GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ANNUAL REPORT

FOR THE YEAR

1964

1965

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EXTRACT FROM THE REPORT OF THE DEPARTMENT OF MINES

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

Under Secretary: A. H. Telfer, I.S.O.

Director, Geological Survey: J. H. Lord.

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1964

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DIVISION IV

Annual Report of the Geological Survey Branch of the Mines Department for the Year 1964

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 for the year 1964, together with some reports on investigations made for departmental purposes.

ORGANIZATION

The professional staff was at full strength until two officers resigned about mid-year. Replacements have been appointed but have not yet arrived.

The numerous requests for the services of the engineering geologists have continued, and to cope with the work required in major governmental development projects, the appointment of an additional officer to the Hydrology and Engineering Geology Division has been approved.

The use of palynology in association with the search for underground water has increased greatly and approval has been given to recruit a palynologist.

The Commonwealth Government is to provide financial assistance to the State for an accelerated programme of search for groundwater which will require the appointment of additional hydrogeologists early in 1965.

With the discovery of oil and gas at Barrow Island and Yardarino and the increased tempo of oil search in this State, the Sedimentary (Oil) Division, with only three officers, is finding it increasingly difficult to contribute to the search for oil as well as keep abreast of current developments.

STAFF

Appointments

Name	Postition	Effective Date
Professional:		
M. E. Redman, B.Sc.	Geologist, Grade 2 (Female)	1/4/64
I. R. Williams, B.Sc. (Hons.)	Geologist, Grade 2— (Temporary) .... (Permanent)	3/2/64 3/8/64
R. Milbourne, B.Sc.	Geologist, Grade 2 (Temporary)	23/11/64
Clerical and General:		
S. W. H. Schellpeper	Geophysical Assistant	6/1/64
E. Grylls	Library Assistant (Female)	3/3/64
G. W. Wiltshire	Clerk	3/3/64
G. Craven	Typist (Temporary Female)	25/5/64
V. M. Marshall	Library Assistant (Female)	19/8/64
J. R. Sorensen	Laboratory Assistant	31/12/64
Promotions:		
J. L. Daniels	Geologist Grade 2 to Geologist Grade 1	31/7/64
Transfers:		
R. M. Landquist	Typist	25/5/64
Resignations:		
E. E. D'Arcy Evans	Library Assistant	3/1/64
B. Yonge	Geologist, Grade 2	20/5/64
C. Emmenegger	Geologist, Grade 2	6/8/64
E. Grylls	Library Assistant (Female)	14/8/64

ACCOMMODATION

The extension to the Dianella Store was completed and the Survey's rock and mineral collection is now housed in it, after being scattered in several stores for some years.

The survey continues to suffer from the lack of adequate and consolidated office accommodation. A warehouse is now being converted into additional office space. This will mean that the offices of this Branch are spread through five separate small buildings in three adjoining streets, with the Head Office of the Department and the Drafting Branch on the opposite side of the city.

The provision of centralized office accommodation at least for the Geological Survey Branch is overdue.

OPERATIONS

HYDROLOGY AND ENGINEERING GEOLOGY DIVISION

E. P. D. O'Driscoll (Chief Hydrogeologist), K. Berliat (Senior Geologist), F. R. Gordon (Senior Geologist), J. D. Wyatt, K. H. Morgan, A. D. Allen, E. E. Swarbrick, P. Whincup, R. Milbourne. J. R. Passmore was on leave without pay while engaged on a Water Research Foundation project.

Hydrology

Exploratory drilling in the Lake Allanooka area, completed during the year, proved substantial groundwater reserves, which are now being developed as a town water supply for Geraldton. Groundwater conditions at Wicherina were also assessed.

Five more bores were drilled near Arrino, and an extensive drilling programme is now underway as an investigation for a town water supply for Morawa. Permian fossils were found at the surface and in some bores, and the hydrogeology is more complicated than at first thought.

At Mandurah, five bores have now been drilled, and work is continuing. Usable water has been found several miles east of the town, but reserves still await proving.

Five of a programme of six deep bores extending west across the Perth Basin from Bullsbrook to the coast were drilled. A test bore was also drilled at Gingin, for town water supply purposes.

In the Gnangara Lake area the initial exploration programme of 12 bores was completed, and the existence of large volumes of good quality water was established.

The groundwater resources of part of the Kimberley area were assessed, in conjunction with the regional mapping programme.

Field work on a district survey at Albany for a town water supply was suspended because of shortage of staff. Drilling of three more production bores in the Sand Patch Area was recommended as a temporary measure.

Three test bores were drilled for the Muja Power Station at Collie. Results were disappointing, and other methods of obtaining water for the project were proposed.

Four bores were drilled to examine groundwater conditions in an area being opened for settlement in the Midlands sand plain country, and four bores were drilled near Hyden as an extension of last year's investigation.

Field surveys on Government projects were made for the towns of Northampton, Hall's Creek, Munglinup, Esperance, Derby, Kununurra, Meekatharra, Roebourne, Port Samson, Port Hedland, Nullagine, Marble Bar and Mt. Magnet; and for Albany High School, Stirling Range National Park and Bindoon Army Camp.

In conjunction with other Departments, proposals were made for the introduction of legislation to control drilling for groundwater within the State.

Engineering Geology

A diamond drilling programme of five holes at the Ord River Main Dam Site was supervised; shafts, bulldozer costeans and quarry sites were mapped; and a detailed geological map was prepared at a scale of 50 feet to an inch. Work associated with the feasibility and design stages of the dam is now complete.

The geological setting of the Secure Bay—Walcott Inlet tidal power scheme was examined during a helicopter survey. A quick reconnaissance was made of three possible dam sites on the Gascoyne and Lyons Rivers.

Advice was given at various stages during construction work at Waroona Dam on engineering problems arising from geological conditions.

Because of rock excavation characteristics, water seepages and varying slope stabilities, a considerable amount of consulting work was entailed on the Avon Valley Deviation of the Standard Gauge Railway. On the Merredin—Kalgoorlie section, reconnaissance work for water supply, quarry sites, and route details was undertaken.

Two alternative dam sites on Wungong Brook and a dam site on Gooralong Brook, were investigated for the Metropolitan Water Supply Board, to enable design to proceed. The work included diamond drilling and electric logging of bore holes. Correlation between water pressure tests and resistivity and self-potential logs proved of value, particularly in zones of core loss.

Minor geological work was also done on such projects as two proposed dam sites at Denmark, Serpentine Dam and Broome Jetty.

SEDIMENTARY (OIL) DIVISION

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

The progress of oil exploration in Western Australia was followed closely during the year, and the work programmes of oil exploration companies were reviewed. These matters occupied considerably more of the Division's time than in previous years owing to the increase in the rate of oil exploration in this State and the discovery of oil and gas at Yardarino and Barrow Island.

Field work during the year was conducted in the Perth, Canning and Officer Basins. In the Perth Basin field mapping was completed as far north as the Moore River and it will be extended further north during 1965. In the Canning Basin the detailed mapping of the Lennard Shelf reef complexes was completed, and the preparation of a bulletin on this project was commenced. A short reconnaissance field trip was made in April through the northern part of the Officer Basin in conjunction with an expedition by the Department of Native Welfare.

