamorphism

G. intrusion of the Giles Complex (levels 2, 4, 6, 8, and 10).

It is not known whether all the porphyritic granite is of the one age. At Giles Creek, porphyritic granite is intrusive into rocks of levels 9 and 11, and this granite is thus younger than event 'E'. South of Mt. Hinckley a porphyritic granite is intrusive into granulite of level 5, and is itself intruded by gabbro of level 6. It thus was formed before event 'G' and after event 'C'; it is considered to be younger than event 'D'. Because it is not known to have intruded rocks of levels 9 and 11 south of the Blackstone Range, the porphyritic granite is possibly older than the unconformity; that is, older than event 'E'. Regardless of age, the structural position of the porphyritic granite at level 7 is clear.

STRUCTURE

The structural layering has been used to construct a tectonic interpretation of the area. It was found necessary to invoke a northeasterly trending discontinuity running diagonally across the region. It is proposed to call this the Giles Discontinuity and it is thought to be a zone of transcurrent faulting. This discontinuity is supported by contrasting structural details, metamorphism and lithology on either side of the line, and by its continuation to the north as a zone of faults which have been mapped by Wells and others (1962).

The overall structure is that of a series of west-northwest trending anticlines and synclines. In the northern part of the area, these folds are recumbent to the south-southwest and dragfolds on the limbs are recumbent, or strongly overturned, to the west-northwest. These recumbent folds involve the unconformity between the volcanic rocks and the rapakivi granite. The recumbent structures were recognized and described by Forman and Hancock (1964).

AGE OF THE GILES COMPLEX

The Giles Complex is considered to be late Proterozoic, although part of it could be older than this. Volcanic flows at Tollu are about 1,100 million years old (Compston, pers. comm. 1965); they are intruded by part of the Giles Complex. Both the volcanic flows and the Giles Complex are cut by dolerite dykes. These dykes also cut an outcrop of basalt with a basal conglomerate at MacDougall Bluff which is known to be younger than the volcanic rocks of Tollu because it is unconformable on the eroded core of an anticline of the layered sequence. By comparison with adjoining areas, the dolerite dykes are considered to pre-date late Proterozoic glacial rocks.

The Giles Complex is thus older than the MacDougall Bluff rocks, the dolerite dykes, and (by comparison) the late Proterozoic glacial rocks; and at least part of it is younger than 1,100 m.y.

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PROVISIONAL SUBDIVISIONS OF THE PRECAMBRIAN IN WESTERN AUSTRALIA, 1966

Compiled by R. C. Horwitz

The accompanying chart (Plate 27) of Provisional Subdivisions of the Precambrian in Western Australia is a revision of that published in the 1965 Annual Report.

Geological Survey mapping, and age determinations carried out at the Australian National University under the supervision of Dr. W. Compston, have added more information to this revision.

The boundaries of the subdivisions of the Precambrian have been amended to fit the revision of these boundaries as proposed by the Geological Survey of Canada (Stockwell and Williams, 1964). The top of the Archaean is placed at 2,400 m.y., the top of the Lower Proterozoic is set at 1,640 m.y., and the top of the Middle Proterozoic subdivision at 880 m.y. The Middle Proterozoic is divided at 1,280 m.y.

The chart emphasizes, in Western Australia, the following grouping of ages: In the Archaean, sedimentation and vulcanism are followed by granite intrusion at about 3,000 m.y. in some areas and at about 2,600 m.y. in other areas. In the Proterozoic, metamorphism followed by granite intrusion occurs at about 1,800 m.y. and at about 1,000 m.y. Work undertaken and in progress indicates that the igneous and metamorphic events, in the Proterozoic, appear to

be spatially related to aspects of the previous palaeogeography while they initiate vulcanism which is preserved according to an aspect of a new palaeogeography.

The igneous events at about 2,600 m.y., 1,800 m.y., and 1,000 m.y. equate with the Kenoran, the Hudsonian, and the Grenville orogenies in the Canadian subdivisions of the Precambrian, provided that the ages of these orogenies are adjusted to the constants used at the Australian National University; a problem outlined in Turek (1966, p. 29).

It is thus concluded that the relationship between palaeogeography and igneous activity is a key to an understanding of the world distribution of the Precambrian.

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SUBDIVISION OF THE GILES COMPLEX, CENTRAL AUSTRALIA

by J. L. Daniels

ABSTRACT

The Giles Complex of Central Australia is a late Proterozoic series of basic masses intrusive into granulites, granites, and mixed volcanic rocks. Most of the basic rocks of the complex display abundant igneous banding features. Among these, cross-banding is locally common and the directions of the currents responsible (probably returning cooler convection currents overturned at the top and outer margins of a convection cell) have been measured and used to subdivide the complex into four major, physically unconnected, sheet-form bodies. These are:

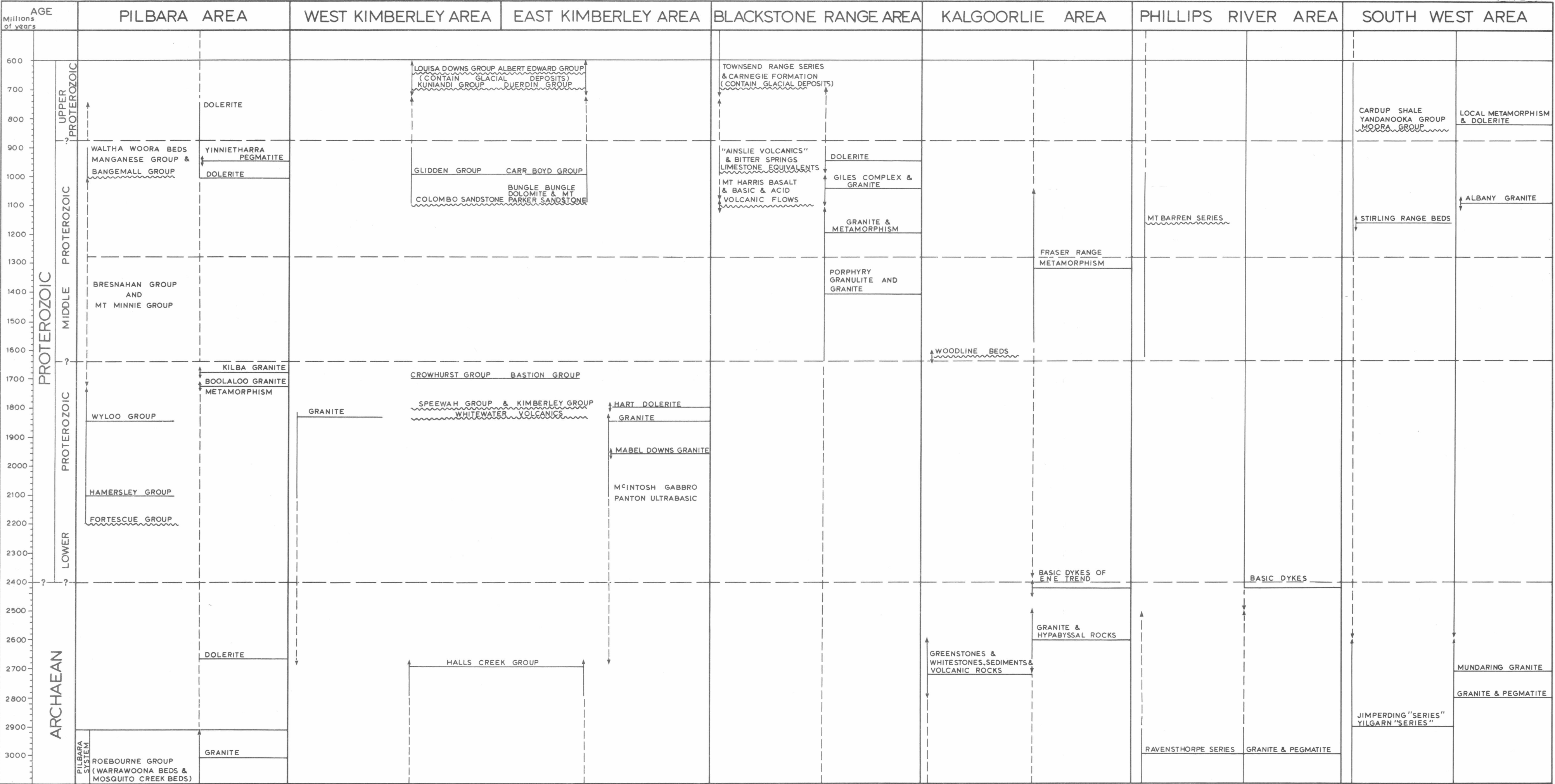
Jameson Range Gabbro
Blackstone Range Gabbro
Hinckley Range Gabbro
Michael Hills Gabbro

Probably all the basic sheets are genetically related, but whether they are temporally distinct remains to be determined in detail. Each sheet displays its own field characteristics as well as strong differences in petrography.

As with many similar associations in different parts of the world, the intrusions have been emplaced in country rocks which had already undergone major intense deformation and metamorphism. Subsequent to emplacement the area was folded into broad anticlines and synclines with wave lengths of approximately 10 miles.

INTRODUCTION

The late Precambrian Giles Complex is in central Australia astride the boundary between Western Australia and South Australia. It consists of a number of basic plutonic masses with associated ultrabasic and acid differentiates which crop out intermittently as a series of monadnocks in sandplain country. The complex has an overall east-west elongation and extends from the Jameson Range in Western Australia to approximately 100 miles east of Mt. Davies in South Australia, a distance of 210 miles. The maximum width of the complex is about 80 miles. The area of the province of the Giles Complex is not known with certainty, but could be between 7,500 square miles and 8,000 square miles.



PROVISIONAL SUBDIVISIONS OF THE PRECAMBRIAN IN WESTERN AUSTRALIA

This report is based largely on field work during 1966 and concerns the portion of the Giles Complex in the Scott and Cooper 4-mile Sheet areas of Western Australia.

Rocks of the complex intrude or are associated with a sequence of charnockites, granulites, acid and basic gneisses, and porphyritic acid and basic lavas. Porphyritic granite is also known in the area. The age of these rocks in relation to the Giles Complex is not known with certainty, but most are believed to be older (Horwitz and others, 1967).

On the whole the basic members of the complex are well banded. It is assumed that this banding developed on a slight slope of no more than a few degrees. As banding dips of between 45° and 90° are common throughout the area it is concluded that the complex was folded after emplacement and solidification. Despite the strong folding, rocks of the complex do not show regional metamorphic effects. Some of the gabbroic rocks of Jameson Range show widespread shearing, but this does not appear to have affected the composition of the constituent minerals and is purely a textural readjustment. The original banding and minor structures are still recognizable.

No direct isotopic age determinations have yet been undertaken on the Giles Complex. It has been referred to as Archaean, but recent work by the Geological Survey of Western Australia has shown that it is intrusive into acid and basic volcanic rocks of the Tollu area. These have been dated as 1,100 million years old (Compton in Horwitz and Daniels, 1967).

DESCRIPTION OF THE COMPLEX

Before describing the field characteristics of the individual basic and ultrabasic masses it is necessary to determine whether they represent dismembered parts of a once continuous lopolith, as suggested by Sprigg and Wilson (1959) or whether several discrete bodies are represented.

Primary igneous banding features are abundant in the majority of these monadnocks. Some of these have been described by Nesbitt and Talbot (1966) who also described some sedimentary-type structures. In addition to those described, abundant examples of cross-banding were found (Plate 28). These were studied in some detail and it was found possible to use the results to subdivide the complex.

It is postulated that cross-banding in basic igneous rocks is produced by a sedimentary process acting in a crystallising magma and is completely analogous to the production of cross-bedding in sedimentary rocks. The currents responsible for the cross-banding in the basic igneous rocks would be the returning, cooler convection currents having overturned at the top and outer margins of the intrusion.

With this in mind, the orientation of the cross-banding will give not only the local direction of the bottom convection currents, but also a regional picture, useful with or without additional geological data, for determining:

1. the number and locality of the original convection cells.
2. the original slopes of the chamber floor and hence the shape of the bottom of the intrusion.
3. the centre of the keel area of an intrusion.

Current directions, measured at a number of localities over the whole of the complex in W.A. are plotted on the accompanying map (Plate 30).

It will be seen that the current directions for the gabbroic rocks in the Jameson Range—Mt. Elliot area are fairly constant with trends to the north and northwest. Two measurements of currents from the north-northeast and northeast are noted. However, in this area, the overall picture is one of bottom convection currents trending in a northwesterly direction indicating that the base of this mass was planar and sloped to the northwest with minor varia-

tions. The centre or deepest part of the intrusion is assumed to lie somewhere to the northwest probably at a great depth.

This pattern is completely different from that provided by a combination of current directions taken from the Cavenagh Range, Blackstone Range, and Bell Rock Range. In this combination, although there is a great variation in current direction, the overall pattern is simple; that is, currents converging on a broad area about 8 miles south of Tollu.

The configuration of the current directions suggests that the Cavenagh Range, Blackstone Range, and Bell Rock Range are part of the same sheet which was originally basin shaped and perhaps somewhat elongated in a north-northwest direction.

Current directions in the gabbroic rocks of Michael Hills are by no means simple and indicate that the action of possibly three convection cells may be represented in what was a continuous mass. One of these cells occupied the northwest portion of the body, another lies at least 8 miles to the east-southeast and the third was located in the southern part of the exposed portion of the intrusion.

This pattern suggests two possibilities: within the original sheet there were at least three basin-shaped depressions, or the original sheet was horizontal and three independent convection cells developed within.

No current directions are available from the gabbro forming a large part of the portion of Hinckley Range in Western Australia as this area has not been studied in detail. In South Australia, approximately 3 miles northwest of Mt. Davies camp, cross-banding is locally well developed in the extension of the range. It is occasionally seen on Mt. Davies, which is probably the continuation of the gabbro of Hinckley Range. Not enough readings were made to produce a coherent picture.

The Giles Complex can therefore be subdivided into a number of separate bodies or units, which have fairly simple convection current characteristics. Their internal stratigraphy and structural position (see especially the Bell Rock Range, Hinckley Range, and Michael Hills region) confirm that these units are discrete bodies and not just dismembered remnants of one large sheet with numerous convection cells.

All the information available shows that there are four major sheets involved in the Giles Complex in Western Australia. These have been named and in order of increasing structural depth are:

10. Jameson Range Gabbro
8. Blackstone Range Gabbro
6. Hinckley Range Gabbro
4. Michael Hills Gabbro

The numbers before each gabbro refer to levels in the total structural sequence of the area which has been described elsewhere (Horwitz and others, 1967). These levels, even where gabbro is missing or poorly developed, can be traced and extrapolated throughout the whole region. The inset in Plate 30 shows the structural interpretation of the area.

DESCRIPTION OF INDIVIDUAL SHEETS

The following descriptions are based largely on fieldwork supplemented by a preliminary examination of some thin-sections. Figure 13 shows selected sections through the four major bodies with the major subdivisions for three of them. The section thicknesses were measured from aerial photographs using dips measured in the field. The subdivisions adopted here are generally obvious in the field, though with the examination of more thin-sections, or those available in detail, modification of these zones may later be necessary.

Except where used in detailed petrographic descriptions the terms gabbro or gabbroic rocks are used in a general sense to include all rock types of the gabbro clan.

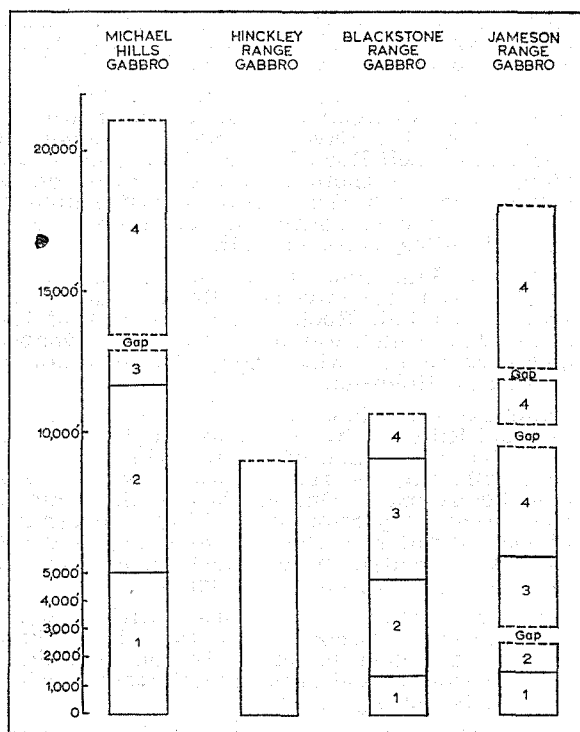


FIGURE 13: SUBDIVISIONS OF THE FOUR MAJOR SHEETS OF THE GILES COMPLEX

Michael Hills Gabbro

The intrusion has been provisionally subdivided into four major zones which together are over 21,000 feet thick. Thicknesses of the individual zones are given in Figure 13.

Zone 1. The basal zone is characterised by the presence of banded leucocratic gabbroic rocks, anorthosites, and interbanded pyroxenites. Igneous banding is well developed on all scales but cross-banding is rare.

Below the base of this zone, granite gneisses and some granulites are observed and within approximately 200 feet of the main contact they have been intruded by several basic sills. These sills have connected the country rock to contact hornfels and are themselves composed of medium to fine-grained hypersthene gabbro carrying strongly antiperthitic, vaguely twinned, plagioclase (An_{40}).

Hypersthene gabbro also forms most of the basal zone. It consists of coarse hypersthene and clinopyroxene, both with exsolution lamellae of one in the other. The orthopyroxene shows schiller structure and moderate pleochroism. The clinopyroxene is commonly multiply twinned. The plagioclase, labradorite, is frequently poorly twinned. Twinning according to the albite law is usually almost suppressed. Pericline and carlsbad twins are not uncommon. Accessories include iron ore and red-brown biotite. Most of the constituent grains have been stressed with the production of bent and fractured crystals and undulose extinction in the feldspar. Some examples have been granulated and appear now as a fine-grained plagioclase mosaic with elongated mafic bands also generally granular. In the lowermost 1,000 feet of the zone antiperthitic plagioclase is abundant.

Interbanded pyroxenites are more common in the lower half of the zone. They are generally between 20 and 50 feet thick and consist of medium to coarse-grained hypersthene and clinopyroxene in approximately equal proportions. Some plagioclase (5%) is generally present as interstitial grains. The pyroxenes appear to be similar to those in the hypersthene gabbro.

Zone 2. The top of zone 1 is not well defined. In zone 2, however, no thick bands of pyroxenite occur and anorthosites are rare. The zone is well banded and the main rock type is a hypersthene gabbro very similar to that of zone 1, and need

not be described further. Antiperthitic plagioclase is present in the upper portion of the zone.

Zone 3. The zone is characterized by thin, well-defined banding and fairly fresh appearance in contrast to the 'crusty' weathering of the two lower zones. Gravity differentiated bands ('graded beds') and cross-banding are common. The rock is a hypersthene gabbro with rare antiperthite and is similar to that of zones 1 and 2. Shearing has affected the rock to a minor extent.

In zones 1, 2, and 3 a conspicuous fine-grained rock is apparently transgressive to the banding, but in places forms 'xenoliths' in the coarser banded gabbros. It is itself a hypersthene gabbro with similar accessories to the main gabbro.

Zone 4. The uppermost zone is banded, weathers black and encloses large sheets of granitic gneiss, which have been partly stoped and assimilated. Hypersthene gabbro with opaque accessory minerals and a red-brown biotite is the commonest rock type. Aligned quartz-feldspar streaks are present in the gabbro. These are discussed at greater length in the section concerning assimilation.

Intrusive into what appears to be the upper part of zone 4 are two apparently cross-cutting rock types. One consists of pegmatitic gabbro, the other is pyroxenite.

The pegmatitic rock (troctolite) is fresh, unshattered and so completely different mineralogically from the rest of the Michael Hills Gabbro that it most probably represents a younger minor intrusion unconnected with the Michael Hills gabbro sheet. It may represent the feeder for a basic sheet at a higher structural level.

The pegmatitic gabbro consists predominantly of coarse olivine and plagioclase (approx. An_{50}). Crystals between 1 and 2 inches are common while crystals up to 4 inches long have been noted. Reaction rims around the olivine are abundant and consist of an inner rim of hypersthene frequently intergrown with vermicular green spinel. Outward is a further zone of cloudy-green aspect made of an extremely fine vermicular intergrowth of a high relief green mineral (? spinel) and a colourless mineral (? feldspar). A partial rim and scattered crystals of a slightly pleochroic pale-brown hornblende is occasionally present. It may be partly intergrown with vermicular green spinel and, when present, the rim occurs interposed between the other two reaction rims. A thin peripheral band of very strong zoning is noted on the plagioclase in contact with the reaction rims. Accessory minerals in the whole rock include magnetite and pleonaste grains.

Another practically circular mass to the west of the pegmatitic gabbro is also probably a late intrusive. However, it consists of ortho- and clinopyroxene in approximately equal amounts and is probably genetically related to the Michael Hills Gabbro.

The two younger intrusions are near the centre of an arc formed by zone 4 of the gabbro. In this zone the orientation of quartz-feldspar 'blebs' in the gabbro was measured. They tend to converge on this same area and may represent flow structures spreading out from a centre. The focal point, therefore appears to have been a centre of repeated activity.

Summary of Michael Hills Gabbro. The Michael Hills gabbroic sheet is a thick well-banded mass of hypersthene gabbro devoid of olivine. The hypersthene is distinctive, being fairly strongly pleochroic and carrying abundant schiller inclusions. It occurs in almost equal or lesser amounts than the accompanying clinopyroxene. Antiperthitic inclusions in the plagioclase are abundant at some levels and these, together with field evidence, suggest that a large amount of granitic material has been assimilated by the gabbro, and presumably drastically changed its original composition. In the lowest zones frequent pyroxenite bands are encountered. Throughout the intrusion the effects of stress are noted to a greater or lesser degree. Two younger intrusions cut the Michael Hills sheet. One is a pyroxenite, possibly genetically related to the main mass. The other is pegmatitic

troctolite, probably younger than the Michael Hills sheet, and possibly a feeder for a gabbroic sheet at a higher structural level.

Hinckley Range Gabbro

Little work has been done on the Hinckley Range Gabbro. The total thickness was not measured during the present study but is given by Nesbitt and Talbot (1966) as approximately 9,000 feet. The gabbro occupies a syncline whose north-northwest axis runs through the length of the Hinckley Range. The southern limb thins out to the west (Plate 30). Two miles east of the point where the mass thins out, the gabbro has thickened to just over 3,600 feet while approximately 9 miles further east it reaches its maximum thickness. Little or no igneous banding is visible until the thickness reaches approximately 3,000 feet. It appears, therefore, that a minimum thickness of approximately 3,000 feet is necessary before igneous banding will develop in the Hinckley Range mass. Cross-banding structures appear to require greater thicknesses as they were not seen in the first banded rocks but are well developed in the thicker part of the section approximately 3 miles northwest of Mt. Davies camp in South Australia.

At much of the lower contact, and above the body, there is a contaminated, fine-grained basic igneous rock forming thick masses and transgressive sheets in the granitic and granulitic country rock, which it has assimilated. Remnant sheets of country rock are too small to depict on the accompanying map. The basic material carries characteristic, quartz-feldspar 'blebs' and schlieren similar to that seen in the contaminated gabbros of the Michael Hills. Antiperthite is common. The main rock type in the contaminated zone is a fine-grained hypersthene gabbro.

The mass has not been subdivided. Rock types present include olivine-norite and olivine-hypersthene gabbro. Accessory minerals include iron ore, pleonaste, and red-brown biotite. Chromite has been found near Wingellina.

On the northern side of the syncline near Wingellina ultrabasic rocks have been intruded probably along shear planes. Fresh samples are not available but the original rock was probably a dunite or serpentinite. Alteration has taken place and produced nickeliferous ochre, a lightweight, pale brown powdery rock of possible economic value for its nickel content.

Blackstone Range Gabbro

One section through the gabbro was measured in the Blackstone Range, approximately 12 miles east of the western extremity of the range. Here the sheet is approximately 11,000 feet thick and divisible into four main units overlying sheared and possibly contaminated basic igneous material with a minimum thickness of 3,000 feet.

Zone 1. The basal zone of the sheet is coarse-grained, shows poorly developed igneous banding and some development of a pegmatitic gabbro facies.

One specimen from this zone is a coarse-grained hypersthene troctolite with sub-ophitic texture. Accessories include iron ore, pleonaste, and red-brown biotite. The hypersthene is weakly pleochroic, shows well developed schiller structure and possesses abundant small rounded enclosures of clinopyroxene in optical continuity.

Zone 2. Fine igneous banding characterises zone 2. Gravity differentiated units are common and cross-banding is moderately abundant. One example of trough banding was noted.

The zone appears to be mineralogically composite. The lower third is composed of olivine-norite which also forms a thin horizon at the top. The rest of the zone is troctolite with rare accessory hypersthene.

Zone 3. This zone consists entirely of hypersthene troctolite with hypersthene present only in small amounts. The lower third is well banded, in contrast to the upper portion which is very poorly banded.