In the Gingin—Dandaragan area the drilling project to evaluate the Cretaceous glauconite deposits was completed. This project, started in 1963, was designed to assist the C.S.I.R.O. in the possible development of a process to extract potash from glauconite.

A core-drilling programme of 17 boreholes in the Collie area was supervised on behalf of the State Electricity Commission. The results assisted in the further evaluation of the structure and coal reserves of the Muja Depression.

REGIONAL GEOLOGY DIVISION

R. C. Horwitz (Supervising Geologist), J. Sofoulis (Senior Geologist), J. L. Daniels, M. J. B. Kriewaldt, I. Gemuts, I. R. Williams.

Eastern Goldfields Area

Field work was commenced on the Kalgoorlie 1:250,000 Sheet; one half of this area is now mapped. Information was supplied to residents and mining companies on hydrology, mineral resources and general geology. Field work was carried out and reports were written on ground water investigations for pastoralists in the Kanowna region, and on the general geology between Kalgoorlie and Koolyanobbing for the Engineering Geology section.

Pilbara Area

Field work was completed on the Yarraloola and Wyloo 1:250,000 Sheets. Information was supplied to prospectors and mining companies on mineral resources and general geology.

Kimberley Area

In conjunction with the Bureau of Mineral Resources, the programme of geological mapping, commenced in 1962, was continued; field work was completed on Lansdowne and Mount Ramsay 1:250,000 Sheets.

Mapping was done and a report was written on the geology of the Ord River Main Dam Site area.

General

Examinations of the Blackstone Range and the Warburton Range were made. Papers were given to the Australasian Institute of Mining and Metallurgy Congress in Kalgoorlie and Perth on problems pertaining to regional geology in Western Australia. Samples were selected, throughout this State, for a joint programme of rock age determination with members of the Australian National University, in Canberra.

MINERAL RESOURCES DIVISION

W. N. MacLeod (Supervising Geologist), L. E. de la Hunty (Senior Geologist), G. R. Ryan and R. Halligan.

A comprehensive survey of the blue asbestos resources of the Hamersley Range area was commenced during 1964. This work had been scheduled for 1965, but was commenced this year to assist Australian Blue Asbestos Pty. Ltd., who are currently engaged in a protracted drilling programme to establish ore reserves in the Wittenoom Gorge area. This survey is a major project and is expected to be continued by two geologists for the next two years.

Manganese deposits at Woodie Woodie and Mt. Sydney were drilled to test their extension in depth.

A mineral appraisal of the Mt. Ramsay and Lennard River 1:250,000 Sheet areas in the Kimberley area was made, in conjunction with the regional mapping programme.

Other investigations included an examination of vermiculite deposits at Young River, Eucla Division; mapping and examination of the new level which was opened up at the Comet Mine at the Pinnacles, near Cue; and examination and sampling of gold prospects near Lake Grace. An initial examination of deposits of glass sands near Gnangara Lake was made, and advice and information given to numerous interested companies and individuals on other industrial minerals in the Perth area.

COMMON SERVICES DIVISION

Petrology (A. F. Trendall)

Sixteen file reports and one Record were written, describing rock collections containing between one and 60 specimens, and including material supplied by all Divisions of the Survey and by the public. In addition, two papers were prepared for publication externally. A total of 1,335 thin sections and 23 polished mounts were prepared in the laboratory.

Geologists from the field parties are encouraged to carry out petrological work in consultation with the Petrologist. Conversely, the Petrologist spent eight weeks in the field: in the Kalgoorlie, Ashburton, Pilbara and Kimberley areas.

Apart from the examination of collections on behalf of the field parties, two special studies occupied much attention: the banded iron formations of the Hamersley Range and what might be called the "isotope petrology" of the Pilbara area. The first of these arises from the recent recovery of a series of diamond drill cores through the Brockman Iron Formation in the Wittenoom Gorge area. The cores constitute a sample of unoxidised, unmetamorphosed, and undisturbed banded iron formation, which is unique in the world and which should give correspondingly valuable information concerning the origin of these rocks and their contained asbestos. The second study involved the collection and examination of over 200 rocks as part of a joint project with the Australian National University to determine the ages, by radiometric methods, of the rock types and stratigraphic successions in the Pilbara area.

Studies which occupied little time but which possessed particular interest were an investigation for the Western Australian Museum of rock weathering over aboriginal engravings and an examination of enigmatic lumps of fused glass which are widely distributed in soil over the southern part of the State. The glass has often been miscalled "slag" in the past but is now known to have a natural origin; whether this is soil fusion by bush fires or lightning has yet to be resolved.

Palaeontology (H. S. Edgell)

The wide range of material submitted during 1964 included fossils, pseudofossils and fossiliferous sediments of ages ranging from Precambrian to Quaternary. Fifty-seven file reports and two Records were written. A bulletin on certain palaeontological groups from the Lennard Shelf reef complexes of the Canning Basin is in preparation.

As in 1963, the majority of requests for palaeontological advice were in the field of palynology. Cores and cuttings from some 56 bores drilled for water, oil and stratigraphic information were examined. Requests for identification of the formation, facies and geological age of most of these samples were made by the Hydrology Division. The more detailed microplankton zonation of the Cretaceous sequence established in 1963, proved useful in stratigraphic correlation of many water bores in the Perth Basin.

Cores from the petroliferous interval in Barrow No. 1 Well were submitted by West Australian Petroleum Pty. Ltd. for identification of the stratigraphic level encountered. Surface and shallow subsurface samples, including megafossils, from the Officer Basin were examined at the request of Hunt Oil Co.

In the field of micropalaeontology, the identification of numerous foraminifera belonging to the endothryrid and tournayellid groups proved useful in stratigraphic studies of the Lennard Shelf reef complexes by the Sedimentary Division. Conodonts were separated by advanced laboratory techniques from stratigraphically important samples from this area. Algae and early coelenterates known as stromatoporoids were also studied in detail as they were major reef-building organisms in the Devonian of the northern part of the Canning Basin.

Research is being continued into the identification of calcareous algae and their use for stratigraphic correlation of Late Precambrian rocks. A preliminary study on calcareous algae and probable medusoids from the Hamersley Range was completed and a paper prepared for publication externally.

Geophysics (D. L. Rowston)

Geophysical activity was centred mainly on various types of investigations for the Hydrology and Engineering Geology Division, and among these well-logging operations predominated. Twenty-two water bores, one coal bore and four diamond drill holes were logged with the Widco Well-logger the results were used for geological correlations and water salinity determinations. The latter were not entirely satisfactory, and a study to establish reliable methods of calculating salinities from the potential and resistivity logs is being continued. Further experimental resistivity work to assist groundwater search was carried out in the Kalgoorlie region.

Two metalliferous surveys were made to test the effectiveness of geophysical prospecting methods. A gravity survey over some manganese deposits in the Mt. Sydney—Woodie Woodie area showed that the gravimeter can detect manganese deposits of reasonable size, and can give a preliminary assessment of concealed ore bodies prior to drilling. The other test survey, at Thaduna in the Peak Hill Goldfield, indicated that electromagnetic methods can delineate the shears and faults with which copper mineralisation in the area is associated.

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

Technical editing of reports, maps and plans continued to be the major function of this section. During the year, 36 Records were prepared for issue and a number of reports and maps were edited for publication.

The library development continued with the rearrangement of books and serial publications. Cataloguing was revised to include locality and subject indexes as well as those for author and mineral. The aerial photograph library was expanded and photo-mosaics and flight diagrams were indexed and reorganised.

The Survey's rock and mineral collection was integrated at the Dianella Store. The sludge sample collection was sorted, and many samples were re-bagged to ensure their preservation.

In conjunction with the Western Australian Museum a geological display was exhibited at the Wild Life Show and an International Exhibit of Hydrogeological Maps was arranged for public display. Many requests from schools, prospectors and others for mineral and rock specimens received attention.

Considerable time was spent in answering oral and written enquiries from the general public.

ACTIVITIES OF THE COMMONWEALTH BUREAU OF MINERAL RESOURCES

The Bureau of Mineral Resources carried out both geological and geophysical work within the State during the year. The following projects were undertaken:

(1) Regional mapping of the Mt. Ramsay and Lansdowne 1 : 250,000 Sheets in the Kimberley area, jointly with the Geological Survey of Western Australia.

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

(3) Low-level aeromagnetic survey (Cessna aircraft) of small selected areas near Kalgoorlie and Norseman.

(4) Aeromagnetic survey (DC3 aircraft) of the Menzies and Leonora 1 : 250,000 Sheet areas.

(5) Regional seismic lines across the central Perth Basin near Bullsbrook and across the southern part of the Carnarvon Basin.

PROGRAMME FOR 1965

HYDROLOGY AND ENGINEERING GEOLOGY DIVISION

Hydrology

(i) Continuation of the hydrogeological survey of the Perth Basin, including deep drilling.

(ii) Hydrogeological investigation and/or exploratory drilling for underground water supplies in the following areas: Mandurah, Gnangara Lake, Arrowsmith River (for Morawa town water supply), Albany, Esperance, Mullewa, Yericoin, Hopetoun and Port Hedland.

(iii) Hydrological assistance to pastoralists in the Kimberley area:

(a) Bore site selection as required by pastoralists.

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

(iv) Miscellaneous investigations as required.

Engineering Geology

(i) Review of investigation for contract purposes: Ord River Main Dam Site.

(ii) Supervision of drilling and geological investigation: Dimond Gorge Dam Site.

(iii) Investigation of dam sites for Public Works Department: Gascoyne River, Harvey and Denmark.

(iv) Investigation of dam sites for Metropolitan Water Supply Board: Wungong Brook, Dandalup Brook and Victoria Reservoir.

(v) Standard Gauge Railway:

(a) Assessment of Koolyanobbing/Kalgoorlie Section.

(b) Investigation of quarry sites, Merredin to Kalgoorlie.

(c) Investigation and advice on railway cuttings.

(vi) Miscellaneous investigations as required.

SEDIMENTARY (OIL) DIVISION

(i) Active interest in the progress of oil exploration in Western Australia.

(ii) Continuation of the mapping programme in the Perth Basin.

(iii) Completion of the study of the Lennard Shelf area, Canning Basin.

(iv) Commencement of a geological survey of the Eucla Basin.

(v) Miscellaneous investigations as required.

REGIONAL GEOLOGY DIVISION

(i) Continuation of regional mapping on the Edmund 1 : 250,000 Sheet in the North-West Division.

(ii) Continuation of regional mapping on the Kalgoorlie 1 : 250,000 Sheet in the Eastern Goldfields area.

(iii) Continuation of regional mapping in the Kimberley area, in conjunction with the Bureau of Mineral Resources.

(iv) Commencement of regional mapping on the Cooper and Scott 1 : 250,000 Sheets in the Eastern Division.

(v) Revision of the Geological Map of Western Australia.

MINERAL RESOURCES DIVISION

(i) Completion of regional mapping and mineral investigation of the Robertson 1 : 250,000 Sheet.

(ii) Continuation of the regional investigation of the blue asbestos deposits of the Hamersley Range.

(iii) Investigation of mineral occurrences in the Kimberley area in conjunction with regional mapping by the Bureau of Mineral Resources.

(iv) Investigation of the pegmatites of the Yalgoo and Murchison Goldfields.

(v) Investigation of the nickel occurrences at Wingellina.

(vi) Miscellaneous investigations as required.

PUBLICATIONS AND RECORDS

During 1964, the first three 1:250,000 Geological Maps with Explanatory Notes compiled by this Survey were issued. One was printed by the Government Printer and two were published by the Bureau of Mineral Resources for the Mines Department. No bulletins were issued.

Thirty-six Records were prepared and issued.

Issued During 1964

Annual Report for 1962.

Geological Map of Boorabbin 1 : 250,000 Sheet (SH/51-13 International Grid) with Explanatory Notes.

Geological Map of Balfour Downs 1 : 250,000 Sheet (SF/51-9 International Grid) with Explanatory Notes.

Geological Map of Dampier and Barrow Island 1 : 250,000 Sheets (SF/50-2 and SF/50-1 International Grid) with Explanatory Notes.

In Press

Annual Report for 1963.

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

In Preparation

The following 1 : 250,000 Geological Maps with Explanatory Notes are being prepared, the field work for each having been completed: Port Hedland, Roy Hill, Newman, Roebourne, Pyramid, Turee Creek, Yarraloola, Wyloo, Widgiemooltha, Augusta and Busselton.

Bulletin—The Hamersley Iron Province.

Bulletin—Devonian Reef Complexes of the Lennard Shelf, Canning Basin.

Bulletin—Palaeontology of the Lennard Shelf, Canning Basin.

Records Produced

No.	Author(s)	Title
1964/1	A. D. Allen	Report on drilling at Billeranga Hills for the Morawa Town Water Supply.
1964/2	J. R. Passmore	Hydrogeology of the Cambridge Gulf, Lissadell and Dixon Range 4-mile Sheets, East Kimberleys, W.A.
1964/3	K. H. Morgan	Groundwater Resources of the Coastal Sand Dune Area, Lancelin Township, W.A.
1964/4	F. R. Gordon	Ord River Main Dam Site No. 2, Rockfill Dam Proposal. Investigations—1963.
1964/5	L. E. de la Hunty	Explanatory Notes on the Mt. Bruce 1 : 250,000 Geological Sheet, Western Australia.
1964/6	F. R. Gordon	Secure Bay—Walcott Inlet Tidal Power Scheme, Preliminary Geological Report.
1964/7	W. N. MacLeod	Report on the Vermiculite Deposits, Young River, Eucla Division.
1964/8	W. N. MacLeod	Gold Mineralization in the Vicinity of Griffins Find, Lake Grace Area, South West Division. *(Restricted.)*
1964/9	W. N. MacLeod	Iron Ore Deposits in the Eastern Section of the Hamersley Iron Province.
1964/10	P. E. Playford	Report on Native Welfare Expedition to the Gibson and Great Sandy Deserts, April, 1964.
1964/11	G. R. Ryan	Explanatory Notes on the Roebourne 1 : 250,000 Geological Sheet.
1964/12	A. F. Trendall	Slaggy Siliceous Glass Occurring Naturally on the Surface at Various Localities in the Southern Part of Western Australia.
1964/13	H. S. Edgell	Lower Cretaceous Fossils from Outcrops of the Wilkinson Range Beds, Officer Basin. *(Restricted)*
1964/14	B. Yonge	Groundwater Investigations in a Part of the Darling Range East of Perth.
1964/15	C. Emmenegger	Report on Exploratory Drilling for Underground Water at Mandurah—Perth Basin, W.A.
1964/16	D. L. Rowston	Geophysical Investigations at Thaduna, W.A., June, 1964. *(Restricted)*
1964/17	K. H. Morgan	Hydrogeology of the Southern Part of the Gnangara Lake Area, South-West Division, Western Australia.
1964/18	R. C. Horwitz	The Geology of the Region Surrounding the Ord River Main Dam Site, Western Australia.
1964/19	H. S. Edgell	Micropalaeontology and Stratigraphy of Core Samples from Barrow No. 1 Well, Carnarvon Basin, W.A. *(Restricted)*
1964/20	W. N. MacLeod & L. E. de la Hunty	Explanatory Notes on the Roy Hill 1: 250,000 Geological Sheet.
1964/21	K. Berliat	Report on Drilling for Underground Water, Watheroo Town Supply.