Zone 4. Mafic troctolite forms the uppermost zone. It is a dark-weathering rock, which in thin-section is seen to be composed of abundant fresh olivine forming a polyhedral mosaic with approximately 10% plagioclase and accessory clinopyroxene, orthopyroxene, iron ore, and red-brown biotite.

The main mass of Bell Rock Range is closely comparable with the Blackstone Range and is regarded as part of the same intrusion on a consideration of the cross-banding results. Rock types distinguished include troctolite (commonest), hypersthene troctolite, olivine gabbro, and poikilitic olivine-hypersthene gabbro near the base.

The smaller range of hills immediately southwest and flanking the main mass of Bell Rock Range is composed of gabbro with some amphibolite. Bands and dykes of granophyre are common. The gabbro consists of laths of dusty plagioclase with interstitial clinopyroxene and accessory iron ore and brown biotite. It is devoid of olivine.

No physical connection is seen with the Bell Rock Range mass and as the rock type and the associated rocks are so completely different from the Blackstone Range Gabbro it must be regarded as part of a gabbro forming a higher structural level. In texture and mineralogy the gabbro is similar to gabbros immediately south of Tollu and 8 miles southeast of Tollu. These are intrusive into lavas and associated with granophyres.

Summary of Blackstone Range Gabbro. This intrusion is generally well banded and consists dominantly of olivine-bearing rocks with troctolite predominating.

Jameson Range Gabbro

Four main zones have been mapped in the Jameson Range sheet, together totalling more than 18,000 feet thick. The sheet is moderately well banded. Some shearing has affected the gabbroic rocks of Jameson Range itself, but the shearing has taken effect as a partial granulation of the minerals. No chemical change seems to have occurred and the primary igneous banding is not greatly affected.

Zone 1. In the field the basal zone is distinctive, being dark-weathering and glomeroporphyritic. The glomerocrysts are composed of plagioclase and weather out to give the rock a pock-marked appearance.

The zone is variable in composition. Generally, it is composed of dusty plagioclase laths with oscillatory zoning, in a groundmass of strongly pleochroic green hornblende. The latter frequently carries abundant, small, rounded quartz enclosures and some samples show relict clinopyroxene. Accessories include iron ore, partially replaced by sphene, and some red-brown biotite. One relatively unaltered sample shows poikilitic clinopyroxene, with rare relict olivine. The pyroxene is surrounded by abundant small laths of red-brown biotite. The associated plagioclase is a calcic labradorite with some laths strongly zoned and having oligoclase margins. The rock may be called an olivine gabbro.

Zone 2. Above the glomeroporphyritic gabbro is a zone of mafic rocks up to 1,000 feet thick. One sample from the zone carries titaniferous magnetite, brown hornblende, olivine, and clinopyroxene with traces of plagioclase and orthopyroxene. Another sample is a clinopyroxenite with traces of ore and plagioclase, but devoid of olivine.

The zone is continuous for several miles, but is poorly exposed on account of a development on laterite on its outcrop.

Zone 3. This zone forms the main part of the Jameson Range itself. It is a well banded zone and the rocks are fairly uniform in composition throughout, being almost entirely hypersthene troctolites with opaque accessories and red-brown biotite.

Zone 4. This zone is distinguished in the field by the presence of anorthosite and titaniferous magnetite bands. The main rock types include

Table 1
PARTIAL ANALYSES OF TITANIFEROUS AND VANADIFEROUS IRON ORES FROM THE GILES
COMPLEX
(Analyses by Government Chemical Laboratories)

| G.S.W.A.
Spec. No. | 523A | 523B | 523C | 1245A | 1245B | 1245C | 1255A | 1255B | 1236 | 1237 | 1261 | 1262 | 1266A | 1266B | 1266C |
|--------------------------------|-------|-------|------|-------|-------|-------|-------|-------|------|------|------|------|-------|-------|-------|
| Fe ₂ O ₃ | 55.4 | 62.6 | 62.4 | 15.6 | 12.7 | 16.4 | 51.3 | 59.1 | 56.9 | 54.7 | 67.3 | 63.0 | 62.5 | 65.3 | 65.5 |
| FeO | 15.7 | 10.1 | 14.8 | 24.4 | 25.7 | 28.4 | 11.3 | 12.3 | 10.8 | 12.6 | 6.75 | 8.06 | 11.0 | 7.68 | 6.80 |
| TiO ₂ | 18.7 | 17.4 | 12.3 | 13.6 | 17.3 | 15.2 | 26.2 | 18.2 | 21.0 | 17.2 | 15.9 | 20.9 | 18.9 | 19.6 | 19.5 |
| MnO | 0.23 | 0.25 | 0.29 | 0.30 | 0.34 | 0.29 | 0.24 | 0.28 | 0.31 | 0.28 | 0.21 | 0.07 | 0.08 | 0.11 | 0.10 |
| SiO ₂ | 1.69 | 1.55 | 1.31 | 24.1 | 23.1 | 19.9 | 1.82 | 1.04 | 1.33 | 3.62 | 1.70 | 1.36 | 1.63 | 1.75 | 1.58 |
| Al ₂ O ₃ | 4.02 | 3.51 | 5.41 | 6.26 | 5.22 | 7.35 | 4.95 | 5.13 | 4.06 | 4.47 | 4.53 | 2.39 | 2.35 | 2.45 | 2.69 |
| P ₂ O ₅ | 0.07 | 0.06 | 0.04 | 0.03 | 0.08 | 0.06 | 0.04 | 0.04 | 0.03 | 0.04 | 0.08 | 0.11 | 0.24 | 0.11 | 0.10 |
| S | 0.01 | 0.03 | 0.03 | 0.04 | 0.08 | <0.01 | 0.05 | 0.03 | 0.02 | 0.03 | 0.03 | 0.02 | 0.06 | 0.02 | 0.09 |
| V ₂ O ₅ | 1.04 | 1.25 | 1.11 | 0.70 | 0.57 | 0.76 | 1.18 | 1.33 | 1.40 | 1.11 | 0.75 | 0.71 | 0.77 | 0.81 | 0.76 |
| Cr ₂ O ₃ | 0.06 | 0.07 | 0.08 | <0.01 | 0.01 | 0.01 | 0.03 | 0.18 | 0.38 | 0.63 | 0.14 | 0.29 | 0.25 | 0.28 | 0.28 |
| NiO | 0.13 | 0.13 | 0.10 | 0.06 | 0.04 | 0.05 | 0.04 | 0.08 | 0.15 | 0.10 | 0.02 | 0.05 | 0.05 | 0.05 | 0.04 |
| MgO | 1.57 | 0.80 | 0.71 | 6.19 | 8.05 | 6.65 | 1.78 | 1.81 | 2.28 | 3.49 | 0.78 | 1.43 | 1.09 | 0.93 | 0.88 |
| CaO | <0.01 | <0.01 | 0.02 | 6.47 | 5.80 | 3.80 | 0.07 | 0.04 | 0.04 | 0.04 | 0.22 | 0.04 | 0.09 | 0.12 | 0.18 |

523A Northeast end Bell Rock Range

523B do. do. do.

523C do. do. do.

1245A Zone 2 of Jameson Range Gabbro

1245B do. do. do.

1245C do. do. do.

1255A Lower part of zone 4 Jameson Range Gabbro

1255B do. do. do.

1236 Finlay Range, part of Jameson Range Gabbro

1237 do. do. do.

1261 Upper part of zone 4 Jameson Range Gabbro

1262 do. do. do.

1266A do. do. do.

1266B do. do. do.

1266C do. do. do.

hypersthene troctolite, troctolite, olivine gabbro, and hypersthene gabbro. Titaniferous magnetite bands increase in frequency and apparently also in thickness, in the upper half of the exposed part of zone 4. These are poorly exposed and frequently covered by laterite. No reliable estimate of tonnage can be given but it must be considerable. Two circular structures in the upper part of the zone are formed of banded titaniferous magnetite and are partly obscured by laterite. These appear as anomalous trends in the overall simple banding and may be diapiric structures.

Summary of Jameson Range Gabbro. This sheet is composed dominantly of hypersthene troctolite with a lower zone of olivine gabbro and upper levels with anorthosite and abundant titaniferous magnetite bands.

Contaminated rocks

The map shows large areas of a contaminated facies of the gabbroic rocks. These rocks are complex and are not yet fully understood. In large part they represent areas of country rock almost completely stoped and assimilated. In other areas they represent a border facies to the gabbros with or without evidence of assimilation.

In the most obvious examples the basic rock can be seen to have fragmented and assimilated granitic gneisses and granulites, to produce a dark, blue-grey, fine-grained rock with abundant quartz-feldspathic 'blebs' or schlieren (Plate 29). With more complete assimilation these blebs become very small, but remain highly distinctive especially on a weathered surface. They are generally composed of plagioclase, ortho- and clinopyroxene with variable quartz, microcline, cordierite, red-brown biotite, and opaques. The plagioclase is commonly antiperthitic as it is in some of the gabbros, especially those of the Michael Hills. In some gabbros cordierite and variable quantities of quartz are present.

The overall picture suggests that contamination is a major factor in the petrogenesis of the gabbros of the Giles Complex.

Minor gabbroic masses

The remainder of the isolated gabbroic masses have been satisfactorily placed within one of the four major gabbro levels with the exception of some gabbroic sheets to the northeast. These are thought to represent a discontinuous level in granitic gneisses.

Both stratigraphy and general petrographic type are useful in determining the structural level of any isolated gabbroic mass. The isolated gabbroic masses intrusive into the volcanic province around Tollu together form the

highest level of intrusion and are probably part of the same sheet as the Jameson Range Gabbro. These isolated masses show general similarities in texture and a degree of saussuritisation and uralitisation are not encountered in the lower levels. Granophyres are frequently encountered, either as dykes or as a sheet-like top to the gabbro. The granophyres, forming the main mass of Skirmish Hill 17 miles south of Tollu and intrusive into quartz-feldspar porphyries, are probably part of this level.

ECONOMIC CONSIDERATIONS

Nickeliferous ochre is known on the north side of the Hinckley Range mass as an alteration product of dunite or serpentinite. Its total extent, depth, and grade are not known, but it is under investigation by Southwest Mining Co. Ltd. Small amounts of chrysoprase are known as thin veins in the ochre.

Titaniferous magnetite bands are abundant in the upper part of the Jameson Range Gabbro. The total amount must be large, but exposures are poor in that region. Partial analyses of some samples from this region and a thin band from the northwest corner of Bell Rock Range are given in Table 1. TiO₂ ranges from approximately 13% to 26%. Vanadium is also generally high ranging from 0.71% to 2.42%. Laterites are locally developed on some of the titaniferous magnetite bands.

A consideration of the bottom convection current directions determined from the cross-banding is of possible major importance for future prospecting. The currents responsible would probably have been most active in the early stages of cooling and could have concentrated early formed sulphides at the bottom of the intrusion. More detailed mapping of the current directions, together with fabric analyses of the gabbros, would almost certainly locate areas worthy of further study by geophysical methods.

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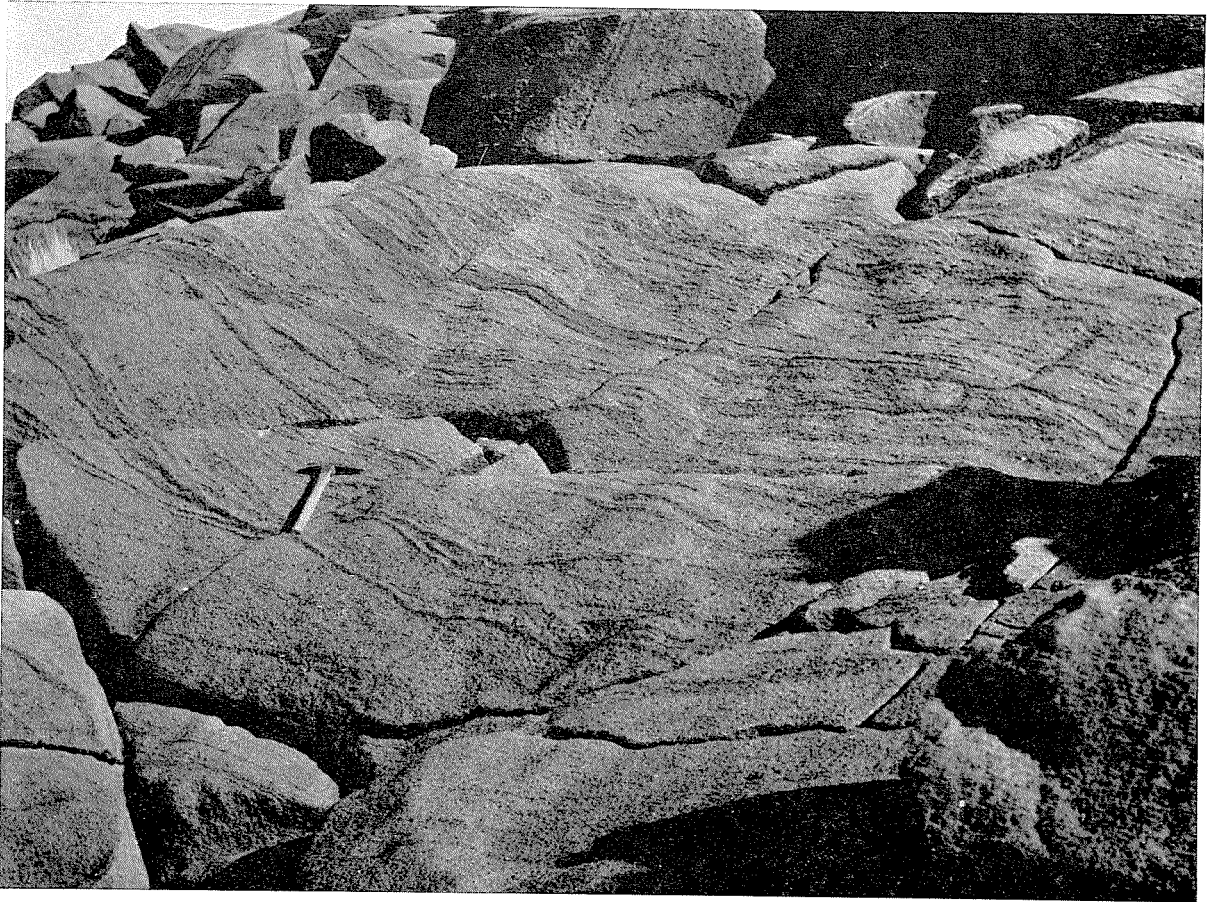
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Vanadium is also generally high ranging from 0.71% to 2.42%
should read
V₂O₅ is also generally high ranging from 0.57% to 1.4%



A—Abundant cross-banded units in steeply dipping gabbro. Northwest end of Bell Rock Range ; F 1160.

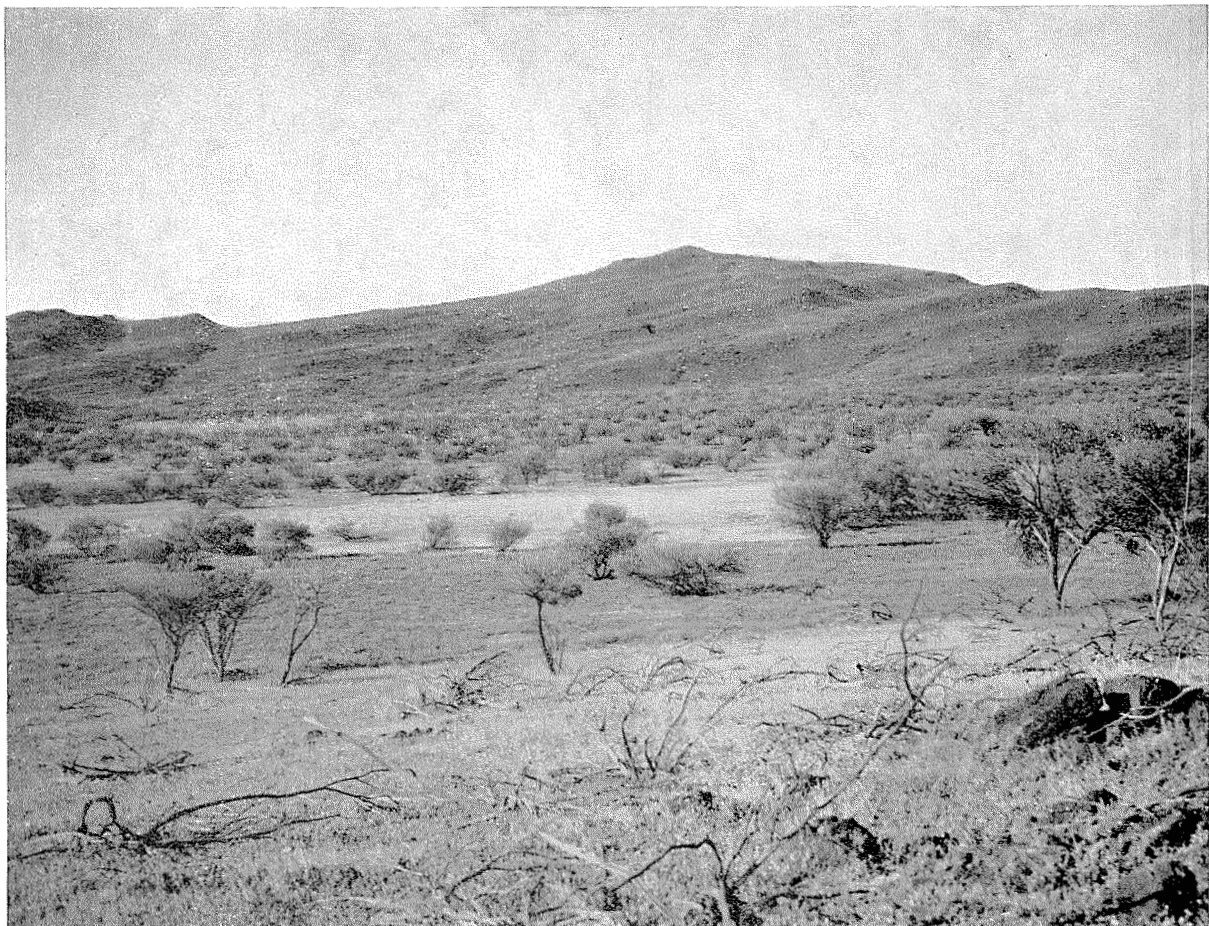


B—Close up of cross-banded unit in gabbro at northwest end of Bell Rock Range ; F 1161.

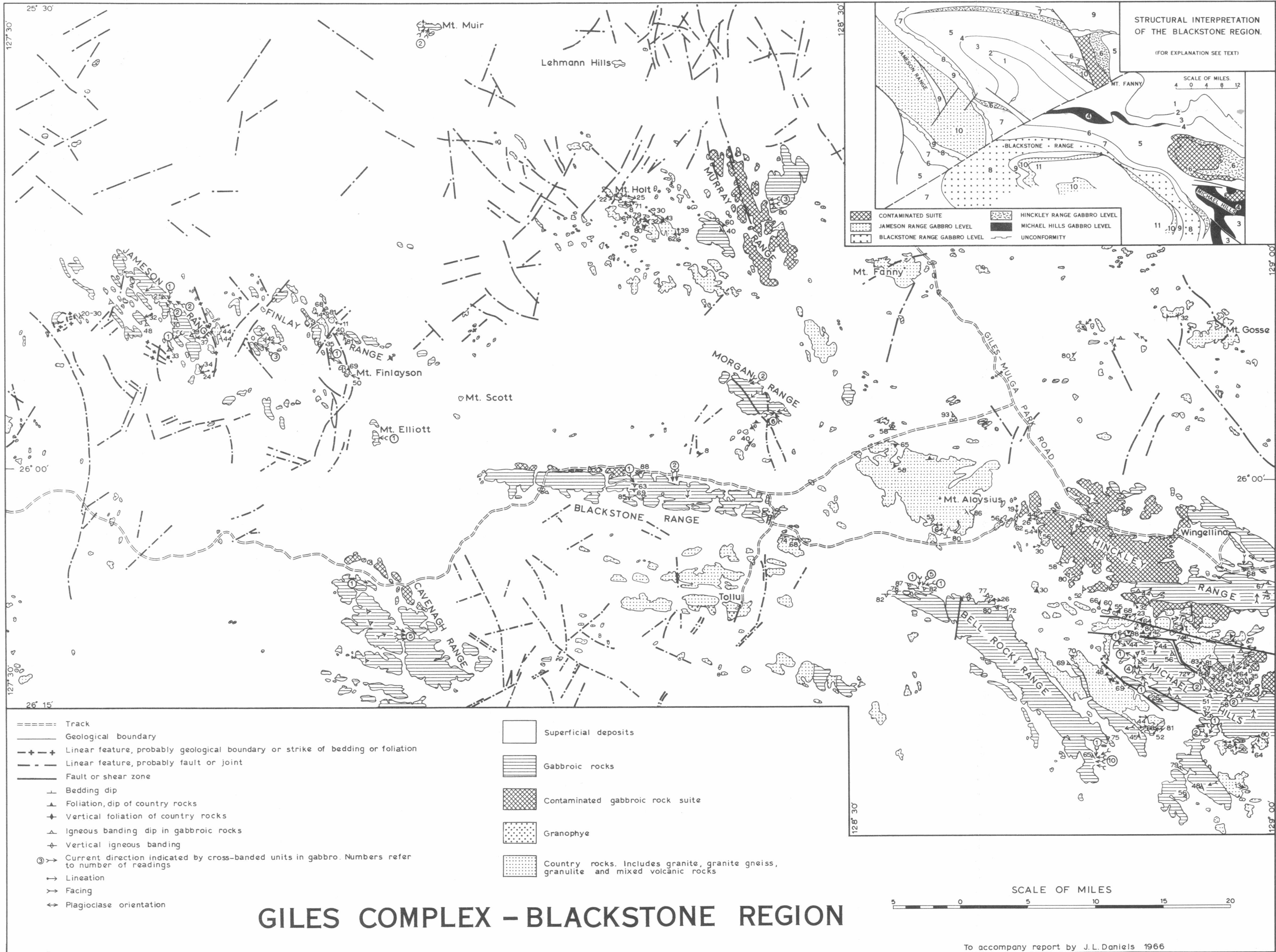
PLATE 29



A—Oriented quartzo-feldspathic blebs in process of assimilation by gabbroic rock, Michael Hills Gabbro ; F 1162.



B—Michael Hills showing benched slopes caused by igneous banding ; F 1163.



DIAMOND DRILLING AT THE GERALDINE LEAD MINE, NORTHAMPTON MINERAL FIELD

by L. E. de la Hunt

INTRODUCTION

In the period June 11 to July 4, 1966, a diamond drilling programme was carried out on the abandoned Geraldine lead mine, location 1, Galena. The programme was subsidised, dollar for dollar, by the Government of Western Australia and was supervised by the writer. The drilling was done by a private contractor.

Three holes, 505, 477, and 447 feet long respectively, were drilled at 60 degrees depression. These intersected the ore channel at an average depth of about 370 feet, on the underlay, but did not prove a depth extension of the ore body.

The mine workings are on the western bank of the Murchison River where it flows south, about 3½ miles west-southwest of the townsite

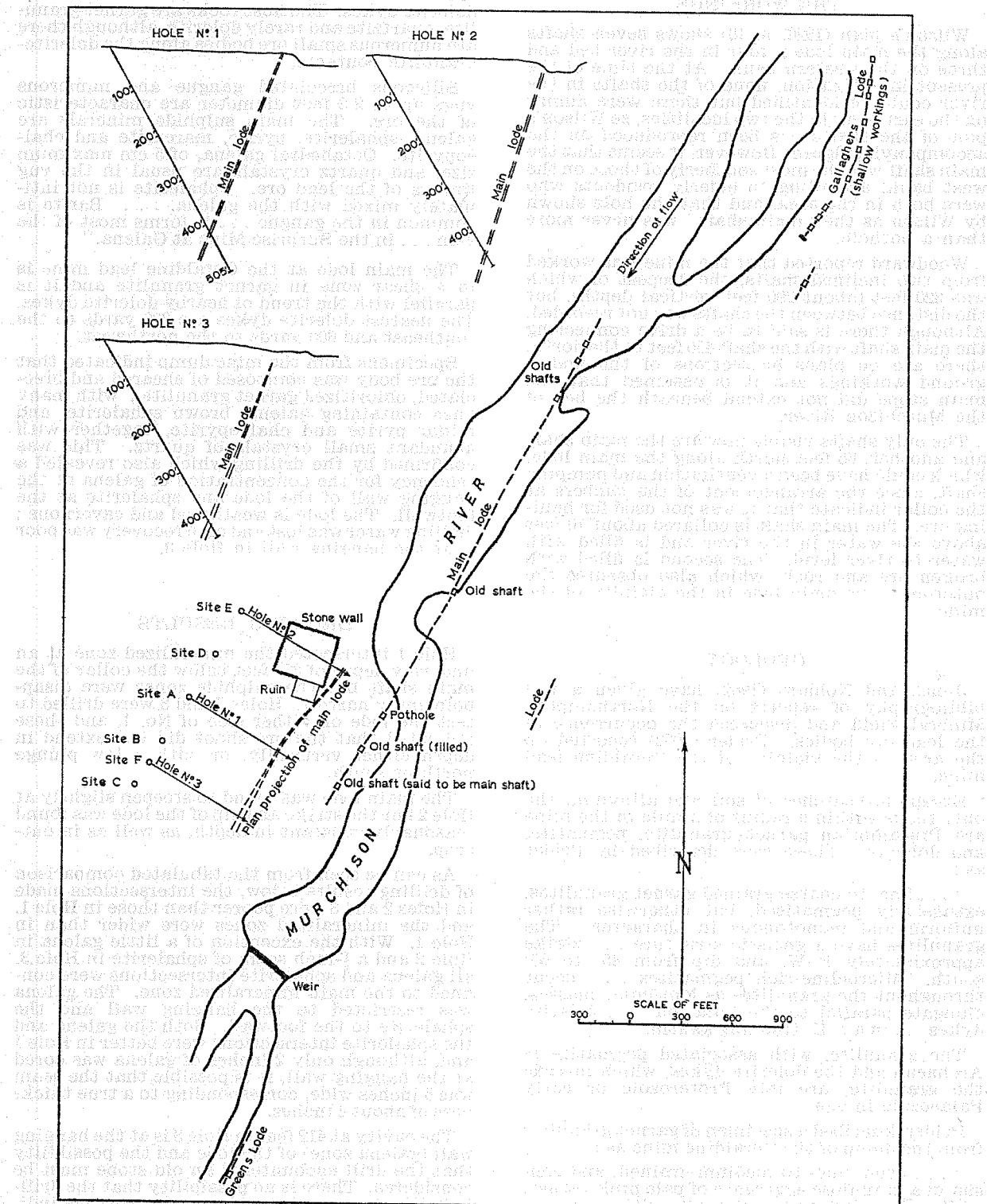


FIGURE 14: PLAN AND SECTIONS OF DIAMOND DRILLHOLES
AT GERALDINE LEAD MINE, NORTHAMPTON MINERAL FIELD

of Galena. Access is by a rough winding track which leaves the North West Coastal Highway a few chains north of the Murchison River bridge.