No.	Author(s)	Title
1964/22	F. R. Gordon	Dimond Gorge Dam Site, Geological Reconnaissance Investigation, 1962.
1964/23	E. E. Swarbrick	Geology and Hydrology of the Wicherina Area, W.A.
1964/24	F. R. Gordon	Kennedy Range Dam Site, Gascoyne River, a Preliminary Appraisal.
1964/25	D. L. Rowston	Pilbara Manganese Deposits, W.A.—Gravity Survey, 1964.
1964/26	F. R. Gordon	Broome Jetty Foundation Investigations.
1964/27	F. R. Gordon & J. D. Wyatt	Engineering Geology of the Jarrahdale Dam Site.
1964/28	W. N. MacLeod ..	The Comet Mine, Pinnacles Group near Cue, G.M.L. 670D and 676D. *(Restricted)*
1964/29	J. Sofoulis	Geological Reconnaissance of Proposed Route between Koolyanobbing and Kalgoorlie—W.A.G.R. Standard Gauge Railway.
1964/30	G. H. Low	Coal Drilling in the Muja Formation near Collie.
1964/31	F. R. Gordon	Ballast Quarry Sites between Merredin and Koolyanobbing, Standard Gauge Railway.
1964/32	L. E. de la Hunty	Report on Investigation of Manganese Deposits in the Mt. Sydney—Woodie Woodie Area, Pilbara Goldfield.
1964/33	L. E. de la Hunty	Glass Sands at Gnangara Lake.
1964/34	R. Halligan	The Narlarla Lead-Zinc Deposits, Barker River Area, West Kimberley District. *(Restricted)*
1964/35	P. E. Playford & D. C. Lowry	Wells Drilled for Petroleum Exploration in Western Australia to the end of 1964.
1964/36		Provisional Subdivisions of the Precambrian, Western Australia.

12th March, 1965.

J. H. LORD,
Director.

GROUNDWATER PROSPECTS FOR ESPERANCE TOWN WATER SUPPLY

by

E. P. D. O'Driscoll

INTRODUCTION

The population of the town of Esperance is rapidly expanding, and future water supply requirements are estimated at 20,000 gallons per hour, with an annual consumption of 80 million gallons. This is considerably more than is available from existing bores, but an inspection of the area indicates that substantial reserves exist, and are as yet undeveloped.

Esperance is on the south coast about 350 miles east-southeast of Perth, and lies in a narrow 25-inch rainfall belt, the rainfall decreasing quickly with distance from the coast. The surrounding countryside for a long distance is a very ancient peneplain underlain by Archaean crystalline and metamorphic rocks, usually capped by thin laterite and sand, and topographic relief is low.

The southern edge of this ancient peneplain is several miles north of the town. In Tertiary times it was the edge of the main land mass with a chain of granitic islands lying offshore. The granites have weathered to provide huge quantities of sand, and an offshore bar appears to have built up and connected the islands together, leaving a channel separating them from the mainland.

This channel gradually filled with marine and paralic sediments, the uppermost of which were saline swamp deposits, until the whole became part of the land mass, with the island chain as the new shoreline. The old channel remains as a low-lying area covered with salt lakes.

However, continued production of sand as a result of weathering of the granites resulted in masses of sand dunes being piled up, mainly by wind action, along the shore. To the west of Esperance these dunes have gradually encroached on the back-dune swamps, so that the salt lake chain loses its character west of Pink Lake. The dunes in places attain a height of nearly 300 feet, although over a large area the interdune flats are at an elevation of 50 feet or less above sea level.

GEOLOGY AND HYDROLOGY

There are thus three quite distinct sets of geological conditions within a few miles of the town. To the north, the granite basement area, with its rainfall decreasing northwards, has intermittent streams which even in winter time have quite saline flows. Many bores have yielded poor supplies and brackish to salty water, although there is an occasional exception. In places thin remnants of Tertiary (Plantagenet Beds) limestone occur, these having been recorded in bores near Shark Lake, six miles north of Esperance, and reported in other localities as far north as Gibson. The limestone is associated with thin sands which in places underlie it, and wherever these Tertiary strata occur the groundwater they contain is of fairly low salinity, that is, less than about 2,500 parts per million. However, in both thickness and extent the aquifers are very limited, and are not a potential source of water for the town.

The strip of salt lake country resulting from the infilling of the back-dune swamp or channel probably has a fairly considerable thickness of Tertiary and younger sediments, but the shallow groundwaters are very saline, and it is not expected that any deeper aquifers which may occur will contain potable water.

The third and remaining area is the coastal sand-dune complex, which is known to contain potable water in the part which lies south of the railway, along the Esperance—Pink Lake road, and southwards towards the rifle range. The Department of Public Works has drilled ten bores, six of which are close together and intended for production, the other four being further afield. There are also some scattered privately owned shallow wells and bores containing very good quality water.

This potable water is a direct result of rainwater runoff from the dunes collecting in the interdune flats and soaking downward into the underlying sands and limestones. The effect is probably more pronounced in those places where a thin and intermittent capping of travertine limestone occurs. Dunes cover an area about 2 miles wide and 5 miles long extending westward from the town itself, and they then spread out to cover a still wider area west and southwest of Pink Lake, where groundwater conditions are unknown. They also continue northeast of the railway, where however, the groundwater quality appears less uniform, and prospects of development consequently not so favourable.

GENERAL

Within the area covered by the dunes, prospects of obtaining the required amount of water are considered reasonably good. However, before consideration is given to enlarging and extending the water supply, the nature and extent of the probable aquifer will have to be proved by drilling. Also, as it has in the past proved difficult to extract the water, consideration will have to be given to proper methods of development. A privately constructed bore at the new drive-in theatre is reported to have a yield of 12,000 gallons per hour, and there is another high-production bore near Pink Lake. Prolonged continuous pumping at such high rates is unwise, as there is a danger of dewatering the aquifer, and possibly increasing the salinity. For a town supply it would be wiser to aim at individual production of 2,000-4,000 gallons per hour, which means using a number of bores simultaneously, and spreading the draw-off over a fairly wide area.

Because of the current rapid expansion of building, the present six town bores are already within or at the edge of the residential area. No sewerage system is available, and the water from these bores can be expected to become increasingly contaminated with detergents from domestic discharge. It may become unusable. Half a mile west of the residential area along the Pink Lake road there is a cemetery, and further west a community rubbish tip, both potential sources of groundwater contamination.

EXPLORATORY DRILLING

Exploratory drilling should be confined to the dune area, which can be subdivided into three parts: one northeast of the railway, the second roughly triangular in shape with apices at Pink Lake, Esperance and the rifle range, and the third extending to the westward of these and south of Pink Lake.

As a part of the general investigation it will be advisable to drill some bores northeast of the railway to establish the areal extent of the aquifer, although this area is not envisaged as a production area.

Considerable quantities of water are expected in the second area which roughly straddles the Esperance/Pink Lake road, but because of possible contamination, there may be some objection to their development.

This still leaves what appears to be a substantial area to the westward in which potable water is expected. Once the extent and thickness of the aquifer and the salinity pattern have been established, consideration can be given to the best locations for production bores, but these unknowns must first be established by exploratory drilling.

Drilling should at first be confined to the inter-dune flats, which the accompanying plan (Plate 1) shows to be widespread. Moreover, the flats tend to form corridors in a west-southwest direction parallel to the prevailing wind, which will facilitate access.

A programme of drilling 25 bores is suggested, at the sites indicated on the plan, the bores being roughly 40-60 chains apart. Most of these bores will be less than 100 feet in depth, although it would be wise to drill occasional widely spaced bores to 200-250 feet in order to test the quality and occurrence of the deeper water. This should be found out because of the possibility of upward movement of saline water in pumped bores. The strata expected are a sequence of sands and limestones, which should be reasonably good drilling, unless the sands, some of which are fine and not very well consolidated, collapse in the hole. The total drilling footage involved is probably of the order of 3,500 feet.

CONCLUSIONS AND RECOMMENDATIONS

An exploratory drilling programme of 25 bores is recommended at the sites indicated on the attached plan. Careful sampling of waters and strata will be needed.

The programme is designed to establish the extent and thickness of the potable water aquifer and the salinity pattern. The proposed drilling may not do this completely, as at this stage the westward extent of the aquifer can only be guessed at, and no drilling has been suggested near the extensive live sand dune southwest of the rifle range.

Sites have been chosen on the interdune flats, because of ease of access and lesser depth of drilling.

When the suggested drilling nears completion, consideration can be given to whether the problems are sufficiently clarified to enable development work to proceed, or whether more exploratory drilling appears desirable.

EXPLORATORY DRILLING FOR WATER IN THE SANDPLAIN COUNTRY 40 MILES EAST OF HYDEN

by

K. Berliat

INTRODUCTION

Extensive areas of vacant light land east of Hyden (218 road miles east of Perth, via York, Corrigin, and Kondinin) are considered suitable for mixed farming, provided adequate stock water supplies are available. The Department of Agriculture therefore sought advice on the groundwater potential, indicating that some exploratory drilling should precede any attempt to develop farms.

Nine shallow bores were subsequently drilled by contract along the Hyden—Norseman Road, in the vicinity of the Department of Agriculture's research area 40 miles east of Hyden.

TOPOGRAPHY, GEOLOGY

Topographically the area is predominantly undulating sandplain, covered by yellow, loamy sands, carrying a dense vegetation of low scrub. Red clayey soils with good stands of salmon gum, gimlet and morrel, are characteristic of the main depressions trending in a southerly direction. Defined drainage lines with incised channels do not occur. Small scattered outcrops of granite are common, particularly in the more elevated places and it is presumed that granite or basic intrusive rocks underlie the whole area at varying shallow depths.

RAINFALL

One of the main factors controlling the accumulations and quality of shallow groundwater is local rainfall, and records over long periods of time are an important indication of an area's potential.

Rainfall records in the drilling area have not been kept long enough to obtain a picture of the long term pattern. The annual rainfall recorded at the Department of Agriculture's experimental area was 15.66 inches for 1960 and 10.33 inches for 1961. Records from Emu Rocks, 5 miles southwest of the drilling area, show a mean annual rainfall of 11.02 inches over a period of some 50 years. These figures indicate that the area under discussion is situated in a low rainfall, saline groundwater province.

EXPLORATORY DRILLING

The drill sites were chosen to provide groundwater information in various topographical environments including high-level sandplain depressions; long, gentle slopes; areas surrounding granite outcrops; and major topographical depressions.

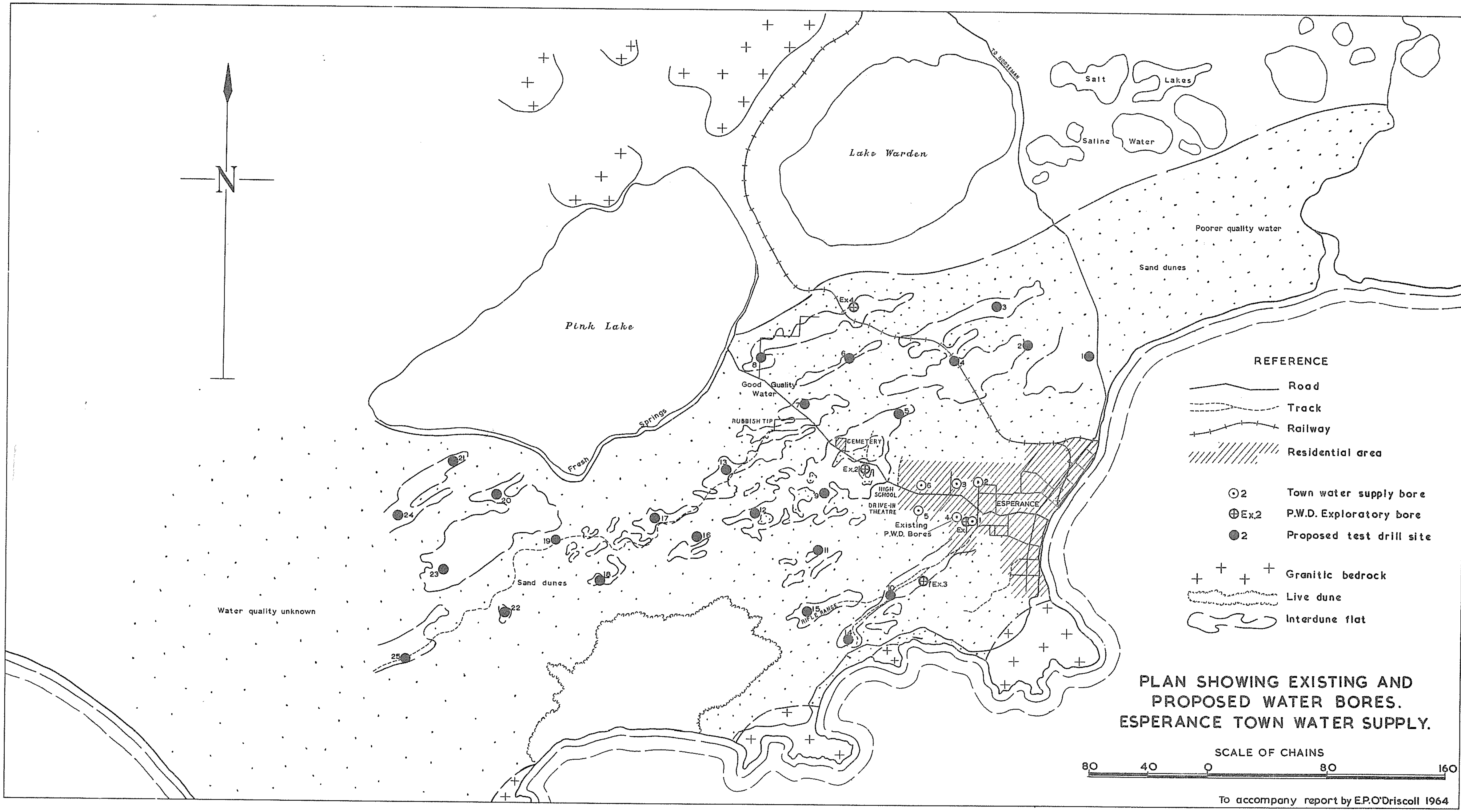
No. 1 Bore, located to test a prominent high-level sandplain depression, was drilled in weathered granite to a depth of 125 feet. Water was encountered at 119 feet, having a salinity of 10,000 p.p.m. (parts per million) total dissolved solids (9,260 p.p.m. NaCl), increasing to 10,600 p.p.m. (9,770 p.p.m. NaCl) at 125 feet. The hole was then abandoned without striking bedrock. The supply was not in excess of 700 gallons per day.