PRODUCTION

The mine was worked from 1857 to 1878, mostly from 1867 to 1872, and several thousand tons of ore were shipped to London during that time. Although 6,500 tons were recorded, it is believed that much more lead was won. According to local report, an appreciable quantity was mined from Gallaghers Lode (about 500 yards north of the mine) and various people have cleaned up around the old workings over the years.

THE WORKINGS

Wilson's plan (1926, p. 18) shows seven shafts along the main lode; four in the river bed and three on the western bank. At the time of the present investigation, none of the shafts in the river could be identified but there were dumps on the east bank in the two localities, so Wilson's plot of the shafts has been reproduced on the accompanying figure. However, it seems that the main shaft was the most southerly of those on the west bank, according to elderly residents who were born in the area, and that the hole shown by Wilson as the 'main shaft' was never more than a pothole.

Woodward reported that the mine was worked from two inclined shafts, the deepest of which was 320 feet (about 290 feet vertical depth), but the distance between the shafts was not recorded. Although there is said to be a drive connecting the main shaft with the shaft 450 feet to the north, there are no plans or sections of the underground workings and it is assumed that the main stope did not extend beneath the bed of the Murchison River.

The only shafts visible now are the main shaft and another, 65 feet north along the main lode, which could have been a ventilation and pumping shaft, since the arrangement of the timbers at the collar indicate that it was not used for hauling ore. The main shaft is collared about 10 feet above the water in the river and is filled with water to river level. The second is filled with broken ore and rock, which also obscures the outcrop of the main lode in the vicinity of the mine.

GEOLOGY

Jones and Noldart (1962) have given a full bibliography of reports on the Northampton Mineral Field and discussed the occurrence of the lead ore bodies. Prider (1958) reported on the area in the vicinity of the Geraldine lead mine.

Except for patches of soil and alluvium, the only rocks within a radius of a mile of the mine are Precambrian garnet granulite, pegmatite, and dolerite. These were described by Prider as:

"... fine- to coarse-grained garnet granulites, extensively pegmatized, but otherwise rather uniform and monotonous in character. The granulites have a gneissic structure ... strike approximately E.-W. and dip from 45° to 65° south. Microcline-rich pegmatites ... occur throughout the granulites as lenticular masses, elongate parallel to the foliation ... dolerite dykes ... in a N.E.-trending swarm."

The granulite, with associated pegmatite is Archaean and the dolerite dykes, which intrude the granulite, are late Proterozoic or early Palaeozoic in age.

Prider described a specimen of garnet granulite from the dump of the Geraldine mine as:

"... even, fine- to medium-grained, and consist of a granulo-se aggregate of pale pink garnet, white microcline and grey quartz with accessory biotite and flake graphite. ... Under the microscope the texture is even-granoblastic, with a slight gneissic structure due to sub-parallel orientation of the biotite and graphite flakes and

elongate quartz grains. The minerals in order of abundance are quartz, microcline, oligoclase-albite, garnet, biotite and graphite, with zircon and monazite as minor accessories. ... The garnet is ... dispersed uniformly throughout the rock, in grains to 1.7 mm diameter. It is an almandine."

Almost complete replacement of garnet by chlorite was noticed in some outcrops and chlorite is well-developed in the vicinity of the ore channel. There was abundant chlorite in the drill core. The biotite in the core was bronze-coloured and probably iron-rich.

Jones and Noldart (1962, p. 39) wrote:

"The lead and copper deposits are confined to the N.E. tension fractures near or alongside the dolerite dykes. The host rocks are garnet granulite, quartzite and rarely dolerite, although there are numerous small ore bodies along the dolerite-granulite contacts.

Siliceous brecciated gangue and numerous vugs up to 2-3 feet diameter are characteristic of the ore. The main sulphide minerals are galena, sphalerite, pyrite, marcasite and chalcopyrite. Octahedral galena, of 5 cm maximum size, and quartz crystals are usual in the vug linings of the lead ore. Sphalerite is not intimately mixed with the galena. ... Barite is common in the gangue ... it forms most of the vein ... in the Surprise Mine at Galena."

The main lode at the Geraldine lead mine is in a shear zone in garnet granulite and it is parallel with the trend of nearby dolerite dykes. The nearest dolerite dykes are 300 yards to the southeast and 600 yards to the northwest.

Specimens from the mine dump indicated that the ore body was composed of sheared and brecciated, chloritized garnet granulite; with many vugs containing galena, brown sphalerite, and minor pyrite and chalcopyrite, together with abundant small crystals of quartz. This was confirmed by the drilling which also revealed a tendency for the concentration of galena at the hanging wall of the lode and sphalerite at the footwall. The lode is weathered and cavernous; drilling water was lost and core recovery was poor near the hanging wall in Hole 3.

DRILLING RESULTS

Hole 1 intersected the mineralized zone at an underlay depth of 380 feet below the collar of the main shaft but the sulphide zones were disappointingly narrow. Holes 2 and 3 were drilled to test the lode on either side of No. 1, and these indicated that the ore shoot did not extend in depth either vertically, or with a low plunge north or south.

The main lode was found to steepen slightly at Hole 2 but the strike and dip of the lode was found reasonably constant in depth, as well as in outcrop.

As can be seen from the tabulated comparison of drilling results below, the intersections made in Holes 2 and 3 were poorer than those in Hole 1, and the mineralized zones were wider than in Hole 1. With the exception of a little galena in Hole 2 and a 1-inch seam of sphalerite in Hole 3, all galena and sphalerite intersections were confined to the main mineralized zone. The galena was restricted to the hanging wall and the sphalerite to the footwall. Both the galena and the sphalerite intersections were better in Hole 1 and, although only 2 inches of galena was cored at the hanging wall, it is possible that the seam was 5 inches wide, corresponding to a true thickness of about 4 inches.

The cavity at 412 feet in Hole 3 is at the hanging wall (galena zone) of the lode and the possibility that the drill encountered an old stope must be considered. There is no possibility that the drill-hole lifted, since the acid-tube dip surveys indicated a reasonably consistent dip to all three drillholes, and the positions of the sulphide intersections in the hole support the survey results.

COMPARISON OF DRILLING RESULTS

| | Hole 1 | Hole 2 | Hole 3 |
|---|--|---|--|
| Length | 505 feet | 477 feet | 447 feet |
| Cavities, with loss of drilling water | 1' at 137' ;
1' at 240' | None | 3' at 412' |
| Core recovery in mineralized zone | High | High | Low |
| Intersections outside main mineralized zone | None | $\frac{1}{2}$ in. core at 403' contains a little galena | $\frac{1}{8}$ in. seam of sphalerite at 401' |
| Hanging wall of shear zone | 415' | 440' | 404' |
| Hanging wall of mineralized zone | 417' | 446' | 409' |
| Footwall of mineralized shear zone | 421' | 454' | 421' |
| Width of mineralized zone | 4' | 8' | 12' |
| Total width of galena intersections | $2\frac{1}{2}$ ($4\frac{1}{2}$?) ins. | $\frac{1}{4}$ in. | 12 ins. |
| Proportion of galena in intersections | High | High | Very low |
| Total width of sphalerite intersections | $6\frac{3}{4}$ ins. | $4\frac{1}{2}$ ins. | $1\frac{3}{4}$ ins. |
| Proportion of sphalerite in intersections | High | 30 % | High |
| Total width of sulphide intersections | $9\frac{1}{4}$ ($11\frac{1}{4}$?) ins. | $4\frac{3}{4}$ ins. | $13\frac{3}{4}$ ins. |
| Proportion of sulphides in intersections | High | Medium | Low |

It could be contended that the old workings were deeper than the recorded 320 feet, and there is no concrete evidence against such a suggestion. However, Jones and Noldart noted that 2 to 3 feet diameter vugs are 'characteristic' of the ore bodies in the area. Furthermore the presence of soft, weathered granulite at 404 to 406 feet in the core, also towards the footwall, supports the contention that the cavity is a natural one which has been accessible to circulating groundwater for a very long time.

COPPER DEPOSITS OF THE LITTLE TARRAJI RIVER
AND OTHER AREAS OF THE YAMPI 1:250,000 SHEET AREA,
WEST KIMBERLEY

by John Sofoulis

ABSTRACT

Minor copper mineralization is widespread in the Precambrian rocks of the Yampi 1:250,000 Sheet (SE/51-3) area. The significant deposits are associated with veins and reefs of quartz and with silicified, sericitic shear and fault zones. These occurrences are mostly restricted to a belt of Halls Creek Metamorphics that extends south and southeast from the Little Tarraji River area. Small showings of copper along the southeast extension of this same belt have been prospected at Mondooma and at Limestone Spring. Similar metamorphic rocks of the Townsend River—Mount Nellie area, north of Oobagooma, contain copper mineralization but not in economic amounts.

The only copper ore mined from the younger Precambrian Kimberley Group has been at the head of Coppermine Creek near Yampi Sound. This deposit is associated with quartz veins impregnating a sericitized and carbonated quartz porphyry which intrudes the Kimberley Group. There are minor occurrences of disseminated chalcopyrite in both the Carson Volcanics of the Kimberley Group and the younger intrusive Hart Dolerite.

COPPER PRODUCTION

Table 1 shows the total copper production recorded from the Yampi 1:250,000 Sheet area. This ore was mined during the period 1905 to 1920, when 109·52 tons of copper ore containing 25·92 tons of metallic copper, valued at \$A3,418 was produced. Copper ore produced prior to 1914

CONCLUSIONS

1. The drilling programme has indicated that the ore body of the Geraldine lead mine does not extend 370 feet, on the underlay, beneath the out-crop.
2. The possibility that the ore body might have a low angle of plunge was adequately tested.
3. The galena was concentrated at the hanging wall of the mineralized zone and the sphalerite at the foot wall.
4. Future exploration for lead in this vicinity could be directed towards Gallaghers Lode, 500 yards upstream on the eastern bank, and also to Greens Lode, about 300 yards downstream on the eastern bank. Gallagher's workings are only shallow, and a pit on Greens Lode has exposed a 6-inch seam of galena beneath 3 feet of colluvium.

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and not reported to the Mines Department would probably amount to less than 350 tons.

A locality plan of the known copper occurrences of the Sheet area is shown on Plate 31A.

Table 1
REPORTED COPPER PRODUCTION—YAMPI
1:250,000 SHEET AREA

| Centre | Lease | Name | Period | Quantity
Tons | Metallic
Content
Tons | Value
\$A |
|------------------|--------|----------------|--------|------------------|-----------------------------|--------------|
| Monarch
Group | ML227H | Holbrook | 1915 | 4·22 | 0·94 | 128·00 |
| | ML228H | Abagama | 1915 | 8·97 | 1·82 | 272·00 |
| Coppermine | ML221H | Yampi
Sound | 1914 | 38·50 | 9·21 | 852·00 |
| Creek | ML221H | Copper
Mine | 1915 | 54·36 | 13·59 | 2,094·00 |
| | Sundry | Persons | 1916 | 3·47 | 0·36 | 72·00 |
| | | | Total | 109·52 | 25·92 | 3,418·00 |

GEOLOGICAL INVESTIGATIONS

The geological information given on the various copper deposits of the area by Maitland (1919) and Simpson (1952) is summarized by Low (1963). The same deposits are described also by Harms (1959). An extensive study of the copper mineralization in the area was made by Western Mining Corporation Ltd., during their tenure of Temporary Reserve 1593H (December 1957—October 1960). This company conducted a series of reconnaissance and detailed

geological, geochemical and geophysical surveys over the metamorphic rocks and adjacent terrains, and subsequently drilled prospects at Grants Find and Wilsons Reward.

The various phases of this exploration programme are described in unpublished company reports by Woodall (1957), Triglavcanin (1958), Harper (1959), and Reid (1958, 1959).

The area is now included in Temporary Reserve 2680H held by Pickands Mather & Co. International, who are currently engaged in a programme of regional mapping and geochemical sampling.

The significant copper occurrences of the area are described in this report. Most of these were inspected by the writer or by other members of the geological party during a regional mapping project conducted jointly by the Bureau of Mineral Resources and the Geological Survey of Western Australia in the area during 1966.

Permission to quote information from unpublished company reports was kindly granted by Mr. J. D. Campbell, Chief Geologist of Western Mining Corporation Ltd.

LITTLE TARRAJI RIVER DEPOSITS

Copper mineralization was first reported from the Little Tarraji River area in 1905, the general locality then being referred to as 'east of Mount Nellie.' Abandoned groups of copper workings in this area are shown now on the Yampi 1:250,000 military sheet area as Grants Find, Tarraji, and Monarch Group. Further workings north of the Monarch Group are known also as Wilsons Reward or Berylton.

Plate 31B is a locality plan of the groups of copper workings and reported centres of copper mineralization.

LOCATION AND ACCESS

The copper deposits are north of the Tarraji River on the Oobagooma pastoral property. Oobagooma homestead, the nearest permanent settlement, is about 20 miles southwest of the deposits. A graded road connects Oobagooma to the port of Derby approximately 100 miles distant.

Access to the easternmost copper localities may be gained from a graded road which extends north from Kimberley Downs homestead through Limestone Spring to Mondooma on the Robinson River. Alternative cross country access to the various copper localities may be gained by four-wheel drive vehicle from either Oobagooma or Mondooma.

GENERAL GEOLOGY

The copper mineralization of the Little Tarraji River area is associated with veins and reefs of quartz which occupy faults or impregnate sericitized shear zones in a metamorphic sequence of steeply dipping sericite-chlorite-muscovite schists, slates, meta-arenites, and amphibolites of the Halls Creek Group. These rocks are intruded, and flanked to the east and west by granite of the Lamboo Complex. In the northern part of the area both the metamorphic rocks and granite are overlain unconformably by younger Precambrian rocks of the Kimberley Group, which are intruded by sills and dykes of the Hart Dolerite at several stratigraphic levels.

GEOCHEMICAL SURVEY

Copper

Soils of the area were systematically sampled by Western Mining Corporation during the 1958 field season. The samples were tested for copper by cold extraction field techniques and gave results which ranged from 1 ppm to 40 ppm of copper (Reid, 1958). Results greater than 2 ppm (taken as background value) were regarded as anomalous. The survey showed that the main anomalies correspond to areas of copper mineralization known within the Halls Creek Metamorphics. Other high values were attributed to the higher copper content in amphibolite of the Halls Creek Group and in the younger Hart Dolerite intrusives, but in these instances the results were not regarded as significant.

Further soil samples collected from the same area during the 1959 field season were tested for copper by total extraction methods using bisulphate fusion with estimation by cuproine. Background values ranged from 10 ppm or less of copper on granitic soils, to 50 ppm or more on shallow soils overlying Halls Creek Metamorphics. High values up to 200 ppm of copper were recorded from amphibolites effectively masking any mineralization associated with these rocks. Values above 100 ppm of copper were regarded as anomalous. The only significant anomalies outlined in the survey corresponded to the known areas of copper mineralization at Grants Find and Wilsons Reward. Other high values were associated with amphibolite or resulted from minor copper showings on faults or shear zones within the metamorphics. A total of 3,677 samples were tested in the complete programme.

Zinc

Of the 611 samples collected during the 1958 copper survey, 147 of them were tested for zinc by total extraction techniques. Results obtained ranged from 1 ppm to 12 ppm of zinc, but no concentration of high values could be demonstrated as the results were not regarded as anomalous for the technique used (Reid, 1958).

MAGNETIC SURVEY

A reconnaissance magnetic survey of the Little Tarraji River area (Triglavcanin, 1958) showed that the highest values of magnetic intensity corresponded to amphibolites and this helped to distinguish amphibolites from metasediments. Boundaries between metasediments and granite also were traced despite very small differences in magnetic intensity. However the detection or indication of copper mineralization was not possible as the differences in magnetic intensity between mineralized and non-mineralized rocks were considered too small to be diagnostic.

SELF POTENTIAL SURVEY

Self potential surveys were conducted by Western Mining Corporation Ltd. over a large part of the area (Triglavcanin, 1958, Harper, 1959). Anomalies were recorded over all the known occurrences of copper but only those at Grants Find and Wilsons Reward could be ascribed to worthwhile mineralization.

In neither locality did the self potential survey reveal extensions of the deposits beneath adjacent alluvium, nor did it indicate deposits of economic potential below soil cover in any other part of the Little Tarraji River valley.

GRANTS FIND WORKINGS

The abandoned copper workings at Grants Find are known also as Grants Prospect, Grants Reward, or Mount Nellie Deposit.

Copper mineralization at this locality can be traced in a fairly continuous line for more than half a mile. The more significant showings of copper are confined to a prominent quartz reef which rises 75 feet above the surrounding plain level. The quartz reef strikes 40° to 45° east of north and dips southeast at 70° to 85°. It consists of multiple pinch and swell quartz layers and contains thin discontinuous lenses and bands of schist, forming a composite banded reef 2 to 6 feet wide.

Disseminated malachite and minor cuprite are associated with limonite and confined mainly to the eastern or hanging wall side of the reef. However, this mineralization is not continuous and large sections of the reef appear barren. Schist remnants within the reef commonly have a higher copper content, and there are malachite stains and thin coatings along joints and partings in the oxidized schist adjacent to the mineralized sections of the hanging wall.

Plate 31C is a plan of the Grants Find reef and workings. The reef has been worked from a vertical shaft sunk on a richer shoot of ore. The shaft was sunk 35 feet at the hanging wall contact with slates, this depth being the lower limit of oxidation. Unstopped hanging wall

drives at this depth extend 160 feet and two adits (one of which has now collapsed) provided access to the drives from the western side of the ridge.

Harms (1959) noted that the ore body consists of quartz with disseminated copper minerals and is 2 foot 6 inches wide at the bottom of the shaft and 5 feet wide at the junction of the north adit and drive. Some ore left in the ore paddock adjoining the shaft consists mainly of limonite-stained quartz with disseminated malachite, and minor cuprite and malachite in joints and partings.

A small parcel of copper ore was open cut from the south extension of the reef. Ore broken at this locality was allowed to fall to the scree floor adjoining the hanging wall. A parallel reef 25 feet west of this locality contained only minor copper disseminations.

Grants South workings

A discontinuous quartz reef, which is probably a dislocated strike extension of the Grants Find reef, crops out as a prominent ridge $\frac{1}{4}$ of a mile southwest of Grants Find shaft. The reef is generally 18 inches to 2 feet wide but there are local zones of mineralization up to 5 feet wide. These consist of schist impregnated by numerous malachite-stained quartz stringers. Some of the quartz veins contain lenticular bunches of disseminated malachite as well as thin malachite veinlets up to several inches thick. The copper showings are commonly associated with iron oxides.

A small parcel of ore has been mined from a pit now 8 feet deep on the eastern slope of the southern end of the ridge approximately 50 feet above plain level. Other quartz veins and reefs in this ridge are barren or have only minor copper showings.

Diamond drilling

The geophysical anomaly outlined at Grants Find was described by Harper (1959) as being broad, closed on three sides, and having negative values of -60 mv (millivolts) extending over 300 feet and -100 mv over 200 feet. Six diamond drillholes, of total footage 3,111 feet, were drilled to test the prospect; five into the main northern part of the Grants Find reef and one into the probable south extension of the same line of mineralization. The holes were planned to intersect the reef 300 to 400 feet below the outcrop.

The main rock types encountered in the drillholes were quartzite, slate, amphibolite, and feldspar porphyry. Unoxidized rocks were intersected 30 to 50 feet below the surface. Reid (1959) noted that the amphibolite was usually carbonated, and the porphyry occasionally so, and that the porphyry contained small blebs of chalcopyrite. In several holes the slate was silicified at the porphyry contact.

The drilling results are summarized in Table 2.

Table 2
DRILLING RESULTS—GRANTS FIND*

| Hole | Length of Intersection | Assay % Cu | Remarks |
|------|--------------------------------------|------------|--|
| GS1 | 17 feet 6 inches | 1.14 | Highest 27 inches at 2.95% Cu. |
| GS2 | 23 feet | 1.23 | H.W. vein 17 inches at 5.34% Cu. |
| GS3 | 4 feet 10 inches | 1.3 | Contains zone 9 feet 6 inches at 3.25% Cu. |
| GS4 | 5 feet 1 inch | 2.6 | Separated by 20 feet of barren rock. |
| GS5 | Main lode almost barren, not assayed | .... | H.W. vein 60 inches at 0.63% Cu. |
| GS6 | 13 feet 6 inches | 1.29 | Included 7 feet at 2.22% Cu. |
| GS6 | True width 10 feet | .... |  |
| GS6 | No mineralization | .... |  |

* Drilled by Western Mining Corporation Ltd. Data from Reid (1959).

The drilling indicated that the pitch of the ore shoots was about vertical and that the grade of the lode intersections in all cases resembled that of the surface outcrop vertically above. The mineralization was primarily chalcopyrite in

quartz, and better grade intersections of the Grants Find reef averaged 1.5% to 2% copper over an average width of 10 feet. Reid (1959) estimated that 11,000 tons per vertical foot of ore at this grade would persist to a depth of at least 400 feet.

TARRAJI OR MT. NELLIE SOUTH WORKINGS (Harms, 1959)

A quartz reef about $1\frac{1}{2}$ miles south of Grants Find shaft is probably a dislocated strike extension of the Grants Find reef. Here the quartz reef is a foot wide and has copper mineralization, where it is exposed in a shallow trench, over a length of 15 feet. This reef is nearly vertical and strikes 320° parallel to the enclosing schists. A shaft sunk 25 feet deep on the line of reef, approximately 1 chain south of the trench, failed to intersect a defined lode.

WILSONS REWARD WORKINGS

This locality is also known as Berylton or Wilsons Prospect. The workings are on the flanks of a low ridge approximately $5\frac{1}{2}$ miles southeast of Grants Find.

The copper mineralization is associated with quartz reefs and veins which trend 20° to 30° west of north and intrude folded phyllitic and amphibolitic schists. Individual lodes are usually a few inches wide and up to 10 feet long, and carry only disseminated malachite. A shaft about 50 feet deep and several shallow trenches and pits failed to locate an economic deposit.

Diamond drilling

The geophysical anomaly outlined at Wilsons Reward was not as well defined as that of Grants Find. Negative values exceeded -40 mv at only a few points close to the outcrop (Harper, 1959). Four diamond drillholes, of total footage 2,478 feet, were drilled to intersect the lode 300-400 feet below the surface. Plate 31D is a plan of the drillholes.

Oxidation is relatively shallow and fresh rocks are encountered 50 to 70 feet below the surface. The main rock types intersected were quartzite, phyllite, and amphibolite; the amphibolite was usually carbonated. Lode intersections were made in all four holes. These consisted of phyllite, partly replaced by quartz with pyrite, subordinate amounts of chalcopyrite, and occasional pyrrhotite. There were small blebs of pyrrhotite on shear planes throughout much of the country rock and some pyrite along joints. The drilling results are summarized in Table 3.

Table 3
DRILLING RESULTS—WILSONS REWARD*

| Hole | Length of Intersection | Assay % Cu | Remarks |
|------|------------------------|----------------------|---|
| WS1 | 33 feet | Less than 0.1 | Contained 24 inches at 1.35% Cu. |
| WS2 | 42 feet 7 inches.... | Less than 0.25 | Highest 14 inches at 0.4% Cu. |
| WS3 | 12 feet 5 inches | 1.4 | 17% Core recovery. |
| WS4 | 35 feet | 0.83 inc. 21" at 4.1 | Drilled to cover possible vertical dip of lode. |

* Drilled by Western Mining Corporation Ltd. Data from Reid (1959).