These results gave reasonable grounds to expect that water of lower salinity might occur at points of higher elevation, and No. 2 Bore was therefore sited in the same depression 40 chains west of No. 1 Bore. The bore penetrated 90 feet of decomposed granite and then encountered solid bedrock without striking any water.

No. 3 Bore, near the southern boundary of the Department of Agriculture's experimental area, tested one of the characteristic long, gentle slopes. At 130 feet a small supply of water not exceeding 200 gallons per day was encountered. This water had a salinity of 9,880 p.p.m. total dissolved solids (9,030 p.p.m. NaCl, which increased to 11,900 p.p.m. (11,000 p.p.m. NaCl) at 134 feet, where solid granite was encountered. The supply at the bottom of the hole was 600 gallons per day.

No. 4 and No. 5 Bores were drilled about 20 chains down the slope from the margin of a granite outcrop. There appeared to be good catchment conditions and the objective of the drilling was to test potential accumulations of groundwater draining down the buried granite slope. The bores bottomed in solid granite at depths of 63 and 73 feet and both were dry.

The remaining four bores (No. 6 to No. 9) were drilled to test the salinity of the groundwater in the low lying valley flats crossing the Hyden-Norseman Road about 2 miles east and 4 miles west of the experimental area (see Plate 2). Two of them were dry, reaching solid granite at 70 feet (No. 8) and 39 feet (No. 9). The other two cut water in decomposed granite at 80 feet and 94 feet. The supply in both bores was at least 5,000 gallons per day, but the salinity was very high, 24,900 p.p.m. total dissolved solids (21,100 p.p.m. NaCl) in No. 6 Bore and 36,900 p.p.m. (35,700 p.p.m. NaCl) in No. 7 Bore.



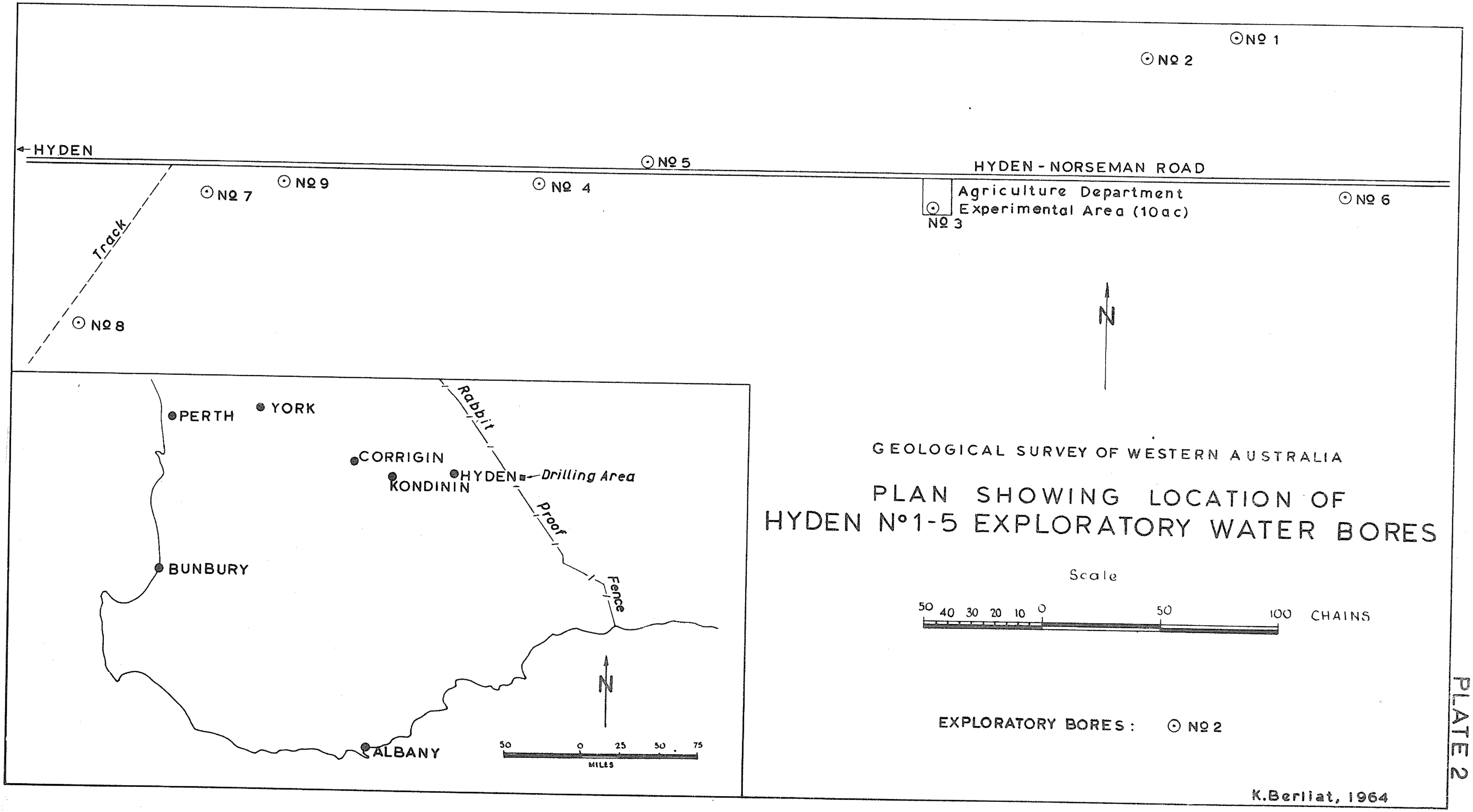
PLAN SHOWING EXISTING AND PROPOSED WATER BORES. ESPERANCE TOWN WATER SUPPLY.