In all holes except WS3, amphibolite was the principal footwall rock. In WS3 the footwall rock was primarily quartzitic and resembled the hanging wall of the lode. This suggested that only the nose of the fold was intersected and that the folded lode either pitched south rather than southeast, as was inferred from the surface mapping, or else the hole had deflected to the east.

Reid (1959) considered that the chances of locating a sizeable tonnage of high grade ore at Wilsons Reward were remote, although the drilling test could not be regarded as complete.

MONARCH GROUP

The area south of Wilsons Reward contains scattered shallow workings which are collectively known as the Monarch Group or Monarch

Workings. Schists of this locality are intruded locally by quartz reefs and veinlets with disseminated copper mineralization. Sharp anomalies of limited extent were recorded in the area during the self potential survey made by Western Mining Corporation Ltd. (Harper, 1959). Some single readings greater than -100 mv were attributed to small pods of copper minerals in veins of quartz.

Some small parcels of copper ore may have been recovered from the area but the copper showings are generally too small to be of economic importance.

ASSAYS FROM LITTLE TARRAJI RIVER COPPER ORES

Simpson (1952) assayed seventeen bulk samples of copper ore from the Little Tarraji River workings. They were collected in 1911 by agents of a German syndicate which was then working several leases in the area. The samples assayed from 2.20% to 16.04% Cu with an average of 7.37% Cu. The chief copper mineral of all the samples collected was malachite. An analysis of the combined sample gave:

| | Per Cent |
|--------------------------------|----------|
| CuO | 9.23 |
| Zn, Bi, Sb | nil |
| Pb, Ni, Mn | trace |
| As | 0.04 |
| Fe ₂ O ₃ | 8.21 |
| Al ₂ O ₃ | 5.86 |
| CaO | nil |
| MgO | 0.83 |
| SiO ₂ | 68.83 |
| CO ₂ | 2.56 |
| S | 0.08 |
| O, H ₂ O, and loss | 4.36 |
| | 100.00 |

Selected samples of carbonate ore from this area assayed as follows:

| Copper % | Lead % | Gold ton | Silver ton | Remarks |
|----------|--------|----------|------------|--|
| 34.63 | 0.72 | grns 20 | dwts 4 | <i>Grants Find ore</i> : cellular mixtures of malachite and limonite with a little quartz. |
| 23.22 | nil | 20 | 1 15 | |
| 37.58 | nil | 20 | 11 10 | <i>Wilson's Reward ore</i> : massive liver ore with patches of quartz and malachite. |

OTHER COPPER OCCURRENCES

ROUGH TRIANGLE PROSPECT

A prospect consisting of a silicified and ferruginized sericitic schist zone was located by Western Mining Corporation Ltd. in hilly schist country approximately 2½ miles west of Grants Find. The line of mineralization which trends north and dips steeply east, can be traced almost continuously for 60 chains. The average width of the zone is 4 feet and the greatest width is 15 feet. There is minor copper mineralization along the zone with richer occurrences where quartz is less abundant (Reid, 1958).

A small parallel lode with similar mineralization is exposed on the banks of a small creek 250 feet east of the main line. Float from this line can be traced for about 1,000 feet south. Despite their length, neither line of mineralization contains economic ore bodies.

AMPHIBOLITE PROSPECT

Sporadic copper mineralization, associated with iron oxides, is exposed along a shear zone in the younger Precambrian Hart Dolerite north of Rough Triangle prospect. The shear zone is intensely sericitized and contains patchy silicification and minor quartz veins.

The mineralized shear zone is part of a strong fault which can be traced on air photos for several miles to the north and dies out to the south in the Rough Triangle area. The line of mineralization has been prospected by three shallow pits sunk in a gossanous ore consisting of a mixture of malachite, bornite, cuprite, and iron oxides.

TOWNSEND RIVER—MOUNT NELLIE AREA

Several small copper showings are associated with quartz in sericitic shear zones of the Halls

Creek Metamorphics north of Oobagooma. The principal showings are referred to as Mangrove Prospect and Townsend River A, B, and C Prospects (Reid, 1958; Simpson, 1952). None of the deposits are economic.

Other showings in this locality are very small and are of little significance. However, they indicate the regional extent of copper mineralization in this area.

MONDOOMA

Some copper workings located 3 miles north-westerly from Mondooma Yard were described by Harms (1959) as the Mondooma Copper Show. Simpson (1952) and Low (1963) referred to the same workings as the Robinson River copper mine.

The workings are in a belt of Halls Creek Metamorphics which extend southeasterly from the Little Tarraji River deposits. The Mondooma workings are north of the Robinson River, in a prominent northwest trending ridge that rises 150 feet above plain level. Granite of the Lamboo Complex flanks the ridge to the northeast.

A prominent quartz reef, subparallel to the schistosity of the metamorphics, can be traced for about 420 yards along the crest of the ridge. Copper staining is visible over half this length.

Harms (1959) noted that the reef, where copper stained, ranges from 3 to 15 feet in width but is barren over most of this width. Primary copper mineralization is apparently confined to soft, iron-stained and kaolinized lenses up to 2 feet wide, from which secondary carbonates have been derived.

Some richer portions of the ore were investigated by trench and a shaft sunk to 10 feet but these did not indicate mineralization of economic grade. Reconnaissance by Western Mining Corporation Ltd. failed to reveal any significant copper mineralization other than that already known, although a large number of quartz veins with occasional rich showings of iron oxides occur throughout the belt (Reid, 1958). A similar quartz vein 4 miles southeast of Mondooma parallels the Mondooma reef but no mineralization is evident.

LIMESTONE SPRING

There are shallow workings 2 miles north of Limestone Spring in a belt of low rises consisting of sericite schist and amphibolite. These rocks trend northwest and are a further southeasterly extension of the Halls Creek Metamorphics from Mondooma. A ferruginized quartz reef, stained with copper carbonates and traces of chalcocite, constitutes the line of mineralization which can be traced for a distance of 300 yards. This reef has been prospected from an inclined shaft about 20 feet deep, a shallow trench 25 feet long, and from a costean.

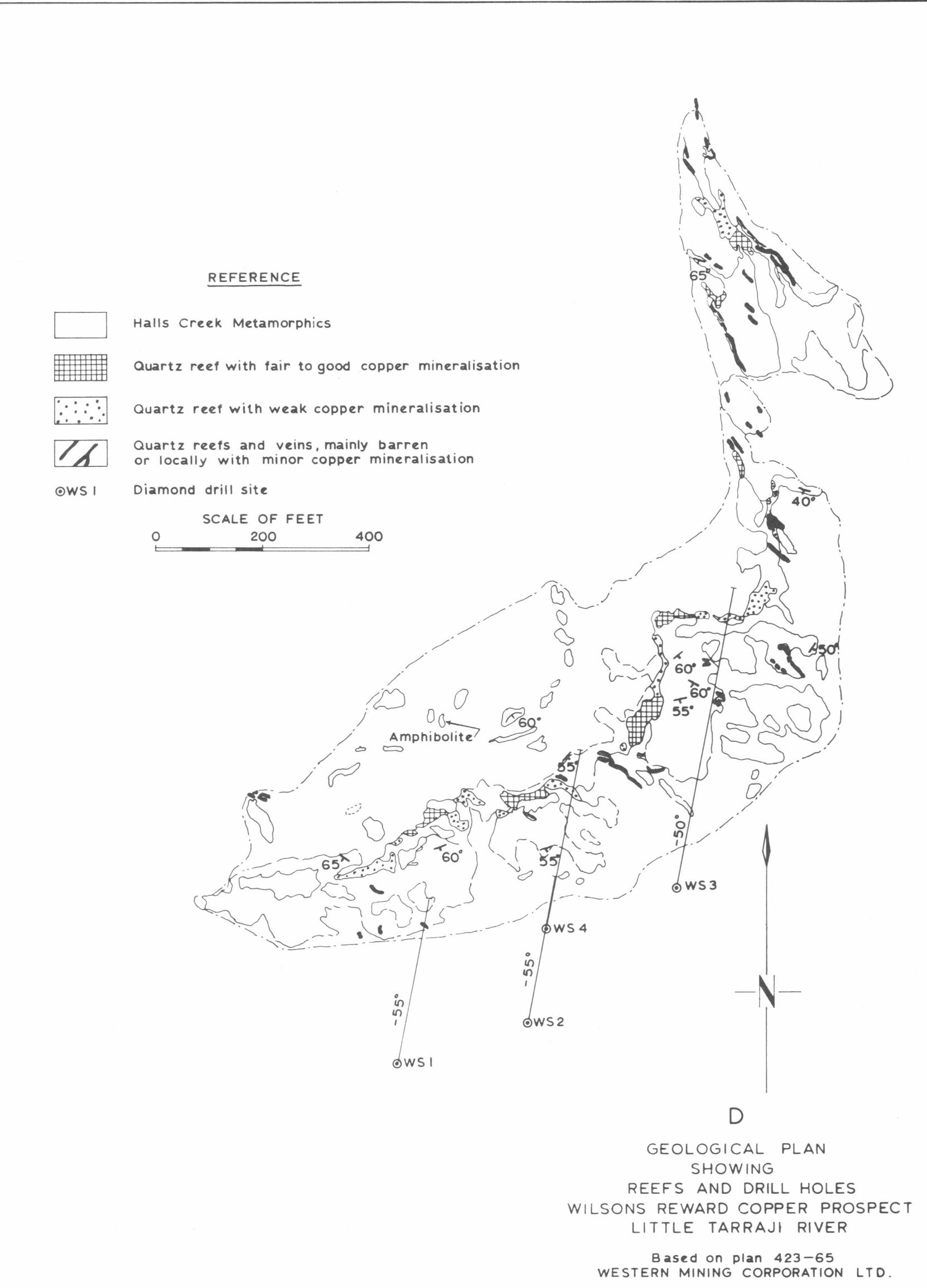
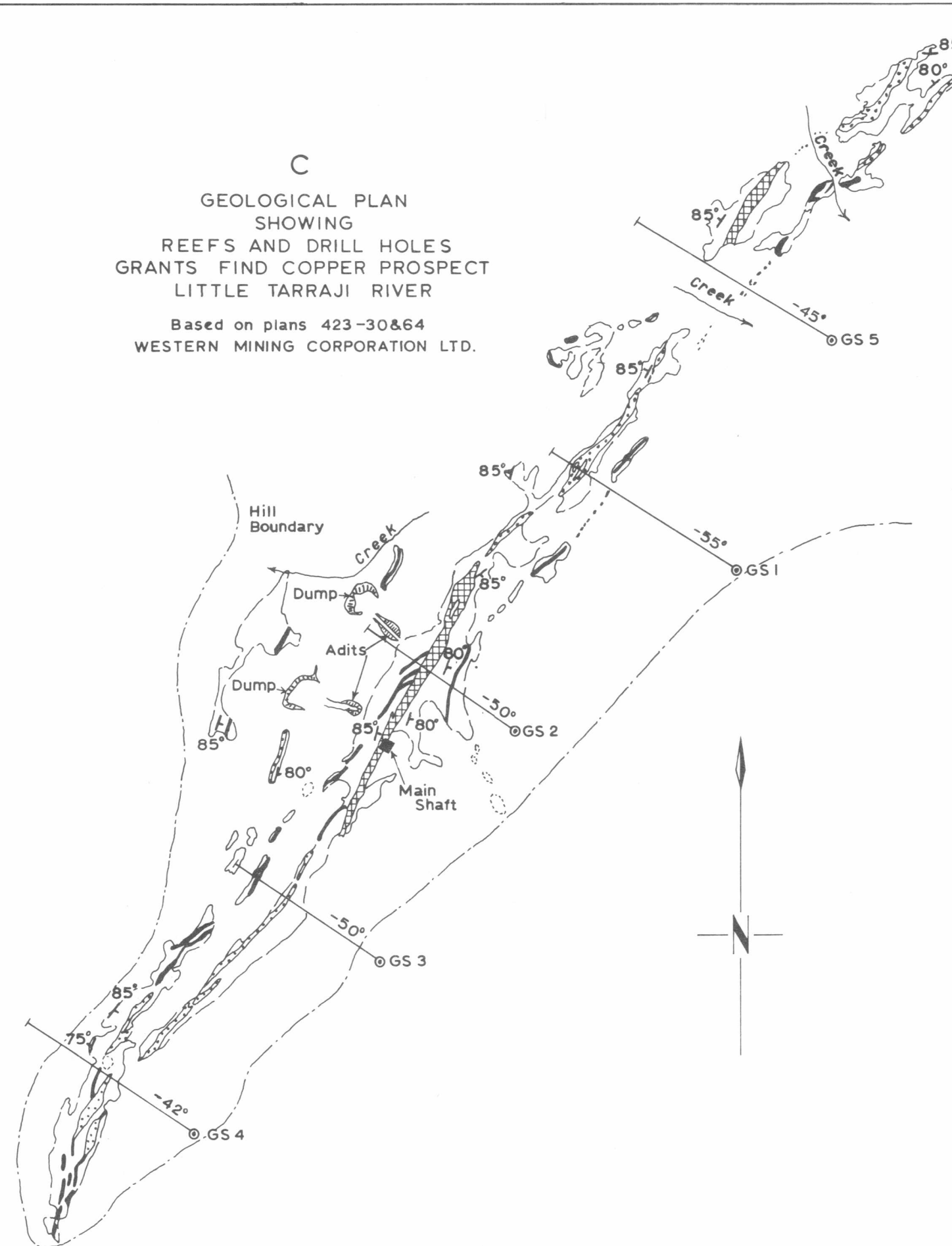
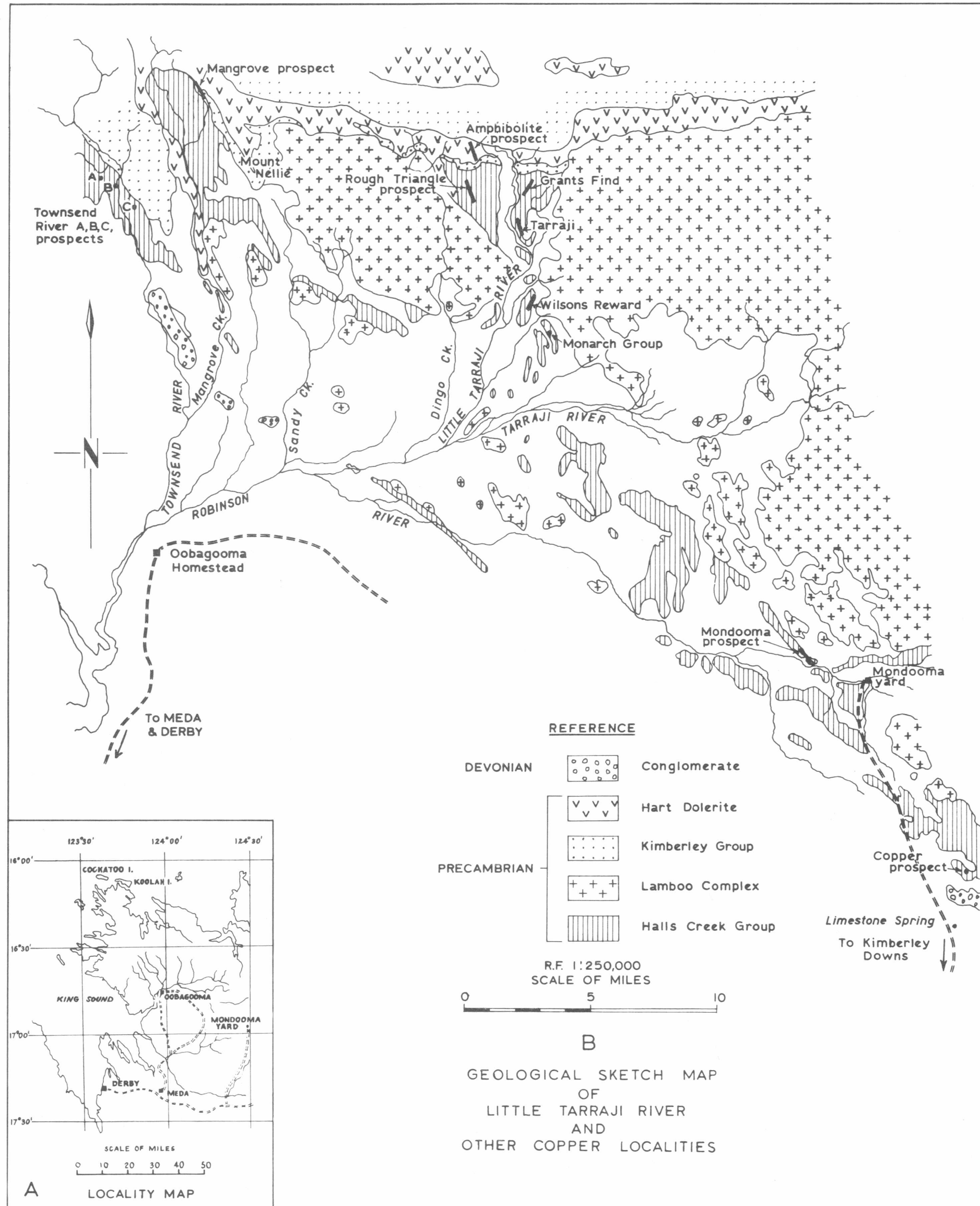
There is no official record of production from this area and from the paucity of mineralization the prospect does not appear to warrant further work.

COPPER MINE CREEK DEPOSIT

The only copper ore mined from the younger Precambrian (Kimberley Group) has been that from the Yampi Sound copper mine. This mine is on the mainland coast at the head of Coppermine Creek approximately 10 miles south of Cockatoo Island. Low (1963) referred to this deposit as Yampi Sound copper deposit, Water Point.

The mineralization is localized in a probable fault zone and consists of copper minerals associated with quartz veins which impregnate sheared, sericitized and carbonated quartz porphyry. Maitland (1919) recorded that the width of the lode at this deposit ranges between 5 and 6 feet and that it underlies to the east. Ore mined from this deposit was described by Simpson (1952) as containing masses of chalcocite, associated with malachite, cuprite, atacamite (copper oxychloride), and brochantite (basic copper sulphate). The deposit has not been worked since 1915. Reported production for the years 1912-1915 was 92.86 tons of copper ore containing 22.70 tons of copper valued at \$A2,946.

It is probable that the porphyry contains further mineralized zones. From the 1966 map-



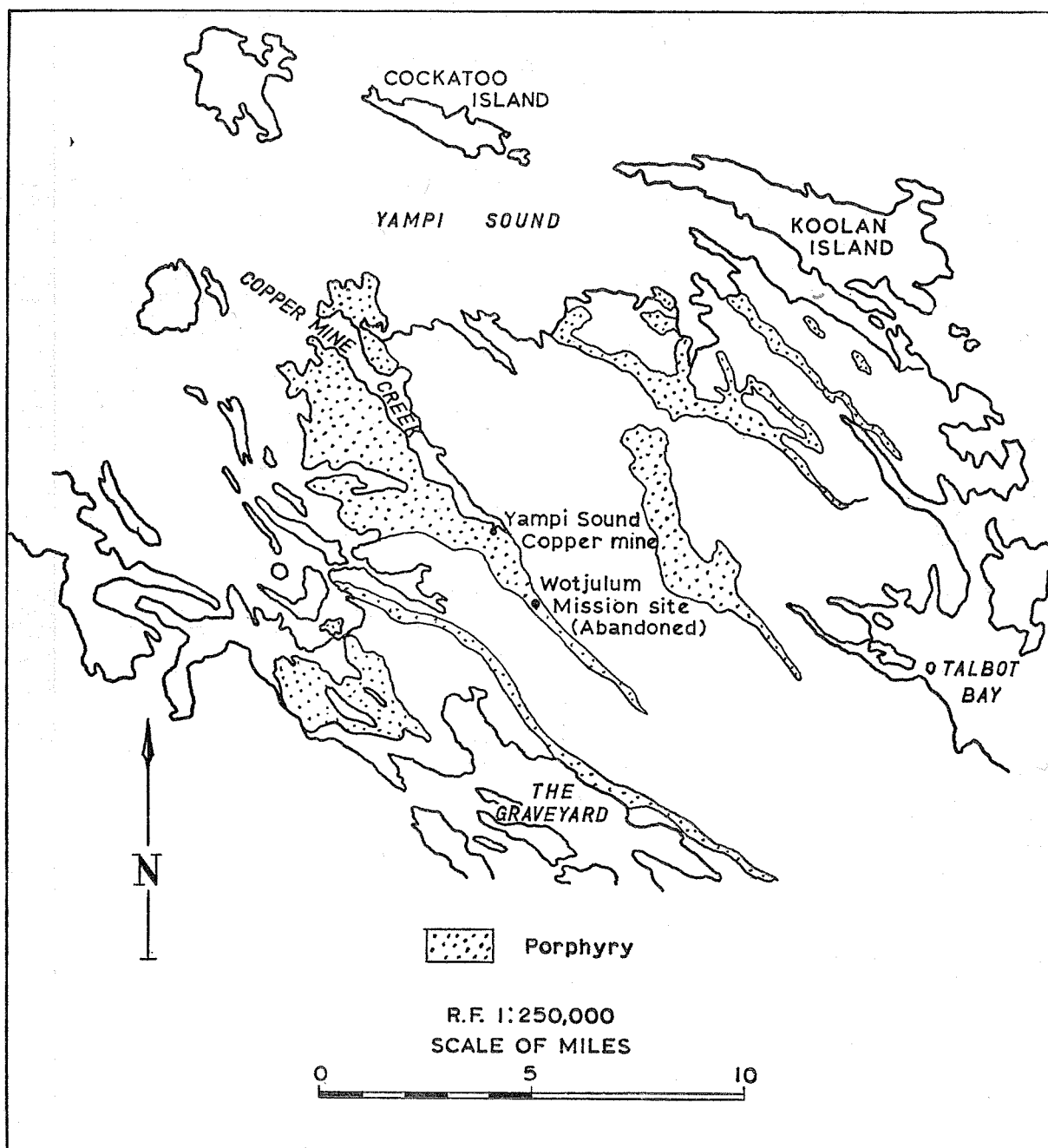


FIGURE 15: LOCALITY AND GEOLOGICAL SKETCH MAP OF PORPHYRY DISTRIBUTION, NORTHWEST YAMPI PENINSULA

ping, it is known that the porphyry intrudes the Elgee Siltstone horizon of the Kimberley Group. The same porphyry is repeated in the area by folding, and has an extensive distribution in the northwestern part of the Yampi Peninsula.

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MICA DEPOSITS OF THE WEST KIMBERLEY AREA, WESTERN AUSTRALIA

by John Sofoulis

INTRODUCTION

Mica production in Western Australia and other Australian States virtually ceased with the termination of the mica mining subsidy by the Commonwealth Mica Pool. All requirements of sheet and block mica are now imported from India while ground and pulverised mica is obtained mainly from South Africa and the United Kingdom.

Two pegmatite dykes, previously mined for sheet muscovite, are located on the Napier Downs and Kimberley Downs properties in the West Kimberley. The mica shows are referred to respectively as Gussys mica deposit and Stuarts mica mine. Each is approximately 100 miles by road inland from the port of Derby.

The deposits, abandoned at present, were inspected in 1966 during the course of a regional mapping programme conducted jointly by the Bureau of Mineral Resources and the Geological Survey of Western Australia. Locality maps and geological plans of the workings are shown on the accompanying plate.

Both deposits could yield small quantities of high grade muscovite.

GUSSYS MICA DEPOSIT

Gussys mica deposit is approximately 6 miles northeast of Napier Downs homestead and 1½ miles southeast of Kongorow Pool on the Barker River. The deposit is known also as Kongarra or Barker Gorge mica mine. It was last worked for mica as P.A.s 47 and 49 during 1943-44 but the production was not reported. The earlier excavations were examined by Finucane and Jones (1939). Other reports on the same occurrence are given by Simpson (1952) and Harms (1959).

General geology

The pegmatite occurs in soil covered country as scattered, low, discontinuous outcrops aligned northwesterly. It intrudes a sequence of chlorite-biotite schists, amphibolites, and meta-arenites of the Halls Creek Group and lies close to the contact of the Halls Creek Group with a coarse-grained, porphyritic feldspar-biotite granite of the Lamboo Complex (see Plate 32).

Both the pegmatite dyke and metamorphic rocks strike northwest and dip southwest at 55° to 75°. Foliations recorded in the adjacent granite have similar attitudes as well as a pronounced lineation plunging southeasterly at 40° to 50°. Dolerite dykes, trending west-northwest, and a network of tourmaline pegmatite and aplite veinlets also intrude the granite near the deposit.

Pegmatite workings

The pegmatite has been tested over a length of about 900 feet by a series of shallow prospecting pits, shafts, and costeans. The deepest shaft is said to have been 30 feet deep but most of the excavations are wash-filled through cyclonic rains and few are now deeper than 4 feet.

Available exposures suggest that the pegmatite consists of an irregular quartz core, flanked by outer zones of quartz, muscovite, and microcline feldspar. Accessory minerals include black tourmaline (usually associated with quartz), sericite, and occasional garnet. A few small crystals and pieces of beryl were recovered from a dump in the central part of the area. Lithium minerals were not recorded.

Pinch and swell structures give the pegmatite a width ranging from 4 to 15 feet. Good quality muscovite is restricted to the outer zone of the pegmatite, and mica books are usually oriented normal to the pegmatite walls in zones up to 5 feet thick.

The mica is somewhat weathered and limonite-stained at the surface, but improves with depth. The pale reddish-brown, fresh mica books from

the deeper workings were likened to the so-called 'ruby mica' of India by Simpson (1952) who stated that "the mica is perfectly transparent throughout except for one or two very small black inclusions in about one sheet in ten".

Finucane and Jones (1939) noted that the maximum size of mica books is about 8 inches and that pieces 6 inches x 6 inches may be cut from them. A parcel of muscovite, submitted in 1938 for examination by the Government Chemical Laboratory, was described by Simpson (1952) as being "in many-sided trimmed sheets almost all of which were free from wrinkles, cracks or twinning planes. The smallest pieces would yield sheets measuring 2 x 1 inches and the four largest sheets measuring 7 x 5, 5 x 4, 5½ x 3½, 5½ x 3½ inches respectively". Simpson considered that this was some of the best mica ever produced in this State.

STUARTS MICA MINE

Stuarts mica mine is in a composite quartz-pegmatite dyke which crops out near the Kimberley Downs—Mondooma Road, approximately 4 miles south of Mondooma and 5½ miles north-northwest of Limestone Springs (see Plate 32). The mine was worked during 1949 as P.A. 58 for mica and beryl.

Production of 31.25 lb of muscovite valued at \$A9.24, and 3.5 tons of beryl containing 38.85 units of BeO valued at \$A593.40, was reported to the Mines Department. Harms (1959) reported a mica production of about 150 lb.

General geology

The composite quartz-pegmatite dyke, containing the mica deposit, intrudes a belt of basic amphibolites and garnet-muscovite schists of the Halls Creek Group. Both the dyke and metamorphic rocks trend northwest and dip southwest at 45° to 75°. A large granite porphyry of the Lamboo Complex flanks the metamorphic rocks approximately 1 mile northeast of the quartz-pegmatite.

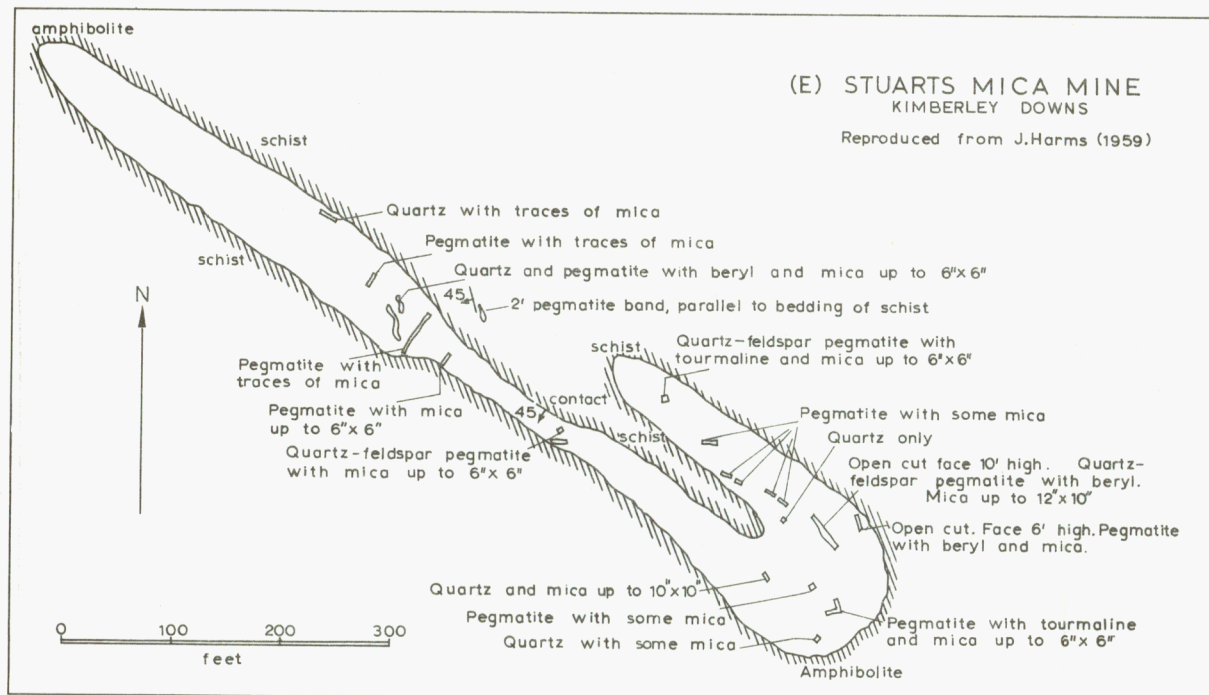
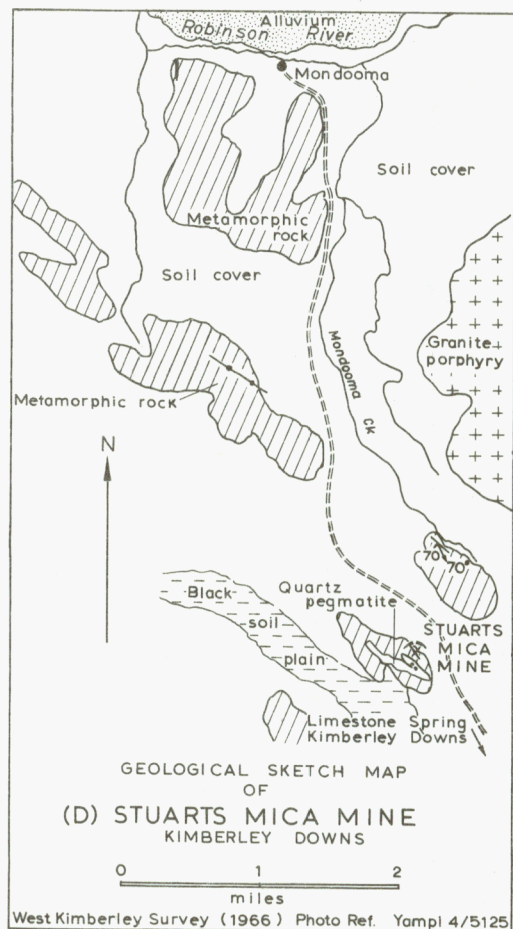
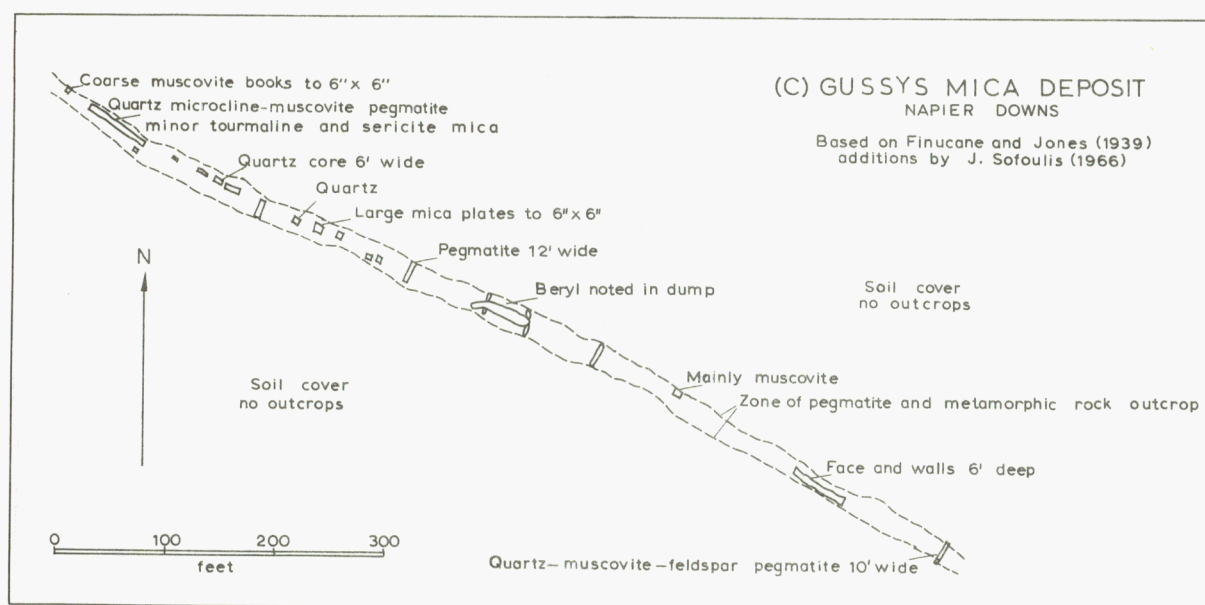
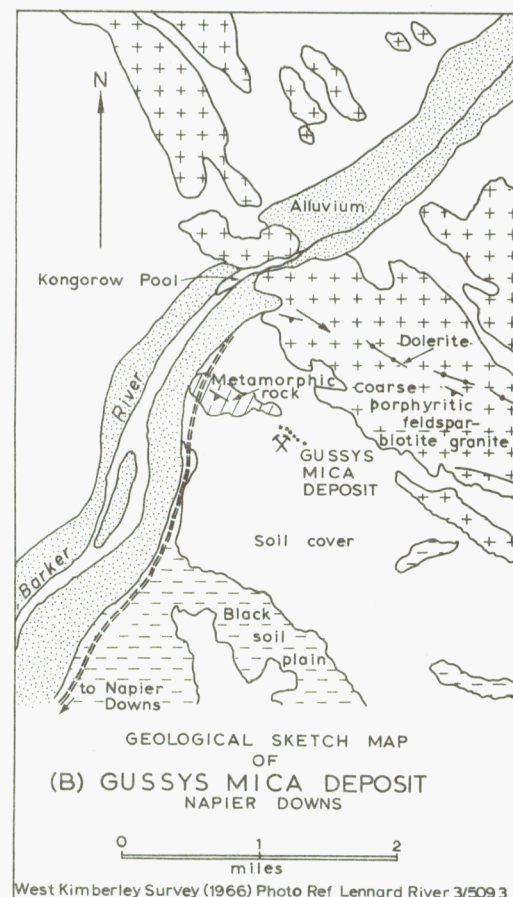
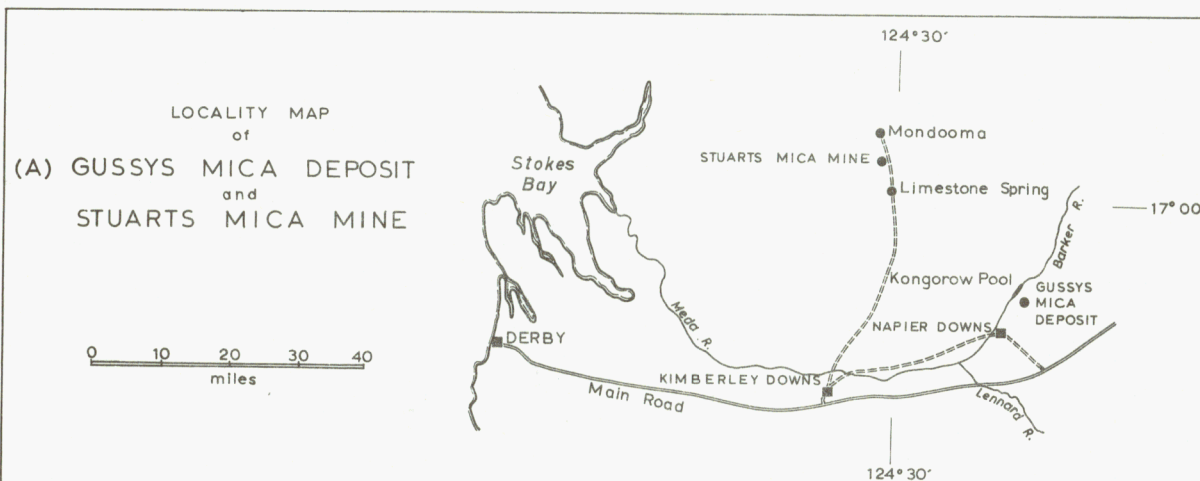
Pegmatite workings

Pegmatite and quartz cover an area of about 15 chains by 2 chains at the deposit locality. The pegmatite phase consists of quartz, microcline, and muscovite with accessory tourmaline and beryl. The southeastern part of the dyke has been tested with pits and trenches over a length of 300 feet. The largest trench, measuring 25 feet x 10 feet x 10 feet, exposes fresh mica books mainly associated with quartz. Single crystals up to 12 x 10 inches are not uncommon. These coarse books have random orientation and in some instances are deformed at the contact with the quartz. Muscovite from other dumps and shallow surface excavations is usually weathered and limonite-stained.

Harms (1959) recorded that beryl crystals up to 6 inches wide have been recovered from this dyke although most beryl production was derived from the adjacent eluvial soils. Harms also reported that some of the beryl was semi-transparent and the better crystals might yield gem quality stones.

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THE CROCIDOLITE DEPOSITS OF MARRA MAMBA, WEST PILBARA GOLDFIELD

by J. G. Blockley

ABSTRACT

At Marra Mamba, 57.6 tons of crocidolite have been mined from three horizons within the Marra Mamba Iron Formation. These are named the Mackay Horizon, Dun Horizon, and Foxall Horizon and are respectively 140, 260, and 350 feet above the base of the formation. Only the Dun Horizon is likely to produce ore bodies of appreciable size.

Structural control of the fibre distribution is mostly obscure, but in places, crocidolite seems to have been localised by early preconsolidation folds which have been modified by later tectonic folding.

Diamond drilling preceded by structural contour mapping is necessary for further development of the deposits.

INTRODUCTION

At Marra Mamba, five deposits of blue asbestos (crocidolite) have been worked in a narrow belt extending from 3 miles west to 9 miles east of Mt. Brockman Station homestead (lat. 22° 18' S., long. 117° 17' E.). Marra Mamba is 80 road miles from Wittenoom Gorge and 210 miles from Point Samson. Repair of an old road through Caliwinya Gorge could reduce the distance to Point Samson to 145 miles.

The first mining tenement at Marra Mamba was pegged in 1931. Intermittent mining of the deposit between 1932 and 1942 produced 57.6 long tons of crocidolite. Although the leases have been held continuously since 1942, there has been no further production. Australian Blue Asbestos Ltd. currently holds five groups of leases and one Temporary Reserve covering the area of the deposits. All the fibre produced has been won from shallow pits and benches on the seam outcrops. There are no deep openings in the field.

The present investigation is part of a regional survey of blue asbestos in the Hamersley Range carried out between 1964 and 1966. In 1965, the area of the deposits was mapped on aerial photographs, at a scale of 20 chains to an inch, by G. R. Ryan and the writer. As a result of this work an area including Mineral Claim 61WP and Mineral Claim 62WP was selected for more detailed mapping and eventual diamond drilling. P. Muhling and the writer completed the detailed mapping in 1966, but no diamond drilling has been done yet.

Foxall (1942) and Finucane (1964 and 1965) have described the Marra Mamba crocidolite deposit. MacLeod and others (1963) and de la Hunt (1966) have related the occurrences to the regional geology. Unpublished reports on the field have been prepared by Ryan and Blockley (1965) and Australian Blue Asbestos Ltd.

REGIONAL GEOLOGY

Mapping by MacLeod and others (1963) showed the crocidolite at Marra Mamba to be in the Marra Mamba Iron Formation, the lowermost unit of the Hamersley Group. The deposits are thus stratigraphically distinct from those worked at Wittenoom and Yampire Gorges where the fibre is in the Brockman Iron Formation, and about 1,300 feet higher in the succession.

Typically, the iron formation at Marra Mamba is a banded, black, brown, and yellow rock with numerous horizons of podded chert and frequent thin partings of stilpnomelane-shale. The chert pods are often elongated in the bedding planes, with the longer axes commonly parallel to one of the major tectonic trends. Individual pods may be separated, and in sections of suitable orientation the iron formation may have the appearance of a well-bedded conglomerate.

In relation to regional structure, Marra Mamba is on the north limb of the Jeerinah Anticline (de la Hunt, 1966). The beds have an average dip of 10°N., but minor folding is common.

STRATIGRAPHY

Nomenclature and general description

Here, as elsewhere in the Hamersley Range, blue asbestos forms as cross-fibre bands parallel to the bedding of the host banded iron formation (b.i.f.). Groups of closely spaced bands have been mined as *seams*, the criterion for a seam being a payable quantity of crocidolite within a convenient mining thickness. Seams occur at several distinct stratigraphic horizons (termed *crocidolite horizons*) within the iron formation, and the presence of several such horizons with associated riebeckite rock over a given stratigraphic interval constitutes a *riebeckite zone*. Where two or more seams are present in one area, it is convenient to name them, e.g., Dun Seam, Foxall Seam, etc. The various crocidolite horizons can then be named after appropriate seams, e.g., Dun Seam Crocidolite Horizon, or Dun Horizon for brevity. A seam name then refers to one particular body of crocidolite and should not be extended further, while a horizon name applies to a certain stratigraphic position and may be used wherever the horizon can be recognized, whether or not crocidolite is present at that point.

The fibre is generally restricted to those parts of the section where the distinction between b.i.f. units and shale units is well-marked. It is associated with yellowish chert containing laminae of magnetite called *cherty b.i.f.* *Shaly b.i.f.* (thinly bedded iron oxides, silicates, and chert) and *podded b.i.f.* (b.i.f. with well-podded chert beds usually separated by shaly material) appear to be unfavourable host rocks.

Seams have been worked at three horizons at Marra Mamba. All three are in the Marra Mamba Riebeckite Zone, the lower of the two riebeckite zones recognised in the Marra Mamba Iron Formation. The upper, or Vivash Riebeckite Zone, is not exposed in the area, but is known to contain fibre some 5 miles west of Marra Mamba. The three productive horizons have been named the Mackay Horizon, and Dun Horizon, (after two of the original discoverers) and the Foxall Horizon, after the former State Mining Engineer who first described the workings (Foxall, 1942). Recognition of these horizons is often difficult because of surface weathering and lack of marker beds, but it is important when prospecting the area.

Description of principal horizons

The Foxall Horizon has been worked on M.C. 62WP and recognized only at the eastern end of the area. Fibre of mineable grade is rare within the horizon. The horizon is about 350 feet above the base of the Marra Mamba Iron Formation. From top to bottom, a section about the fibre horizon is:

| Thickness
Ft. In. | Description |
|----------------------|--|
| 6 | Top shale |
| 2 0 | cherty b.i.f. with fibre in favourable positions |
| 9 | shaly b.i.f. |
| 3 3 | podded b.i.f. |
| 7 | shaly b.i.f. |
| 2 | cherty b.i.f., finely laminated |
| 3 | chert, yellow |
| 6 | shaly b.i.f. |
| 4 | shale, blocky weathering |
| 3 0 | cherty b.i.f. with riebeckite and fairly persistent fibre bands. |
| 1 2 | shaly b.i.f. |
| 1 0 | cherty b.i.f. with fibre developed in favourable positions. |
| 1 0 | shaly b.i.f. |
| 6 0 | podded b.i.f. |
| 9 | shale. |

In the field, the Foxall Horizon is best recognized by the beds immediately overlying the most persistent fibre bands, as shown in the above table.

The *Dun Horizon*, formerly called the "C" Horizon, is the most productive and extensive crocidolite occurrence in the Marra Mamba Iron Formation. It bears crocidolite in many places around the Jeerinah Anticline, and on the southern limb of the Mt. Brockman Syncline. The horizon is 260 feet above the base of the formation and is readily recognized by its position in the middle of a sequence of cyclic repetitions of b.i.f. and shale, also by a distinctive internal stratigraphy. A typical section about the fibre horizon is:

| Thickness
Ft. In. | Description |
|----------------------|---|
| 3 0 | Top.
podded b.i.f. |
| 9 | shale. |
| 1 6 | cherty b.i.f., sometimes with fibre. |
| 3 | chert, yellow, fibre developed immediately above. |
| 10 | shaly b.i.f. |
| 6 | cherty b.i.f., riebeckitic,
develops fibre. |
| 2 to 4 | frequently two complementary
fibre bands. |
| 1 3 | cherty b.i.f., riebeckitic, sometimes with fibre. |
| 5 | b.i.f., well bedded. |
| 8 | cherty b.i.f., sometimes with fibre. |
| 1 0 | b.i.f., well bedded. |
| 6 | shaly b.i.f. |
| 6 | shale. |
| 6 0 | b.i.f., sometimes with fibre. |

The presence of the twin crocidolite bands 6 inches below the 10-inch bed of shaly b.i.f. is characteristic of the Dun Horizon.

The *Mackay Horizon* has been recognized only at the western end of the Marra Mamba area. Its stratigraphic position is difficult to determine, due to incomplete exposure, but the adjacent succession of rocks resembles that about the "A" Horizon (see below). Ryan and Blockley (1965) equated it with the Dun Horizon, but this correlation is now considered invalid. On M.C. 65WP, the Mackay Horizon contains the most spectacular development of fibre seen at Marra Mamba, with grades ranging up to 7 inches over a 6-foot seam thickness. A typical section is:

| Thickness
Ft. In. | Description |
|----------------------|--------------------------|
| 3 | Top.
shale. |
| 1 7 | b.i.f. |
| 3 | shale. |
| 3 2 | b.i.f. |
| 4 4 | cherty b.i.f. with fibre |
| 1 3 | shaly b.i.f. |
| 2 10 | cherty b.i.f. with fibre |
| 1 2 | shaly b.i.f. |
| 4 | shale. |
| 14 4 | b.i.f. |

The shaly b.i.f. in the middle of the seam is similar to that in the Dun Horizon, but the absence of the twin fibre bands, and the different spacing of the surrounding shales, serves to distinguish the two horizons.

Other crocidolite-bearing horizons include one containing up to 4 inches of fibre over 2 feet seam thickness exposed in three gorges between M.C. 62WP and M.C. 64WP. It is about 120 feet below the Dun Horizon and comprises three bands of fibre within a 2-foot thick chert bed which in turn is part of a 12-foot thick b.i.f. unit. Because of the low stratigraphic position, few gorges have been cut deeply enough to expose the horizon. No fibre has been won from this seam, which is provisionally called the "A" Horizon. As stated above, it may be equivalent to the Mackay Horizon.

Other low-grade seams of apparently small extent have been seen at positions 85 feet and 60 feet below, and 30 feet and 47 feet above the Dun Horizon, and at 35 feet above the Mackay Horizon.

STRUCTURE

Folding

Minor folds are common at Marra Mamba and mapping has revealed two types. The earlier folds trend nearly east-west between 260° and 290°. These may change direction and usually die out within a short distance along strike. Crumpling is common in the limbs, and the north-dipping limbs are often steep, even being overturned in places. These folds may appear abruptly in evenly dipping strata and usually only a small area is involved in the folding. It would seem that

the rocks were incapable of transmitting stresses over any great distance during folding.

Probably these structures represent 'flow-folds' (Billings, 1942, p. 87) and were caused by the sliding of incompletely consolidated beds northwards from the rising Jeerinah Anticline, in the early stages of regional folding. A few monoclines which face northwards were probably formed in the same way.

The later and more intense folds control the form of the outcrop, and trend at 300°. Their south-dipping limbs are the shorter, indicating a normal drag-fold relationship with the Jeerinah Anticline. Many folds can be traced for several thousands of feet and are in wide belts, suggesting that the causative stresses were transmitted through a considerable body of rock. It is believed that these folds are of tectonic origin and were formed during the period of Ophthalmanian folding (Halligan and Daniels, 1964).

Faulting

Most faults at Marra Mamba trend either northwest or northeast and have little displacement. They may contain weathered dolerite dykes, as do many faults with similar trends elsewhere in the Hamersley Range. Towards the eastern end of the area shown on Plate 33, a fault trending west-northwest displaces the beds a few hundred feet laterally but the vertical component is unknown.

Structural control of crocidolite distribution

Two deposits of crocidolite at Marra Mamba have obviously been controlled by structure. The first is on M.C. 65WP where the Mackay Horizon has 7 inches of fibre on a 'flow-fold' anticline, but is poor or barren elsewhere. The second occurrence is about 4,000 feet southeast of M.C. 61WP where fibre has developed in two horizons on the steeply dipping north face of a monocline. The fibre is absent where the dips flatten to the north and south.

Structural control is less apparent at other deposits, but since the fibre often occurs at changes in dip on the limbs of tectonic folds, it is possible that earlier folds may have been incorporated into later structures in these situations. An example of this is the Foxall Horizon on M.C. 62WP (Plate 34) where the fibre grade is higher at a sharp dip change on the north limb of a small anticline.