PLATE I

To accompany report by E.P. O'Driscoll 1964

8626

PLATE 2


№ 1
№ 2
← HYDEN
№ 5
HYDEN - NORSEMAN ROAD
№ 7
№ 9
№ 4
Agriculture Department
Experimental Area (10 ac)
№ 3
№ 6
Track
№ 8
N
PERTH
YORK
Rabbit
Proof
Fence
CORRIGIN
HYDEN
Drilling Area
KONDININ
BUNBURY
ALBANY
N
50 0 25 50 75
MILES
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
PLAN SHOWING LOCATION OF
HYDEN N°1-5 EXPLORATORY WATER BORES
Scale
50 40 30 20 10 0 50 100 CHAINS
EXPLORATORY BORES: № 2
K.Berliat, 1964

8098

CONCLUSIONS

The exploratory drilling programme of nine bores was confined to a relatively small area in the sandplain country 40 miles east of Hyden. It cannot be considered comprehensive enough to draw final conclusions concerning the groundwater in the region as a whole, but the results suggest that the general conditions are poor.

Groundwater in the major topographical depression is excessively saline, and useless for stock and irrigation purposes.

Bores drilled on the more elevated sites were favourably located from the point of view of catchment and run-off, and the negative results are thought to be due to one or more of the following factors:

1. The configuration of the buried granite surface (bores not located in the lowest portions of the bedrock relief).
2. The low permeability of the decomposed granitic material.
3. The bores were located topographically too low. This applies to No. 1 Bore in particular.

In spite of the fact that in general the results were discouraging, they do not necessarily mean that no stock waters occur. Some of the high-level depressions and gullies may hold some promise of success, provided there are favourable conditions of catchment and run-off, and bores are located in a basement "low". This last condition raises a difficulty, because the depth to hard rock cannot be predicted from surface inspection. However, in the best of cases only limited supplies of water of stock quality can be expected.

The bare granite outcrops on higher ground, a common feature throughout the region, form good catchments only when the run-off is efficiently concentrated. Many granite outcrops are boss-like and shed the water all around their periphery; others are flat, or saucer-shaped, and much of the rain falling on them will simply accumulate and evaporate.

There is a possibility that usable supplies of water might occur in fractured zones in the basement rocks. Drilling in fresh granite with a percussion rig is difficult if not impossible, but if suitable rock drilling equipment is available some bores should be drilled 60 to 70 feet into bedrock. This applies only to areas where conditions are otherwise favourable, but which have failed to yield water from decomposed material. Waters occurring in hard unweathered granite will probably be no better in quality than any shallower water occurring in the same hole, and at the best are expected to be of poor stock quality.

GROUNDWATER IN THE COASTAL SAND DUNES AT LANCELIN, PERTH BASIN

by

K. H. Morgan

ABSTRACT

Inspection of the Lancelin area and test drilling of two bores to depths of 80 and 150 feet in an area about one mile east of the town indicate that probably 1.5 million gallons per acre of domestic quality water is available. Pump rates from a single bore may be more than 16,000 gallons per hour with little drawdown. Ample water is available for town water supply needs.

INTRODUCTION

At the request of the Department of Public Works the Geological Survey investigated the possibility of obtaining a groundwater supply for the town of Lancelin. After a geological inspection, two test bores were drilled in late 1963 (Plate 3). These bores proved the existence of a fairly extensive and comparatively thick zone of usable water a short distance east of the town.

Lancelin is 78 road miles north of Perth and is in an early stage of development. Water supplies are obtained from numerous private shallow bores, wells and rain water tanks. Domestic wastes are disposed of into soakage wells and drains, and wastes from the fish processing plants are mainly pumped into the sea. Beside the permanent population, there is a seasonal influx of holiday makers. The peak population at Christmas is estimated at 2,500.

Present water requirement has been estimated at 17.5 million gallons per year. The average annual rainfall is about 22 inches.

TOPOGRAPHY AND VEGETATION

The town is located near the shore of a sandy bay fringed by scrub-covered foredunes rising about 10 feet above sea level. Behind these dunes are beach ridges, rising 3 to 8 feet above the general level and covered by coastal heath.

At high tide the water table rises and saturates the interdune area, on which most of the buildings and roadways are located.

Farther inland is an eroded, bare, flat strip of rocky country, 20 to 40 chains in width and standing about 12 feet above sea level. Still farther eastward is a half mile wide belt of mobile sand dunes rising to slightly more than 50 feet above sea level.

Table 1

STRATIGRAPHIC UNITS AT LANCELIN

Bay Area	Shore Area	Eroded Rocky Area	Sand Dune Area
Contemporary marine sand	Contemporary foredunes		Sand dunes
Marine sand	Beach ridges { aeolian sand, beach sand Stratified marine sand Buried limestone reefs	Aeolianite Travertine cap	Aeolianite Travertine cap
	Erosion Surface		
Coastal Limestone	Coastal Limestone { aeolian, marine	Aeolianite Part leached beach sand	Aeolianite with solution pipes highly leached beach sand
	Disconformity		
	Upper Cretaceous marl (Lancelin Beds)		
	Unconformity		
	? Jurassic		

GEOLOGY AND HYDROLOGY

The rock sequence is set out in Table 1.

The youngest rocks are the contempoary foredunes along the coast, the mobile sand dunes a half mile east of the shore, and the marine sand being deposited in the bay at the present time. These are composed mainly of marine carbonate sediments.

Stratigraphically below the sand dunes is a sequence of friable calcareous sand and calcarenite. In the eroded rocky area and the sand dune area calcareous aeolianite, with an abundance of rootlet structures and cocoon casts, overlies a travertine band that represents an older land surface. Near the shore the sequence of calcareous sand and calcarenite is mainly of marine origin, and comprises low sandy beach ridges of aeolian sand overlying a coarse grained shelly beach sand. Shallow bores and wells in the aeolian ridges yield small water supplies, but screens or spears in the bores soon become blocked with fine sand and carbonate cement. For this reason wells are more effective. The beach deposit yields slightly larger supplies of more saline water. Being close to the surface both these aquifers are subject to pollution.

Below the beach sand and extending to 30 feet below sea level on the shore line is stratified fine to coarse-grained fossiliferous marine sand with sea weed beds. It contains brackish to saline water, brown in colour and usually has a strong sulphurous odour. An abnormally high nitrate content in three water samples suggests pollution (see Table 2).