DESCRIPTION OF CLAIMS

M.C. 61WP

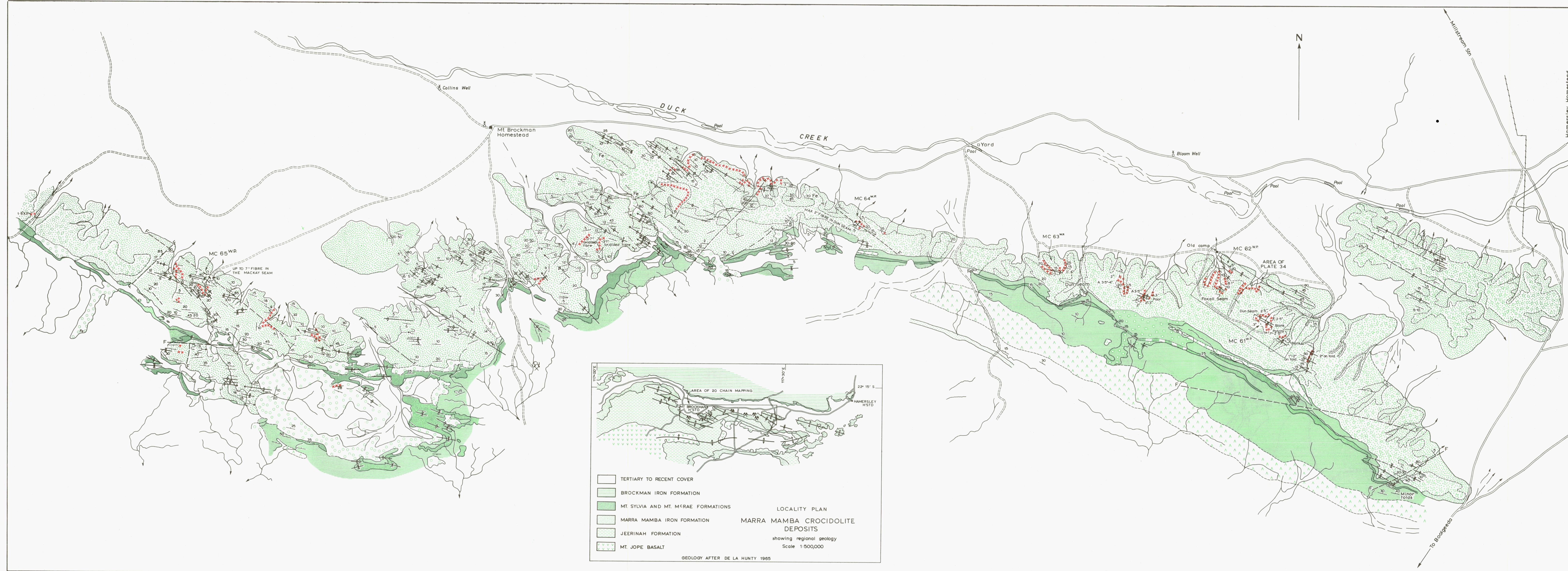
This claim covers the easternmost group of workings where the productive seam is in the Dun Horizon. Recorded production from this deposit is 47.55 tons. Mining was restricted to the northern part of the outcrop where the seam contains aggregate fibre lengths of up to 2½ inches over about 2 feet seam thickness. Benches extend continuously for 500 feet along the eastern side of the gorge and intermittently for the same distance on the western side.

The Dun Horizon was also mined in another branch of the gorge 1,200 feet to the southwest. Here, benches extend 250 feet along the cliffs on the western side of the ravine. Fibre grades range 2 to 3 inches over 2 feet seam thickness.

There is little evidence for structural control of crocidolite distribution on M.C. 61WP, although the fibre is restricted to the more steeply dipping beds. Slight warps trending across the strike are shown by the structural contours on Plate 34, and may have helped to localize the fibre.

M.C. 62WP

Mining on M.C. 62WP was restricted to a lens of spectacular growth of fibre on the Foxall Horizon where exposed for a length of 150 feet on a low bluff. The seam dips northwards below creek level and still contains oxidized fibre at this point. To the south of the workings however, the fibre is low-grade and patchy. Although the outcrop of the horizon was traced for some thousands of feet in the gorges to the south and west, no further rich seams were found.



REFERENCE

- Soil, alluvium
- Duricrust (some pisolite etc. indicated by symbol Fe)
- Marra Mamba Iron Formation
- Jeerinah Formation
b.l.f. quartzite
shale, chert
arkose, sandstone
- Dolerite
- Crocidolite seam
- Geological boundary (definite)
- Geological boundary (indefinite)
- Geological boundary (concealed)
- Axis of anticline
- Axis of syncline
- Fault
- Strike and dip of bedding
- Dip and strike of cleavage
- Dragfold
- Locality of old workings
- Graded road
- Track
- Copper prospect

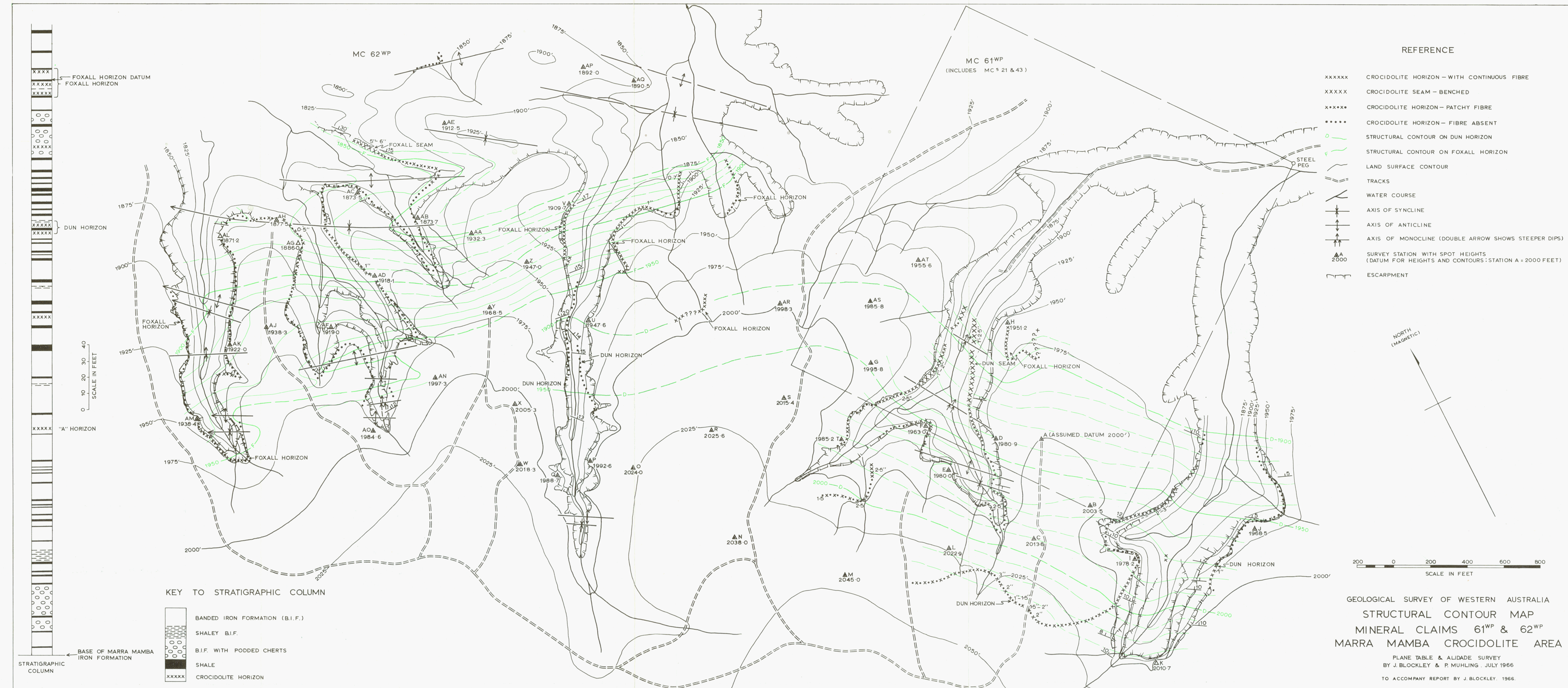
SCALE



GEOLOGICAL PLAN
MARRA MAMBA CROCIDOLITE AREA

Mapped by G.R. Ryan and J.G. Blockley June 1965

To accompany report by J.G. Blockley 1966



Foxall (1942) quotes an assay from the seam as 9 to 10½ inches over 8 to 8½ feet. However, the overall average is nearer 5 inches over 10 feet. Recorded production from this seam is 0.15 tons. The enrichment is on the northern limb of an anticline at a place where the dip steepens from 15° N to 30° N.

M.C. 63WP

The area of M.C. 63WP includes two groups of workings in adjacent gorges, both exploiting a seam in the Dun Horizon.

In the western gorge, the seam has been benched for about 250 feet along its outcrop. The workings start at creek level and extend southwards into the cliffs on the eastern side. The fibre grade ranges up to 3 inches over 2 feet. To the south there is a nearly blank zone of 350 feet, but values improve again on a monocline. Oxidized fibre can be traced eastwards from the southern end of the exposure into the next gorge. Here the seam has again been mined on the eastern side of the gorge with the diggings extending intermittently for 500 feet along the outcrop. Fibre grades of 3 to 4 inches over 2 feet seam thickness are common, and the seam is still of good tenor where it dips below creek level. Another seam 30 feet above the Dun Horizon has also been trenched for a short distance.

The better fibre on M.C. 63WP is located on the steeper dips of a gentle monocline.

M.C. 64WP

On M.C. 64WP the Dun Horizon can be traced for about 800 feet along the cliffs, but contains significant fibre only where it has been mined at the head of the gorge. Aggregate fibre length does not exceed 2 inches over 2 feet and only a little work has been done. A fault close to the benches has displaced the horizon a few feet vertically. Any relationship of fibre to structure is obscure.

M.C. 65WP

This claim contains the only workings on the Mackay Horizon. Although the horizon can be traced for about 1,000 feet along the gorge, mining was restricted to the limbs of an anticline of the 'flow-fold' type where there is a spectacular enrichment of crocidolite. This enrichment has been benched on the western side of the gorge and on a spur at the junction with an eastern tributary. Fibre grades reach 7 inches over 6 feet seam width on either side of the anticline's crest, but decline appreciably further from the fold axis.

CONCLUSIONS

1. Of the three chief crocidolite horizons at Marra Mamba, only the Dun Horizon seems likely to contain deposits of an appreciable size. It is expected that the grade of any such deposit would be marginal, say 2½ to 3½ inches over a normal stopping width. The Foxall and Mackay Horizons contain spectacular enrichment of small size, but are generally too low-grade to be considered as mining propositions.

Due to lack of continuous exposures, no estimate of the potential of the "A" Horizon could be formed. However, it is thought to be stratigraphically equivalent to the Mackay Horizon.

2. The origin of blue asbestos in iron-formation is not yet fully understood. Cilliers and Genis (in press) and Trendall (1966) have demonstrated that it is a late-stage diagenetic mineral. The first authors speculated that colloids of riebeckitic composition, migrating into early structures, controlled the distribution of the fibre. Trendall showed that riebeckite replaces the cherts of the iron-formation, suggesting that sodium (the only additional constituent needed to convert b.i.f. to riebeckite or crocidolite) was introduced in solution.

At Marra Mamba it seems that the sodium-rich solution (or gel?) was concentrated in early folds formed by the sliding of the unconsolidated

iron formation off the rising Jeerinah Anticline. These structures have been obscured by later tectonic folding.

3. Attempts to develop the Marra Mamba crocidolite deposits will face the following problems:

a. individual deposits are small and considerable exploration would be required to keep up ore reserves;

b. the fibre is associated with riebeckitic cherts which may give milling problems;

c. folding of some deposits would raise mining costs;

d. many of the known deposits are too close to the surface to be mined safely by underground methods.

These difficulties suggest that a rise in the price of crocidolite may be necessary before the Marra Mamba deposits can be worked profitably. However, with the rapid development of the Pilbara iron-ore deposits, the problems of remoteness and labour shortage in the North may become less acute, so reducing one of the obstacles encountered in past attempts to exploit these deposits.

4. As any mining operation would probably be based upon the deposits within the Dun Horizon, the first step in developing the field would be to evaluate one or more of these by diamond drilling. Those seams worked on M.C. 61WP and M.C. 63WP would be suitable, as both extend some distance along strike and still carry fibre where they dip below creek level. This drilling would best be preceded by structural contour mapping such as has been done on M.C. 61WP. The holes should penetrate at least as far as the "A" Horizon in order that all the known horizons should be tested.

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COLUMBITE-BERYL DEPOSIT ON MINERAL CLAIM 313,
PILBARA GOLDFIELD, AND ITS SIGNIFICANCE

by H. A. Ellis*

ABSTRACT

Production of economic minerals from pegmatites in Western Australia has mainly been from intrusions into Archaean greenstones. An occurrence of beryl and columbite, where the pegmatite host intrudes granitic rocks is described from a locality about 22 miles southeast of Port Hedland.

Because granitic rocks have not proved to be favourable hosts for gold mineralization, such areas have been largely neglected by prospectors. In view of the described rock association however, pegmatites intruding granitic rocks should now be more closely examined.

INTRODUCTION

Mineral Claim 313 is situated about 22 miles southeast of Port Hedland, and about 9 miles southeast of Pippingarra homestead on Pippingarra Station, at approximately latitude 20° 35' S. and longitude 118° 46' E. The position of the workings is shown by a conventional mine sign on the 4 miles to one inch Port Hedland Topographical Sheet published by the Lands Department.

GEOLOGY

When first examined by the writer in July 1955, work done since discovery in about 1953 indicated a decomposed mass of pegmatitic material striking N. 60° E. with an unascertainable dip. The pegmatite occurs in a low ridge with three conspicuous knolls of white quartz, surrounded by flat, brown, sandy spinifex country with no sign of any greenstone. The pegmatite appears to be emplaced in a granitic terrain and its approximate dimensions are from 500 to 600 feet wide and 60 chains long.

A lower section at the northeastern end of the claim is much more decomposed than other sections and was the main producing area. Here, eluvial columbite and beryl are in red clay loam some 2 feet thick, changing at that depth into partially decomposed dyke material. This material contains muscovite plus feldspar, and muscovite plus quartz concentrations, with a prominent distribution of pale blue quartz in both assemblages.

Numerous lenses of muscovite were noted with plates up to 2 inches wide, but a fine scaly development was much more common. Some beryl was seen in situ in association with the white scaly muscovite but no columbite was seen in situ. Much albite feldspar, some microcline feldspar, numerous quartz masses, and some pale-coloured scaly lepidolite were also noted in the area being scraped by a small bulldozer. The deepest excavation at the time of inspection was only 8 feet, and no systematic attempt had been made to define either the limits of the pegmatite dyke or the boundaries of the beryl and columbite bearing zones.

There were not enough exposures available to determine the zones in which the beryl and columbite occurred, but from the reported localities of the richest eluvium, it appeared that those zones near or adjacent to the larger quartz masses were the main producers.

A specimen of columbite ore weighing about 15 lb seen at the treatment plant 1 mile southwest of the workings, consisted of columbite, fine-grained albite, quartz granules, and brown coarsely lamellar albite ('curly albite'). The size of the columbite in the eluvium ranged from wheat grain size to places up to 2 inches square and ½ inch thick.

Two specimens of columbite from this locality showing some crystal faces, one weighing 13 lb

4 oz and the other 9 lb, (the latter obviously a twinned crystal), were seen at Pippingarra homestead. No large crystals of beryl were seen; the largest size of the pieces of beryl in the eluvium are reported as being approximately 6 inches by 3 inches by 2 inches.

PRODUCTION

The first recorded production was in 1953 and the last in 1957. During this period 60.54 tons of beryl containing 718.23 long ton units of BeO valued at \$A21,508.7 F.O.B. were reported as coming from the deposit (Table 1).

In the same period 6.55 tons (14,769 lbs) of columbite valued at \$A20,824.3 F.O.B. were produced (Table 2). Reliable assay data for all of this production are not available, but there are some assay data which are useful as a guide to the grade of the columbite mined and assayed "as received" by the buyer.

Table 1
BERYL PRODUCTION FROM MINERAL CLAIM 313

| Year | Ore tons | BeO units long tons % | Est. Value F.O.B. \$A |
|-------|----------|-----------------------|-----------------------|
| 1953 | 7.61 | 85.18 | 2,555.4 |
| 1954 | 9.77 | 112.17 | 3,364.9 |
| 1955 | 43.16 | 520.88 | 15,588.4 |
| Total | 60.54 | 718.23 | 21,508.7 |

Note.—Production after 1955 not available, sales credited to Crown Lands, Marble Bar District generally.

Table 2
TANTO/COLUMBITE PRODUCTION FROM MINERAL CLAIM 313

| Year | Ore & Concentrates lb. | ASSAY | | | Metallic content TaNb units | Est. Value F.O.B. \$A |
|-------|------------------------|------------|--------|------------------------|-----------------------------|-----------------------|
| | | Ta % | Nb % | TaNb Combined Oxides % | | |
| 1953 | 3,654 | 8.52 | 65.52 | 74.04 | 120.78 | 9,960.0 |
| 1955 | 1,151 | 10.85 | 59.80 | 70.65 | 36.30 | 2,942.5 |
| | 329 | Not stated | 73.95 | 73.95 | 10.84 | 876.6 |
| | 867 | Not stated | 73.77 | 73.77 | 28.52 | 2,406.0 |
| | 3,701 | 20.61* | 43.05* | 73.56* | 105.00 | 1,056.0 |
| 1957 | 3,107 | 20.51* | 43.05* | 73.56* | 88.17 | 1,649.2 |
| | 1,870 | Not stated | 66.82 | 66.82 | 55.75 | 1,034.0 |
| Total | 14,769lb. or 6.55 tons | | | | 445.36 | 20,824.3 |

* Not true assays—material bulked in with other parcels for sale purposes and overall average applied as basis of payment.

Concentrates reported for 1953 amounted to 3,654 lb containing 8.52% Ta₂O₅ and 65.52% of Nb₂O₅ (combined oxides 74.04%) and another parcel of 1,151 lb of concentrates reported for 1955 contained 10.85% Ta₂O₅ and 59.80% Nb₂O₅ (combined oxides 70.65%).

The lowest figure for combined oxides in the production data is 66.82% and the highest 74.04%.

The average BeO content of the 60.54 tons of beryl was 11.86%, a normal figure for this part of the State.

ENVIRONMENT OF THE DEPOSIT

Throughout Western Australia, the pegmatites occur in rocks of presumed Archaean age, and are nearly always transgressively intrusive into greenstones in the case of those carrying columbite and tantalite. This is noticeably

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the case in the Pilbara and West Pilbara Gold-fields in the northwestern part of the State, examples being Wodgina, Tabba Tabba, Strelley, and Pilgangoora, all within a radius of 50 miles of the M.C. 313 occurrence.

No outcropping greenstones are known in the locality of M.C. 313, and the limited exposures of the surface eluvial mining operations on this claim at the time of inspection did not reveal any traces of these rocks. The nearest greenstone occurrences known to the writer are at Tabba Tabba, some 12 miles to the southeast.

It appears that this columbite-bearing pegmatite mass has granite or granitised rocks as its host rock.

For many years, the country for 80 miles or so south of Port Hedland, which is predominantly granitic (either massive or schistose) in nature, has been the source of considerable quantities of eluvial beryl, reported in the Mines Department statistics as from 'Crown Lands'. There is a strong development of white quartz as both hills and ridges in this area, and the eluvial beryl occurs in the vicinity of these quartz masses. The writer has seen localities here where beryl has been mined from the edge of a large quartz mass, from 3 to 18 tons being obtained from several occurrences.

It is possible that small quantities of eluvial columbite or even tantalite may have been won from this general area and traded by natives or prospectors to the owners of producing claims at Wodgina, Tabba Tabba, Strelley, and Pilgangoora, but no holdings are known to have been previously taken up in the area away from the greenstones.

POTENTIAL OF GRANITISED ZONES

The above occurrence is a good example of the potential of a granitised zone, and another one is the mica-beryl Yinnietharra locality some hundreds of miles to the south. The cassiterite and high-grade tantalite-bearing pegmatitic developments in granitised rocks almost adjacent to unreplaced greenstone bands at Greenbushes are yet another example.

Many of the most productive columbite—tantalite—beryl-bearing pegmatite dykes so far worked in Western Australia have been found, however, in transgressively intrusive pegmatite dykes with greenstones as host rocks. In addition to the Wodgina, Strelley, Tabba Tabba, and Pilgangoora localities, the following come readily to mind:

Location 6 miles southeast of Roebourne
Londonderry feldspar quarry (south of Coolgardie)

Beryl—columbite claims at Spargoville (south of Coolgardie)

Ravensthorpe pegmatites at Cattlin Creek
Poona locality and Kathleen Valley (south of Wiluna).

Discoveries in the greenstone belts are expected to be more frequent because it is in this environment that prospecting for gold has been most active. The granitic terrain, much of which is actually granitised greenstone, has not been attractive to gold prospectors. Its potential for beryl, columbite, tantalite, and cassiterite is sufficiently important to warrant a special effort being made in regional mapping to indicate this class of rock whenever possible, in a clear manner on the maps, and to stress its mineral potential.

A NEW CRANIACEAN BRACHIOPOD FROM THE TERTIARY OF WESTERN AUSTRALIA

by A. E. Cockbain

ABSTRACT

Westralicrania allani gen. nov. et sp. nov. is described from Palaeocene strata in Denham 2 bore, Shark Bay.

INTRODUCTION

The Denham water supply bore (Denham 2) was sited behind the Water Supply building in Knight Terrace, Denham, on Peron Peninsula, Shark Bay. Full details of the bore are on file at the Geological Survey of Western Australia. The sequence penetrated is similar to that already established in other bores in the Shark Bay area (Konecki and others, 1958, Plate 5).

The sample from which the new species was recovered consisted of well cuttings from a depth of 520 feet. Other fossils recorded from this sample include numerous cyclostomatous and cheilostomatous bryozoans, cytheracid ostracods, *Bairdia* sp., *Discorbis* cf. *midwayensis*, *Vaginulina longiforma*, and *Guttulina problema* species group. The foraminifera suggest a Palaeocene age and the sample comes from part of the Cardabia Group, most probably the Pirie Calcarene (Condon and others, 1956, p. 36).

SYSTEMATIC PALAEONTOLOGY

Phylum : Brachiopoda
Class : Inarticulata
Order : Acrotretida
Suborder : Craniidina
Superfamily : Craniacea
Family : Craniidae

WESTRALICRANIA gen. nov.

Genoholotype : *W. allani* sp. nov.

Diagnosis

A genus of Craniidae with a flat ventral valve with mixoperipheral growth and a convex dorsal valve with holoperipheral growth; internally the ventral valve bears a short median ridge.

WESTRALICRANIA ALLANI sp. nov.
(Plate 35)

Diagnosis

A species of *Westralicrania* with short spines scattered over the surface of both valves. The species is named in honour of the writer's former colleague, the late Professor R. S. Allan.

Material

Seven nearly complete ventral valves, 3 nearly complete dorsal valves, 15 incomplete ventral valves, 3 incomplete dorsal valves.

Dimensions

| Specimen No. | Valve | Length (mm) | Width (mm) | Thickness (mm) |
|--------------|---------|-------------|------------|----------------|
| F 6102/1 | Ventral | 6.8 | 7.0 | 0.8 |
| F 6102/2 | Ventral | 2.6 | 2.2 | 0.3 |
| F 6102/3 | Dorsal | 2.2 | 2.5 | 0.7 |
| F 6102/4 | Dorsal | 3.2 | 3.4 | 0.9 |
| F 6102/5 | Ventral | 5.6 | 5.7 | 0.6 |
| F 6102/6 | Ventral | 3.9 | 3.8 | 0.5 |
| F 6102/7 | Ventral | 4.2 | 4.2 | 0.5 |
| F 6102/8 | Ventral | 4.9 | 5.0 | 0.6 |
| F 6102/9 | Ventral | 4.2 | 3.9 | 0.6 |
| F 6102/10 | Dorsal | 4.0 | 4.0 | 1.0 |

Description

The holotype is a ventral valve (F 6102/1; Plate 35A).

The exterior of the valve is almost round and wider than long; nearly straight anterior margin, gently curved laterally and posteriorly;

roundly triangular umbonal region; postero-lateral angles not marked; valve very slightly convex at margins, more or less flattened centrally; growth mixoperipheral with apsacline pseudointerarea; ornamentation consists of concentric growth lines and irregularly scattered pustules which are slightly elongate radially and may develop into short spines.

The interior has a wide limbus which is separated posteriorly from the pseudointerarea by a very narrow raised rim; the limbus is ornamented with small pits which tend to be concentrically and regularly arranged distally and more irregular proximally; within the limbus the valve is slightly concave; a strong but short median ridge arises in the centre of the valve. There are two pairs of muscle scars. Except for the ridge and muscle scars the interior surface of the valve is covered with irregularly arranged pits. The posterior adductor scars cut back into the limbus so that it is narrow opposite them; the scars are widely spaced. The anterior adductor scars are close together on either side of the median ridge. A slight U-shaped depression embraces the median range; three small ridges separate shallow radial depressions on either side. These depressions are taken to represent the position of the vascula lateralia.

The paratype is a ventral valve (F 6102/4; Plate 35B).

The exterior is nearly round in outline with curved anterior and lateral margins and straight posterior margin; posterolateral angles obtuse. Growth is holoperipheral and the valve is conical, with the umbo about one-quarter of the diameter from the posterior margin. Ornamentation consists of concentric growth-lines and irregularly scattered short spines.

In the interior the limbus is feebly developed except posteriorly where it is widest; elsewhere it is hardly differentiated from the interior of the valve. The valve is markedly concave, the greatest depth being immediately in front of the posterior limbus. The interior of the valve is ornamented with numerous pits which are irregularly arranged. The two pairs of muscle scars are smooth raised areas. The posterior adductor scars are round and widely spaced, and cut into the limbus at the posterolateral angles of the valve; they are slightly below the level of the limbus. The anterior adductor scars are elongated antero-posteriorly, close together, and situated just anterior to the greatest depth of the valve. In front of them in the midline is a very low median swelling.

Ontogeny of ventral valve

The smallest specimen (F 6102/2; Plate 35C) is elongate triangular, tapering posteriorly to the umbo. Mixoperipheral growth is marked and the pseudointerarea is one-fifth of the total length of the valve and nearly orthocline. The exterior is ornamented with concentric growth lines and scattered spines. The limbus is broad and radially striated distally; proximally it is irregularly pitted as is the rest of the interior of the valve. Two pairs of muscle scars are arranged as previously described. The median ridge is long and low and extends from the anterior edge of the anterior adductor scars to the midline of the posterior adductor scars.

Other specimens show that as the ventral valve increases in size the pseudointerarea becomes proportionately smaller and more apsacline. Interiorly the median ridge becomes higher and shorter until in the adult it extends between the posterior adductor scars only as

a low swelling. As growth proceeds the ornamentation of the limbus changes. The early radial striae become confined to the distal edge or are lost completely, and the limbus is ornamented with concentric or irregularly arranged pits. The external ornamentation consists of well-marked short spines in the young stages. Later the shell thickens and the spines appear as pustules. The earliest growth stages (up to about 1 mm) have very few or no spines. In some specimens the smooth umbo is flattened or slightly concave suggesting attachment to some object. Whether the animal was attached throughout life or only when young is impossible to determine.

Ontogeny of dorsal valve

The smallest dorsal valve (F 6102/3; Plate 35D) differs from the large valves only in size, in the lack of even a slight median swelling, and in having the limbus distally striate.

The few incomplete specimens of dorsal valves show that as the valve becomes larger the posterior portion of the limbus increases in size, especially between the posterior adductor scars. The median swelling never becomes very large but seems to be variable in its development: it is a low swelling in some specimens and a slight ridge in at least one specimen.

REMARKS

The genus *Westralicrania* most nearly resembles *Crania* from which it differs in the strong mixoperipheral growth of, and median ridge in, the ventral valve. *Isocrania* has a conical ventral valve. The dorsal valve in all three genera is very similar in that it is conical and lacks internal processes. This serves to separate these genera from all other post-Palaeozoic craniaceans which possess such processes in the dorsal valve.

The only other Tertiary craniacean known from Australia is *Ancistrocrania skeatsi* Allan, 1940 (= *Crania quadrangularis* Tate) from the Oligocene of Victoria. The writer has been able to examine stereoscopic photographs of Allan's figured topotype; it is distinct from *Westralicrania allani* in shape and ornamentation, and, since it does not possess well developed apophyses, probably is not referable to *Ancistrocrania*.

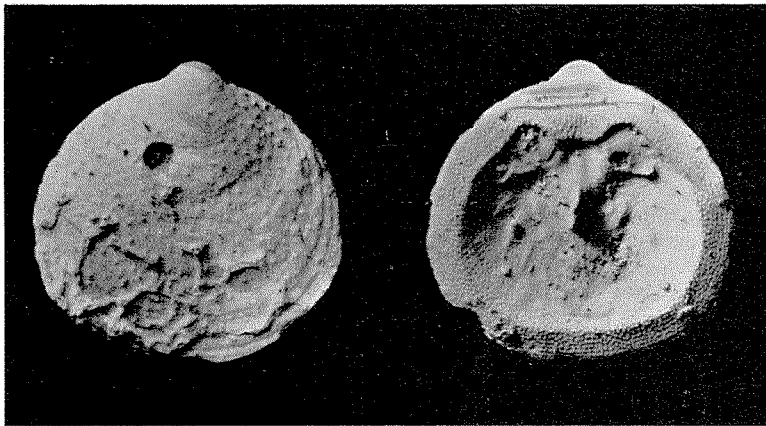
ACKNOWLEDGEMENTS

I wish to thank Professor M. Gage of the University of Canterbury, New Zealand, for making available photographs of Allan's topotype of *A. skeatsi*.

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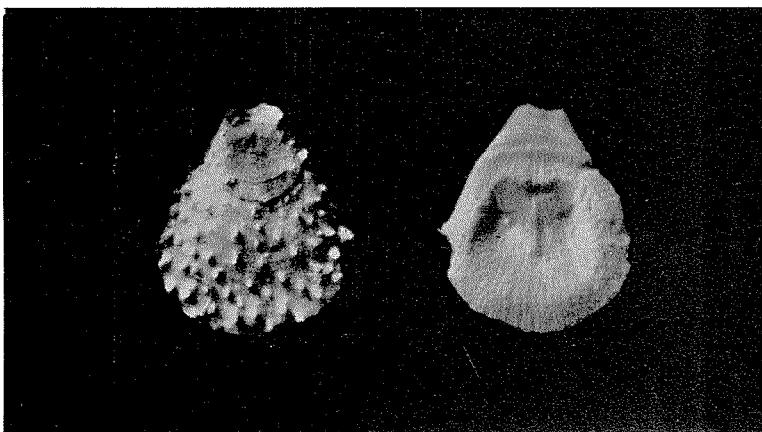
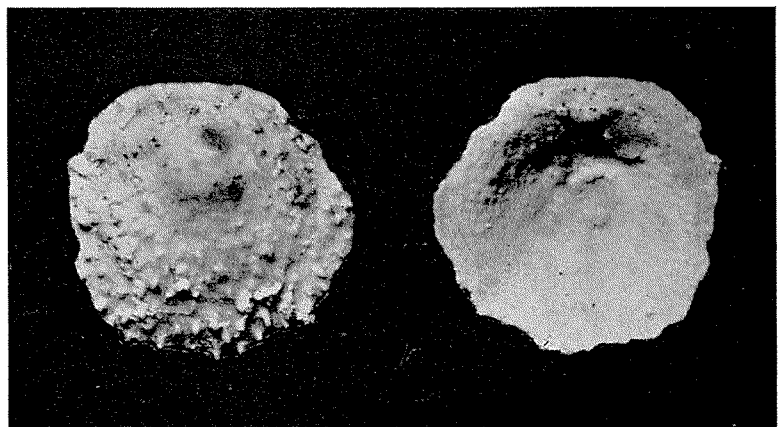
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WESTRALICRANIA ALLANI gen. nov. et sp. nov.



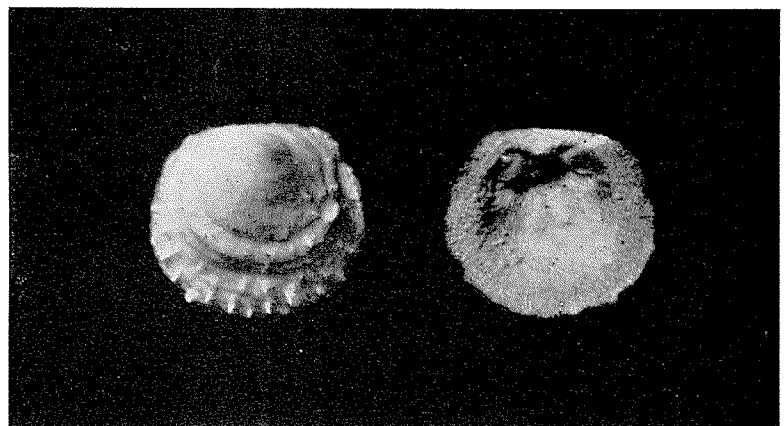
A—Holotype ; external and internal views of ventral valve ; F 6102/1, x6.

B—Paratype ; external and internal views of dorsal valve ; F 6102/4, x12.

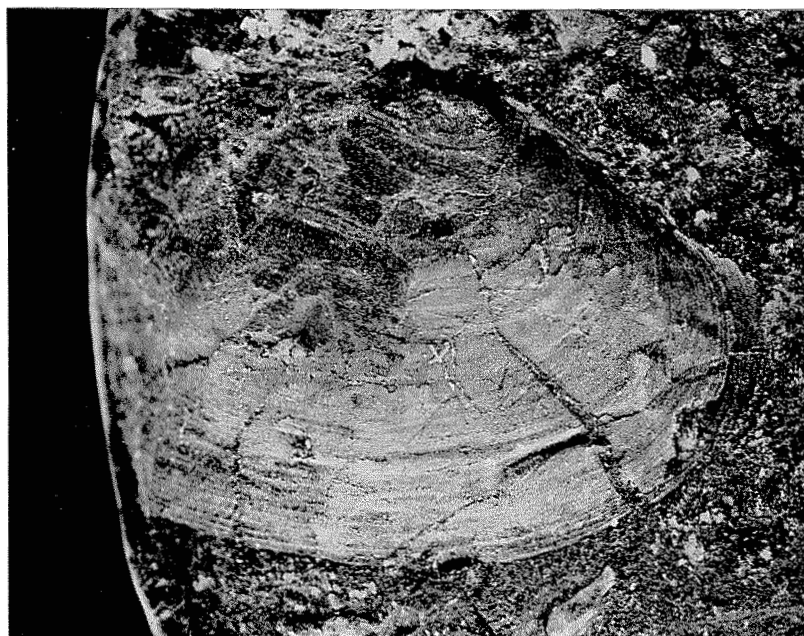


C—External and internal views of a small ventral valve ; F 6102/2, x12.

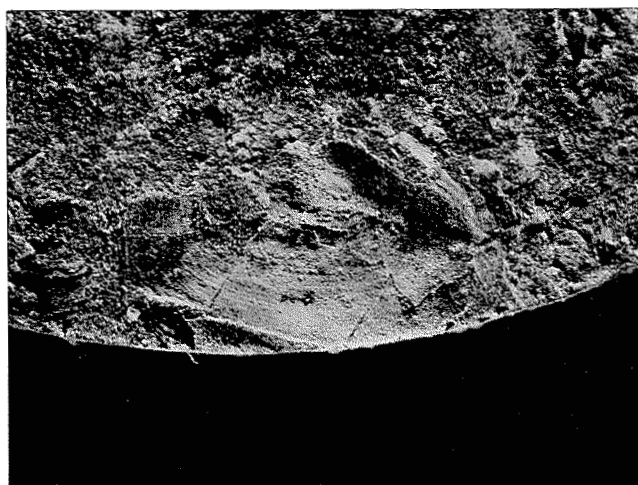
D—External and internal views of a small dorsal valve ; F 6102/3, x12.



UNIONACEA gen. et sp. indet.

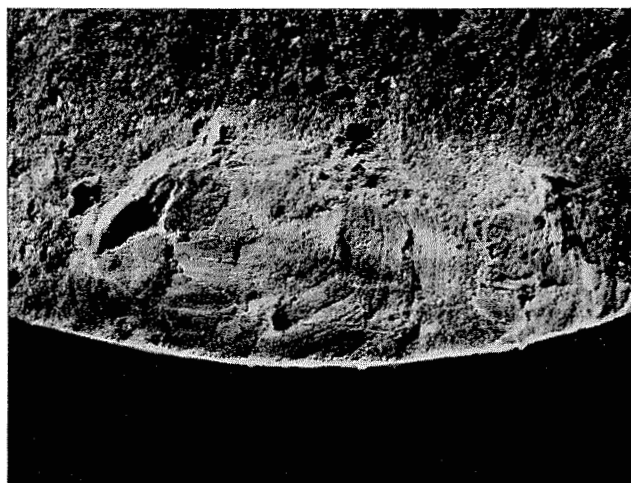


A—Right valve, shell material carbonised ; F 6140/2A, x5.



B—Left valve, external mould ;
F 6140/3A, x5.

C—Left valve, shell material carbonised
F 6140/3B, x5.



PELECYPODA FROM THE YARRAGADEE FORMATION

by A. E. Cockbain

ABSTRACT

Indeterminate unionacean pelecypods are illustrated from the Yarragadee Formation encountered in Gingin Brook 6 bore.

INTRODUCTION

Half a dozen fragments of a pelecypod have been found in core 13 (2,600 to 2,610 feet) from Gingin Brook 6 bore during hydrogeological investigations in the Gingin area. The core consists of dark grey siltstone with irregular sandy patches and comes from the Yarragadee Formation. The microflora from this bore belongs to Ingram's zone B of probable Neocomian age (Ingram, 1967). Molluscs have been recorded previously from the Yarragadee Formation by Mr. S. P. Willmott of WAPET but have not been illustrated.

SYSTEMATIC PALAEOLOGY

Phylum : Mollusca
Class : Pelecypoda
Superfamily : Unionacea

UNIONACEAN gen. indet, et sp. indet.

Description

The fossils are preserved as thin carbonaceous films showing the external ornamentation. The description is based on an examination of the shell and external mould of the two most complete specimens.

The largest fragment (Plate 36A) has most of the posterior end missing. A somewhat smaller and more complete shell (Plate 36B and C) is 10.5 mm long and has a height of 7 mm. The valve is oval in lateral view with the umbo one third of the length from the anterior end of the shell. The anterior end is gently curved

whilst the posterior end is straighter, meets the hinge line at an obtuse angle, and curves sharply into the ventral margin. The valves are slightly convex but there has been some flattening and fracturing of the shell during fossilization. The ornamentation consists of growth lines (6 per mm measured on the mid-ventral portion of specimen No. F 6140/2A) and coarser concentric wrinkles which are irregularly spaced but average about 1 mm apart.

Remarks

The specimens available are too poorly preserved to determine generically. They almost certainly belong to the fresh and brackish water mussel superfamily Unionacea. The lack of surface sculpture suggests that the shells may be mutelids rather than unionids although the material is not closely comparable with any of the Australian fossil unionaceans figured by Newton (1915), McMichael (1957), or Ludbrook (1961). A complete determination must await the discovery of less fragmentary material.

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A PRELIMINARY PALYNOLOGICAL ZONATION OF THE YARRAGADEE FORMATION IN THE GINGIN BROOK BORES

by B. S. Ingram

ABSTRACT

Three preliminary palynological assemblage zones are suggested within the Upper Jurassic—Lower Cretaceous strata of the Yarragadee Formation encountered in the Gingin Brook bores. The problems of correlation, both local and regional, of this formation are briefly discussed.

During 1965-66 the Geological Survey drilled the Gingin Brook line of bores across the Perth Basin, approximately along the latitude of the town of Gingin. Cores taken in all six bores were examined for their spore and pollen content. This examination suggested a threefold palynological zonation of the Upper Jurassic—Lower Cretaceous strata of the Yarragadee Formation which predominates in the sections encountered. The occurrence of these zones is shown on the accompanying diagram (Figure 16).

The incentive to search for palynological zonation of these strata comes from the amount of drilling for underground water information being carried out by the Mines Department in the Perth Basin. A more accurate palynological correlation of the Yarragadee Formation than is available would be extremely useful. In fact, the only published work on Western Australian spores and pollen grains of this age is

the preliminary paper of B. E. Balme (1957). Balme (pers. comm. 1966) now uses subdivisions within the broad zones postulated in 1957 but they are still completely informal. The lack of sustained interest is due mainly to the dominantly continental nature of the Yarragadee Formation and hence its lack of oil potential. However, for a complete understanding of the hydrogeology of the Perth Basin, a detailed knowledge of the Yarragadee Formation is essential.

Palynology is probably the only practicable method available for correlation and zonation because of the otherwise unfossiliferous nature of the continental sediments, the impersistent lithologies, and lack of distinctive electrical logging characteristics. The great thickness of sediment represented (e.g. over 10,000 feet in WAPET's Gingin No. 1 well), and lack of diverse microfloral assemblages add further complications.

In the early stages of this work, problems were encountered by trying to correlate Western Australian zones directly with the European stages. Later it became apparent that this broad correlation is very difficult to make at the present state of knowledge, and furthermore it appears that two different interpretations of Australian palynomorph assemblages are being used. There is some evidence from

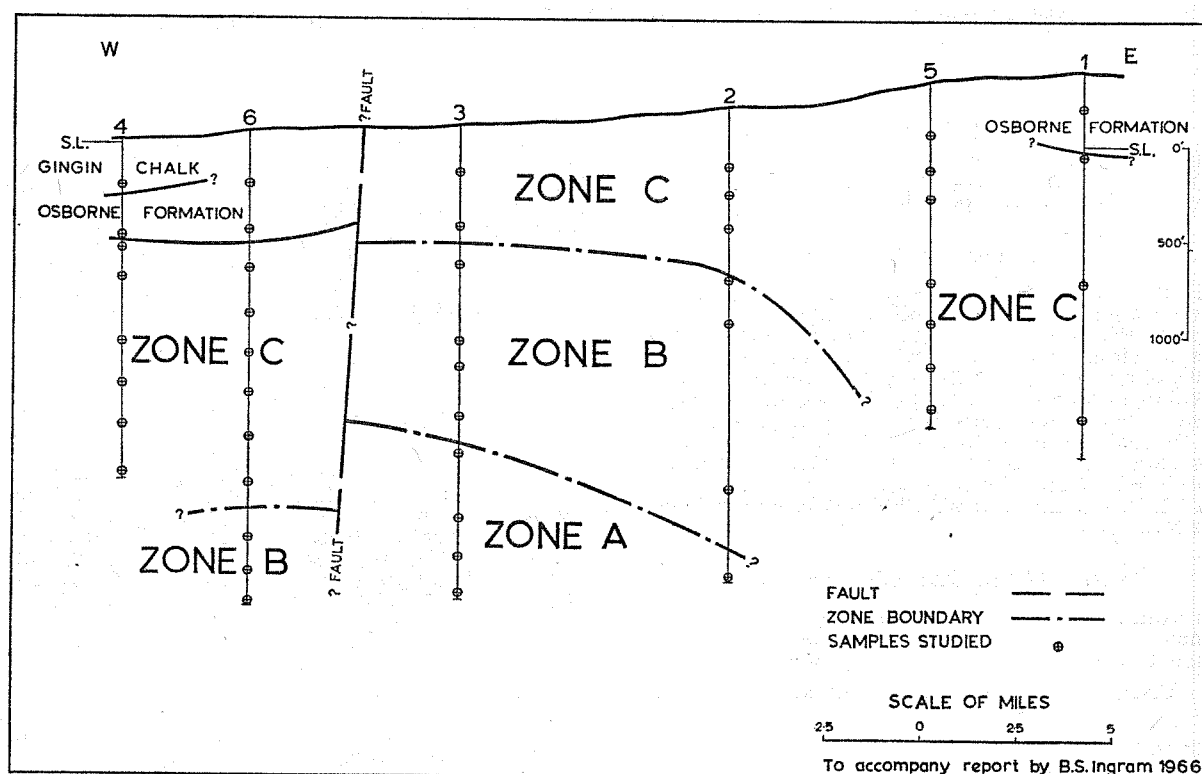


FIGURE 16- CORRELATION OF TENTATIVE UPPER JURASSIC-LOWER CRETACEOUS PALYNOLOGICAL ZONES IN GINGIN BROOK BORES

Evans' (1965) work that eastern Australian assemblages are considered to be about one stage lower than their suspected Perth Basin equivalents, within upper Jurassic-Lower Cretaceous strata. This can be seen in the chart below, summarizing the zonation. This possible discrepancy may be because of the lack of detailed stratigraphic work on the Western Australian section rather than a true time lag (i.e., the slow migration of floras from east to west). However the three zones, whatever their geological stage status, are still considered useful for local correlation.

As the zones are preliminary, they are described only in general terms.

Zone A, the oldest assemblage encountered, occurs low in Bores 2 and 3. It is restricted in types, containing mainly gymnospermous pollen with very rare spores, and long-ranging forms such as *Cyathidites australis* Couper and *Baculatisporites comaumensis* (Cookson). The restricted nature of the assemblage makes it difficult to use but it has been considered to occur only in the uppermost Jurassic-lowermost Cretaceous portion of the Yarragadee Formation. Evans' (1965) J4 (or J5) zone appears to be similar, and hence this zone is considered most likely to be of Jurassic age.

Zone B is found in Bores 2, 3, and 6. The assemblage is still dominated by gymnospermous pollen but with a slightly larger variety of spores including the first occurrence in the Gingin bores of *Contignisporites* and *Foveosporites*. Such an assemblage is being considered in the Perth Basin as probably lowermost Cretaceous or possibly uppermost Jurassic (hence the ?Neocomian assignment) but its resemblance to Evans' J5 zone suggests this may also be Jurassic.

Zone C, the youngest, occurs in all bores. The assemblage is much more diverse, and contains many more spore genera including *Murospora*, *Laevigatosporites*, *Trilites*, *Trilobosporites*, and *Cicatricosisporites*. Variations were noted within this assemblage and it is considered detailed work would allow further subdivision. Unfortunately not enough of Dettmann's (1963) diagnostic species have been identified to allow

firm correlation with her assemblages. In terms of Evans' zones this assemblage would appear to include parts of J5 and K1a. Thus it is possible that this zone also includes some Upper Jurassic strata although it has been considered as definitely Lower Cretaceous (Neocomian-Aptian) in the Perth Basin. Rare microplankton in a few samples from this zone in Bores 4 and 6, although poorly preserved could be worth further investigation to allow some check on the spore and pollen evidence.

It is encouraging that the proposed zones generally agree with the stratigraphy and structure of the area as described by Sanders (1967). However it must be emphasized that the zones are preliminary and at present of only local significance.

SUMMARY OF ZONATION

| Preliminary zones of Yarragadee Formation, Gingin Brook bores | | Zone A | Zone B | Zone C |
|---|--|---------------------|-------------|------------------|
| Current terminology in W.A. | | Tithonian-Neocomian | ? Neocomian | Neocomian-Aptian |
| Possible correlation with Evans (1965) | | J4-J5 | J5 | J5-K1a |
| PALYNOFORMS | " Alisporites " | | | |
| | <i>Araucariacites australis</i> | | | |
| | <i>Tsugaepollenites</i> spp. | | | |
| | <i>Cyathidites</i> spp. | | | |
| | <i>Baculatisporites comaumensis</i> | | | |
| | <i>Contignisporites cooksonii</i> | | | |
| | <i>Foveosporites canalis</i> | | | |
| | <i>Ischyosporites crateris</i> | | -- | |
| | <i>Murospora florida</i> | | | |
| | <i>Laevigatosporites</i> sp. | | | |
| | <i>Trilites</i> spp. | | | |
| | <i>Cicatricosisporites australiensis</i> | | | -- |

ACKNOWLEDGEMENT

The writer wishes to thank Mr. B. E. Balme of the University of Western Australia for his continual help and for reading the manuscript.

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PALYNOLOGY OF THE OTOROWIRI SILTSTONE MEMBER, YARRAGADEE FORMATION

by B. S. Ingram

ABSTRACT

The palynomorph assemblage of the Otorowiri Siltstone Member, a new member of the Yarragadee Formation in the Mingenew-Arrino area of the Perth Basin, contains several distinct microfloras ranging in age from Devonian to Lower Cretaceous. The Lower Cretaceous forms, being the youngest, indicate the age of the rock unit; the pre-Cretaceous elements are the result of reworking. The remanie microfossils indicate the provenance of the Otorowiri Siltstone Member and suggest, for the first time, the presence of Devonian and possibly marine Upper Jurassic sediments in the Perth Basin.

INTRODUCTION

A very distinctive palynomorph assemblage has been discovered in a siltstone from bores drilled for the Morawa town water supply in the Arrowsmith River area near Arrino, 200 miles north of Perth (Figure 17). Edgell (1963) first recorded the assemblage as 'weakly marine, Lower Cretaceous' in an unpublished palaeontological report of the Geological Survey of Western Australia on Bore 1. He recorded a similar assemblage from Mingenew P.W.D. Bore 7 (202 feet) in the following year (Edgell, 1964a). It was later found to have been recorded previously by B. E. Balme (1956) in an unpublished report on a bore near Mingenew (Mingenew 2 at 126 feet).

The same siltstone has been encountered in about half of the 26 deeper bores of the Arrowsmith River Drilling Project, including cores 8 and 9 from Bore 25, the only rotary hole. It has been found also in several Gemco holes, sited to check the band at shallow depths near a suspected outcrop. The unit is particularly helpful as the Yarragadee Formation encountered in these bores, and elsewhere in the Perth Basin, has otherwise impersistent lithologies and very slowly changing microfloral assemblages.

STRATIGRAPHY

The siltstone from which the palynomorph assemblage is derived is named the Otorowiri Siltstone Member of the Yarragadee Formation. It is lithologically distinct from the sediments above and below, and extends from Mingenew to Arrino. The name was suggested by R. Milbourne

after Otorowiri Spring which is situated 7 miles east of the Arrino townsite. The type section is chosen herein in Arrowsmith River Bore 25 (29° 32' 40" S., 115° 32' 10" E.) from 830 feet to 910 feet. From this interval the only two core samples of the member were obtained. The member is 80 feet thick but it is known to be up to 120 feet thick in other bores. The lithology is predominantly siltstone and the age is Lower Cretaceous.

PALYNOMORPH ASSEMBLAGE

In addition to the distinctive lithology, the Otorowiri Siltstone Member contains an extremely interesting and diverse palynomorph assemblage. This is dominated by Lower Cretaceous microspores (within Zone C, Neocomian-Aptian, of Ingram, 1967), with rare Lower Cretaceous microplankton suggesting a slight marine influence during deposition. The remainder of the assemblage consists of older remanie spores, pollen grains, and microplankton derived from assemblages of the following ages.

- a. probably Upper Jurassic
- b. Middle-Upper Triassic
- c. Lower Triassic
- d. Upper Permian
- e. Lower Permian and undifferentiated Permian
- f. Devonian.

Although some of these categories are rarely represented, enough distinctive species have been found to prove their presence among the contamination. It is not unusual to find Lower Permian microspores in Lower Cretaceous sediments in the Perth Basin, but the variety and number of contaminants in the Otorowiri Siltstone Member is both remarkable and distinctive.

To illustrate the percentage of each microflora in the assemblage, counts of about 300 specimens were made from eight different samples. Two samples from each of the two available cores (from Bore 25), sludges from two intervals in Bore 18 and sludges from two other bores were used. Table 1 shows the variation between these samples.

Table 1
PERCENTAGES OF THE VARIOUS MICROFLORAS PRESENT IN THE OTOROWIRI
SILTSTONE MEMBER

| G.S.W.A. Arrowsmith River Bores | | | | No. 25 | | | | No. 18 | | No. 19 | No. 23 |
|--|--------------|-------|-------|---------------------|-------|--------|-------|---------|---------|--------|---------|
| Samples counted | Material | | | Core 8 | | Core 9 | | Sludges | | | |
| | Depth (feet) | | | 839 | 847 | 901 | 910 | 117-130 | 230-240 | 420 | 750-760 |
| | Reg. No. | | | F6275 | F6277 | F6278 | F6279 | F6283 | F6284 | F6281 | F6128 |
| MICROFLORAS
(excluding small 'leiospheres') | | | | PERCENTAGES PRESENT | | | | | | | |
| Lower Cretaceous microspores | | | | 50 | 47 | 45 | 45 | 57 | 65 | 44 | 62 |
| Lower Cretaceous microplankton | | | | x | 1 | | x | | x | x | |
| 'Upper Jurassic' microplankton | | | | | x | | | x | x | x | |
| M.-U. Triassic microspores | | | | x | x | | x | | x | x | |
| L. Triassic microspores | | | | 4 | 3 | 2 | 3 | 9 | 4 | 6 | 6 |
| 'L. Triassic' microplankton | | | | 38 | 36 | 47 | 46 | 27 | 26 | 45 | 25 |
| U. Permian microspores | | | | x | | | | | x | | x |
| Permian microspores (undifferentiated) | | | | 7 | 11 | 5 | 5 | 6 | 3 | 2 | 6 |
| Devonian microspores | | | | | x | | x | x | x | | x |
| Palynomorphs in count | | | | 389 | 310 | 297 | 307 | 210 | 303 | 295 | 300 |
| counted palynomorphs | | | | 3 | 1 | 1 | 1 | 2 | 1 | 1 | 2 |
| Ratio : small 'leiospheres' | | | | 1 | 3 | 5 | 2 | 1 | 1 | 9 | 1 |

x = less than 1%

MICROFLORAS PRESENT IN THE ASSEMBLAGE

Following are some of the important species recognized in the various microfloras within the assemblage.

LOWER CRETACEOUS (NEOCOMIAN—APTIAN) (Plate 37: 1-7)

Microspores

Aequitriradites spinulosus (Cookson&Dettmann)
Cicatricosisporites australiensis (Cookson)
Contignisporites cooksonii (Balme)
C. glebulentus Dettmann
Dictyophyllidites crenatus Dettmann
Dictyotosporites complex Cookson & Dettmann
Ischyosporites crateris Balme
I. sp. cf. I. punctatus Cookson & Dettmann
Laevigatosporites sp. nov.
Matonisporites crassiangulatus (Balme)
M. sp. cf. M. phlebopteroides Couper
Murospora florida (Balme)
Pilososporites ?notensis Cookson & Dettmann
Trilobosporites pulverulentus (Verbitskaya)
T. sp. cf. T. tribotrys Dettmann
 —and many other species.

This is a somewhat unusual assemblage for Western Australia containing many forms common in eastern Australian sediments. Although it bears some of the characters of Dettmann's (1963) Speciosus Assemblage it is as yet not known how accurately her palynological zones can be correlated with the microfioral sequence in Western Australia. Also the presence of common *Murospora florida* with several species of *Trilobosporites* and *Pilososporites* is not consistent with her evidence in Eastern Australia. This may be explained by the youngest microflora being of Aptian age with Neocomian contamination. Until the ranges of these species are known in detail in the Perth Basin, the age of this microflora is best considered as Neocomian—Aptian.

Microplankton

Rare and poorly preserved specimens of *Pterospermopsis australiensis* Deflandre & Cookson (identified by Edgell, 1964b), *Baltisphaeridium hirsutum* (Ehrenberg), and indeterminate species of *Gonyaulax* and *Canningia* are present. These are considered to be of Lower Cretaceous age.

UPPER JURASSIC MICROPLANKTON (Plate 37: 8, 9)

Dingodinium jurassicum Cookson & Eisenack and *Wanea clathrata* Cookson & Eisenack have

been identified. Evans (pers. comm. 1966) considers *D. jurassicum* to be restricted to early Upper Jurassic at least in Northern Australia and New Guinea. Cookson & Eisenack (1958, p. 58) similarly restrict *W. clathrata* in a study which included some Carnarvon Basin samples. The two forms are commonly found together in the Dingo Claystone, Carnarvon Basin which is no younger than Lower or Middle Kimmeridgian. However, the possibility that these forms existed in the Perth Basin in the Lower Cretaceous cannot be dismissed.

MIDDLE—UPPER TRIASSIC MICROSPORES (Plate 37: 10, 11)

Two species of spores, recorded only from Middle—Upper triassic strata in Australia have been identified, i.e. *Guthoerlisporites cancellosus* Playford & Dettmann and *Polycingulatisporites crenulatus* Playford & Dettmann.

LOWER TRIASSIC MICROSPORES AND MICROPLANKTON (Plate 37: 12-16)

Many microspores species recorded by Balme (1963) from the Kockatea Shale are present. These include:

Krauselisporites cuspidus Balme
Densoisporites playfordi (Balme)
Lundbladispora willmotti Balme
Osmundacidites senectus Balme
Taenisporites ?noviaulensis Leschik

Abundant specimens of small microplankton of the genera *Veryhachium* (?*Wilsonastrum*), *Micrystridium*, and *Leiosphaeridia* are also present. Although these are long-ranging forms, Balme (1963) records that, in Kockatea Shale samples, ratios of spores to microplankton similar to the above forms are as high as 1 to 65. Therefore, although a few are probably of Lower Cretaceous age, for the purpose of the counts all such microplankton were considered Lower Triassic. Separated from these were smaller (10-15 μ) leiospheres (or ?*Spheripollenites* of Jansonius, 1962) which due to their abundance and unknown age (although most likely Lower Triassic), were only estimated as a proportion of other grains counted.

UPPER PERMIAN MICROSPORES (Plate 37: 17,18)

Among the many Permian grains recorded, at least four species are most common in the Upper Permian although they may be found occasionally in the late Lower Permian. These are *Dulhunthispora dulhuntyi* Potonié, *D. parvithola* (Balme & Hennelly), *Acanthotriletes villosus* Balme & Hennelly and *Marsupipollenites sinuosus* Balme & Hennelly.

As previously stated Lower Permian microspores are often common contaminants within Lower Cretaceous strata in the Perth Basin. Many undifferentiated Permian forms were included in this microflora, due to the relative abundance of Lower Permian compared to Upper Permian strata in the Perth Basin. *Nuskoisporites*, *Krauselisporites*, and 'Striatites' are some of the common Permian forms in the Otorowiri Siltstone Member.

DEVONIAN MICROSPORES (Plate 37: 22, 23)

Rare grains identified as *Emphanisporites* sp. and *Leiozonotrilletes carnarvonensis* Balme are definitely of Devonian age. They are only known in Western Australia from the Gneudna Formation of the Carnarvon Basin (Balme, 1960). More common grains, assigned to *Punctatisporites* and *Geminospira* are tentatively considered to be Devonian.

GEOGRAPHICAL EXTENT

The Otorowiri Siltstone Member is known from a narrow linear belt, west of and adjacent to the Urella Fault extending from Mingenew 2 Bore in the north to G.S.W.A. Arrowsmith River 25 Bore in the south (Figure 17). In the Arrowsmith River area it occurs at 0 to 200 feet above sea level in bores in a graben 3 to 4 miles wide (containing Bores 11, 16, 13 etc.). To the west it possibly crops out on the adjoining horst, occurring in bores at 500 to 700 feet above sea level. The suspected outcrop was examined for its microflora but only Quaternary spores and pollen grains were obtained. Shallow Gemco holes nearby, sited stratigraphically higher, intersected siltstones at the same level as the outcrop. These siltstones contained microfloral assemblages typical of the Otorowiri Siltstone Member. The outcrop may thus be the member, with all the original assemblage oxidized and now replaced by recent contaminants trapped in the exposed mud, or it may be a fortuitously sited Quaternary deposit.

STRATIGRAPHICAL SIGNIFICANCE

The main use of the Otorowiri Siltstone Member is as a stratigraphic marker in the sediments drilled in the Arrowsmith River area which consist of impersistent sand and silt of the Yarragadee Formation. The member is considered to have a distinctive lithology, and after correlations have been made on palynological grounds, the evidence suggests that there is only one siltstone unit.

Confirmatory evidence for the usefulness of the member as a stratigraphic marker was provided from seismic work. A fault with a downthrow of 500 feet to the east, roughly parallel to the Urella Fault and running just west of the position of Bore 6, had been postulated from palynological evidence. A seismic line across the area located a fault in a similar position with an estimated downthrow of 600 feet to the east.

AGE OF THE MEMBER

With the great extent of geological time represented by the various microfloras recognized within the assemblage, the actual age of the rock unit must be that of the youngest microflora. This cannot be defined more closely than Neocomian—Aptian for the reasons given above.

ORIGIN OF THE MEMBER

Sedimentation of the Otorowiri Siltstone Member is considered to have been initiated by a sudden movement on the Urella Fault (or an associated fault) in the Lower Cretaceous. The evidence of the slight marine influence during deposition could indicate a basin downward movement, rather than eastern basement upwards, causing a brief marine incursion. However, the major result was rapid erosion (presumably to the east), exposing fresh, older sediments. These were swept into the basin before

the palynomorphs they contained could be oxidized, as would be the case under slower conditions of erosion.

The assemblage thus formed gives an indication of the various strata cropping out to the east during Lower Cretaceous times. The excellent preservation of many of the remanie grains suggests they were not transported very far; actual distances are of course impossible to ascertain. The problem of the provenance of the various microfloras will now be considered, with the more easily accounted for being discussed first.

A Lower Permian source is easy to envisage. Edgell (1965) described a marine fauna of this age from an outcrop on the eastern margin of the Arrowsmith River area near Bore 5. Lower Permian palynomorph assemblages have also been found in Bores 7 and 15, one of Sakmarian age and the other of Artinskian age. Thus a ready source of Lower Permian palynomorphs is still available, and in fact they were still being reworked into Quaternary strata. The Permian sediments west of the Urella Fault also illustrate the complexity of the zone associated with this fault. It apparently has many thin fault blocks of various ages along its length, and these blocks are considered the most likely source of most of the contamination.

This source for the remanie grains can be further illustrated by the unexpected occurrence of Kockatea Shale at 80 feet in U.W.A. Bore 10 (Balme, pers. comm. 1966), drilled near Mingenew in 1965 by the Department of Geology, University of Western Australia. This, or a similar occurrence could be the source of the Lower Triassic grains although the closest known present day outcrop is in Kockatea Gully about 40 miles north of Mingenew.

The closest known Upper Permian outcrop is the Wagina Sandstone in the Woolaga Creek area, about 12 miles east of Mingenew. Middle—Upper Triassic strata of the Perth Basin (Lesueur Sandstone and Woodada Formation) have at present only one known 'possible outcrop' (Willmott, 1964)—in the Cockleshell Gully area, 60-70 miles southwest of Arrino. However, these two microfloras may also have been derived from fault blocks now either completely eroded, too deeply weathered to be recognized, or covered by Quaternary sands.

It is more difficult to account for the origin of the Upper Jurassic and Devonian palynomorphs. If the Upper Jurassic microplankton are in fact of this age (see above) then their source is not known. Drilling in many bores in the Yarragadee Formation in the Perth Basin has not as yet shown any marine strata in the lower (Upper Jurassic) parts of the formation.

Devonian strata also are not known from the Perth Basin, the nearest rocks of this age being in the Carnarvon Basin. In fact the most southerly known occurrence is in the Pelican Hill Bore north of Carnarvon, about 350 miles north of Mingenew (see Balme, 1960). It is considered unlikely that the Devonian grains found in the Otorowiri Siltstone Member have been transported this far and therefore it is suggested that Devonian strata are (or were) present in the Perth Basin—or on the shield to the east.

CONCLUSIONS

1. The Otorowiri Siltstone Member is a distinct stratigraphic unit of the Yarragadee Formation in the Arrino—Mingenew area.
2. It contains a distinct palynomorph assemblage with grains present ranging in age from Devonian to Lower Cretaceous.
3. The youngest microflora (Lower Cretaceous) denotes the age of the member.
4. The older remanie grains indicate sediments of the ages represented were cropping out in the area in the Lower Cretaceous.
5. Unoxidized portions of these sediments were deposited in the basin, probably after a sudden movement on the Urella Fault caused rapid erosion of the older fault blocks.
6. Devonian and possible marine Upper Jurassic palynomorphs are recorded from the Perth Basin for the first time.

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PLATE 37

Magnification of all photomicrographs x 500

Lower Cretaceous (1-7)

1. *Matonisporites* sp. F 6284/5
2. *Trilobosporites* sp. F 6284/4
3. *Klukisporites* sp. cf. *K. scaberis* (Cookson & Dettmann) F 6128/8
4. *Pilosporites* sp. cf. *P. notensis* Cookson & Dettmann F 6284/3
5. *Contignisporites* sp. F 6128/5
6. *Cicatricosisporites australiensis* (Cookson) F 6128/10
7. *Laevigatosporites* sp. F 6128/7

Upper Jurassic (8 & 9)

8. *Dingodinium jurassicum* Cookson & Eisenack F 6284/6
9. *Wanea clathrata* Cookson & Eisenack F 6284/6

Middle—Upper Triassic (10 & 11)

10. *Guthoerlisporites cancellosus* Playford & Dettmann F 6282/5
11. *Polycingulatisporites crenulatus* Playford & Dettmann F 6282/14

Lower Triassic (12-16)

12. *Osmundacidites senectus* Balme F 6282/6
13. *Lundbladisporea willmotti* Balme F 6128/4
14. *Krauselispores cuspidus* Balme F 6281/4
15. *Taenisporites* sp. cf. *T. noviaulensis* Leschik F 6128/19
16. *Veryhachium* sp. F 6281/12

Upper Permian (17 & 18)

17. *Dulhuntpora parvithola* (Balme & Hennelly) (31.9 x 94.6)* F 6281/1
18. *Marsupipollenites sinuosus* Balme & Hennelly F 6282/10

Lower Permian (19-21)

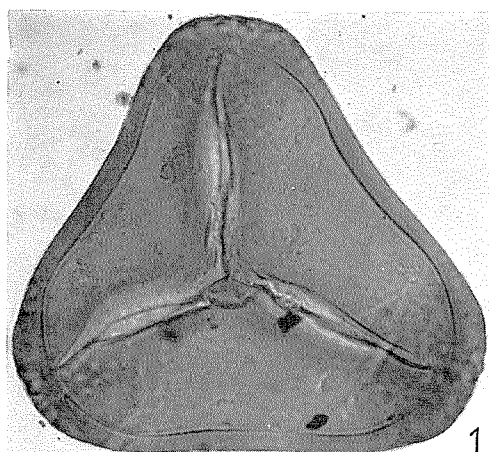
19. *Vittatina* sp. F 6128/11
20. "*Striatites*" sp. F 6275/1
21. *Krauselispores* sp. F 6284/7

Devonian (22 & 23)

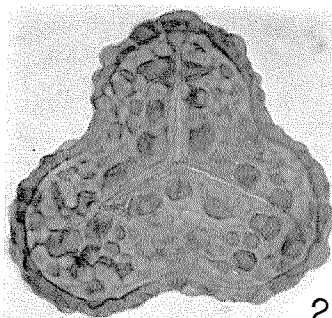
22. *Emphanisporites* sp. F 6284/9
23. *Spinozonotriletes carnarvonensis* Balme F 6284/10

* Coordinates on Leitz Ortholux microscope 587962

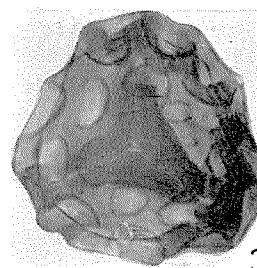
All other slides are single grain mounts



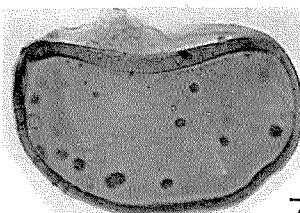
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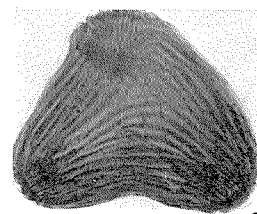
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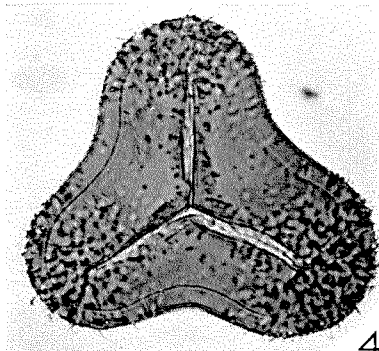
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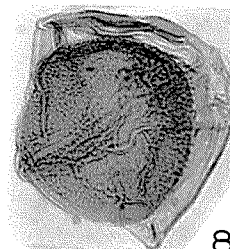
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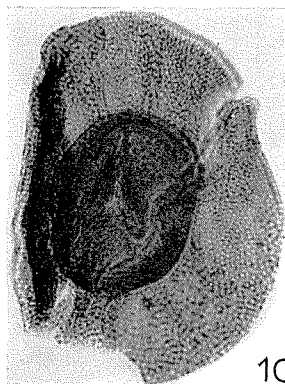
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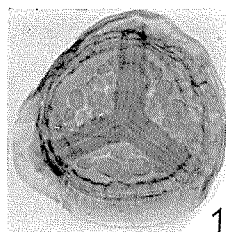
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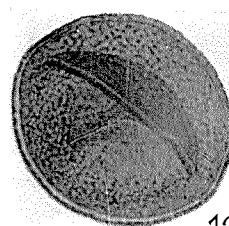
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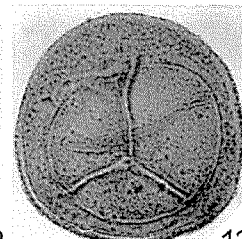
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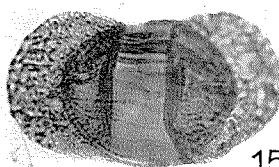
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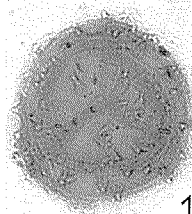
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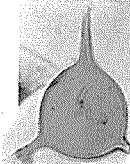
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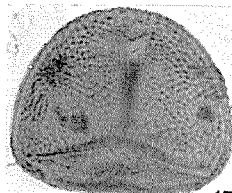
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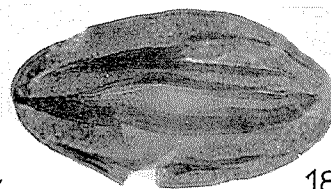
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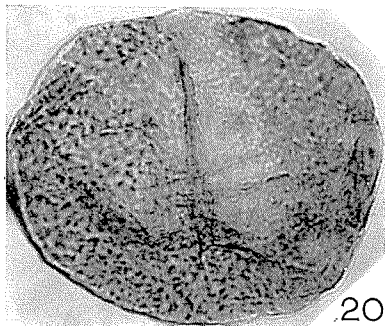
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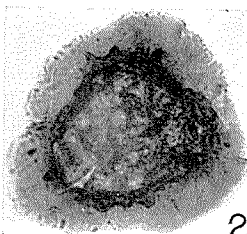
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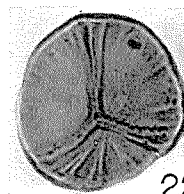
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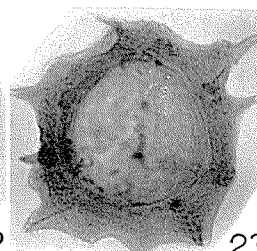
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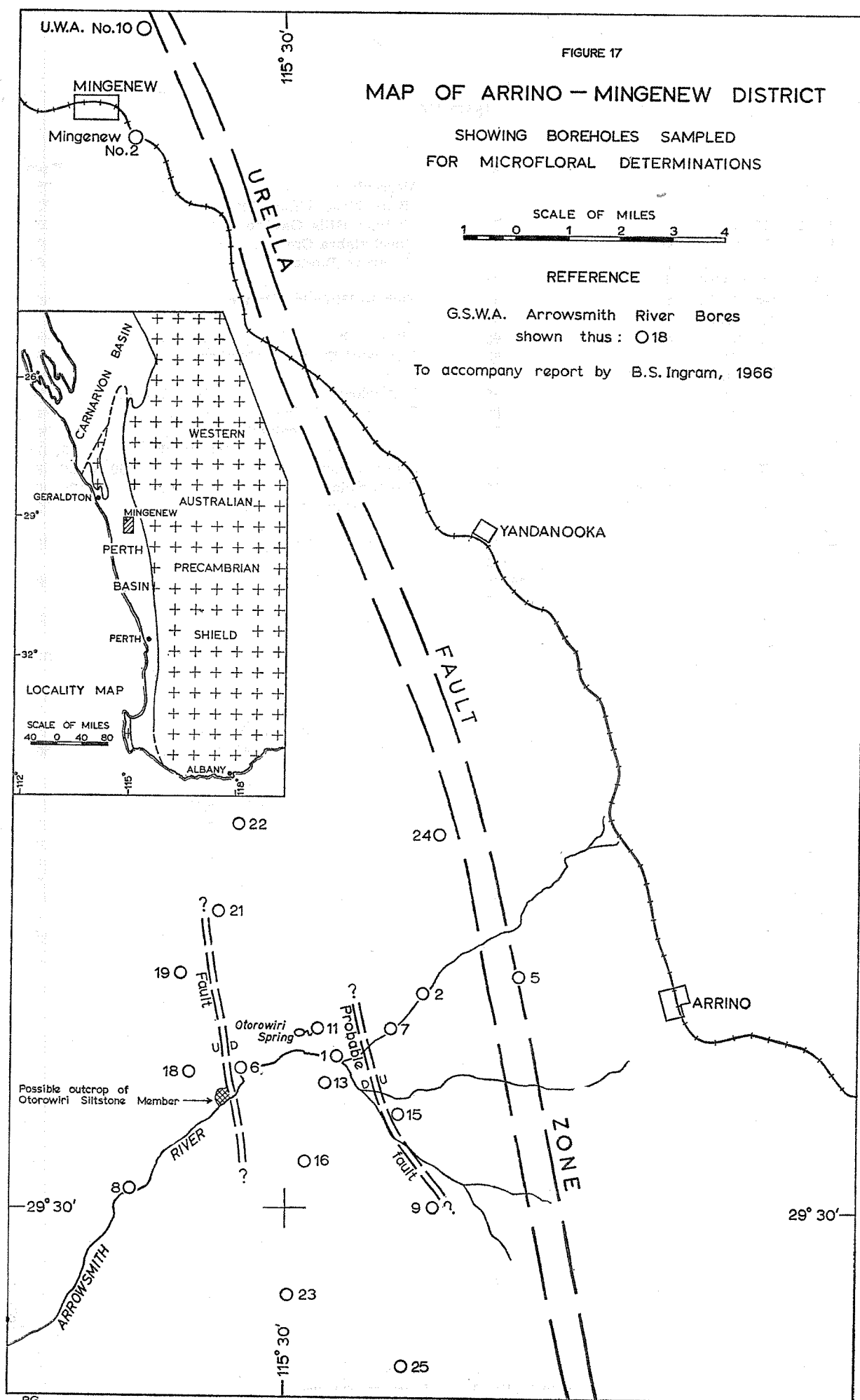
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