Table 2

WATER ANALYSES OF SAMPLES FROM SOME BORES AT LANCELIN

(See sketch map for locations)

Bore Sample No.	9809	9812	9816	9811	9813	9814	9815	Bore 2B Final Sample
Specific Conductivity 20°C	2140	....	....	....	....	....	....	680
Odour	Nil	Nil	Nil	Hydrogen sulphide	Hydrogen sulphide	Nil	Nil	Nil
pH	7·4	7·2	7·4	6·7	6·7	7·6	7·0	7·6
Analyses in parts per million :								
Calcium, Ca	78	....	....	....	....	....	....	71
Magnesium, Mg	59	....	....	....	....	....	....	15
Sodium, Na	351	....	....	....	....	....	....	69
Potassium, K	16	....	....	....	....	....	....	3
Bicarbonate, HCO_3	299	....	....	....	....	....	....	235
Carbonate, CO_3	Nil	....	....	....	....	....	....	Nil
Sulphate, SO_4	89	....	....	....	....	....	....	14
Chloride, Cl	610	544	112	874	336	144	579	132
Sodium Chloride, NaCl	....	897	184	1440	554	237	954	....
Nitrate, NO_3	28	4	2	....	....	....	....	....
Silica, SiO_2	10	....	....	....	....	....	....	....
Iron, Fe	less 0·1	....	....	....	....	....	....	not detected
Total : by conductivity	1500	1360	410	2000	860	480	1450	480
by summation	1540	....	....	....	....	....	....	439
Hardness (calculated as $CaCO_3$) :								
Total hardness	438	....	....	....	....	....	....	239
Bicarbonate hardness	245	....	....	....	....	....	....	193
Calcium hardness	195	....	....	....	....	....	....	177
Magnesium hardness	243	....	....	....	....	....	....	62
Non-carbonate hardness	193	....	....	....	....	....	....	46

Most of the present water supplies are extracted from the beach sand and the stratified marine sand described above.

Limestone reefs at the base of the marine sand represent the marine top of the Coastal Limestone. This erosion surface is 20 to 30 feet below sea level under the shore and is the marine equivalent of the travertine cap in the eroded rock and sand dune areas to the east. Where exposed the Coastal Limestone has a hard travertine cap with "karst" features and solution pipes extending below sea level. Under the travertine cap it is friable and easily wind eroded. Below water level it is also friable. The upper part is aeolian, the basal part shallow-water marine, with coarse-grained beach deposit between. In Bores 1 and 2B the very coarse-grained sections, between 20-35 feet and 45-70 feet respectively, are thought to be the beach deposit leached of carbonate cement and shell fragments. Under the town area the beach deposit is partly leached of carbonates and the comparatively good water sometimes found there is thought to result from intake in the sand dunes to the east.

At the shore the Coastal Limestone extends to approximately 100 feet below sea level and unconformably overlies impervious Upper Cretaceous (Campanian) marls having a thickness of at least 45 feet. The unit is younger than any previously dated Cretaceous rocks in the Perth Basin and has been assigned the provisional name, Lancelin Beds (Edgell, 1964). They probably overlie Jurassic sediments which are expected to be water bearing.

DRILLING

The drilling and pump testing were done by contract, with the following results:

Bore No. 1 reached a depth of 80 feet, passing through domestic quality water from 15 feet to about 70 feet. Below this, the salinity quickly increased. This particular locality should not be developed, as heavy pumping will result in encroachment of saline water.

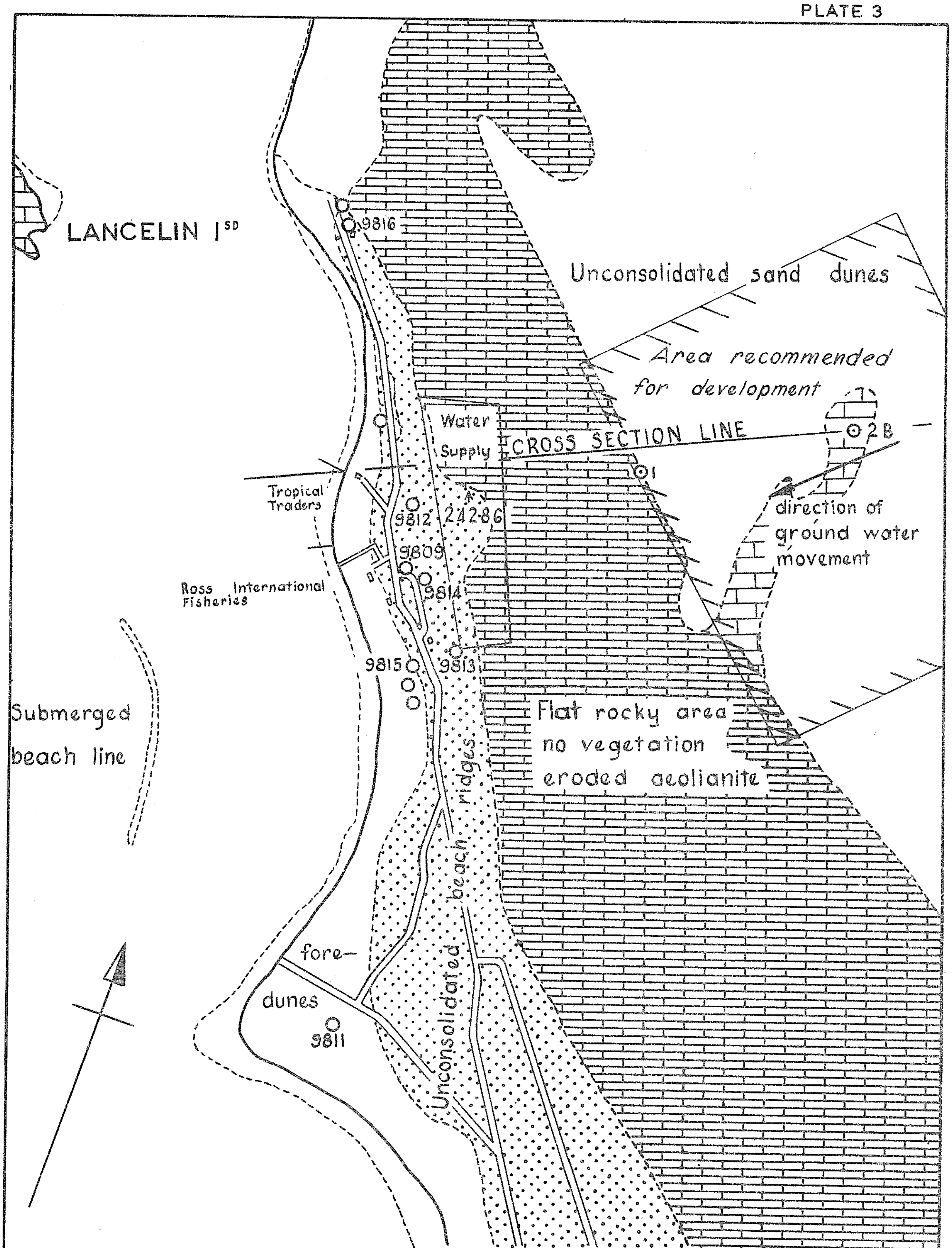
Bore No. 2B was drilled to a depth of 150 feet and intersected domestic quality water between 8 feet and 90 feet, below which the salinity also increased rapidly. This bore was screened between 50 and 60 feet, and test pumped at 12,500 gallons per hour for 20 hours, with a drawdown of 1.1 feet; then at 16,200 gallons per hour for 10 hours, with little alteration in the drawdown. During this 30 hours the salinity rose from 410 p.p.m. (parts per million) total dissolved solids to 525 p.p.m. total dissolved solids (see Table 2).

CONCLUSIONS AND RECOMMENDATIONS

Drilling and testing have proved the existence of a large volume of water suitable for the town supply.

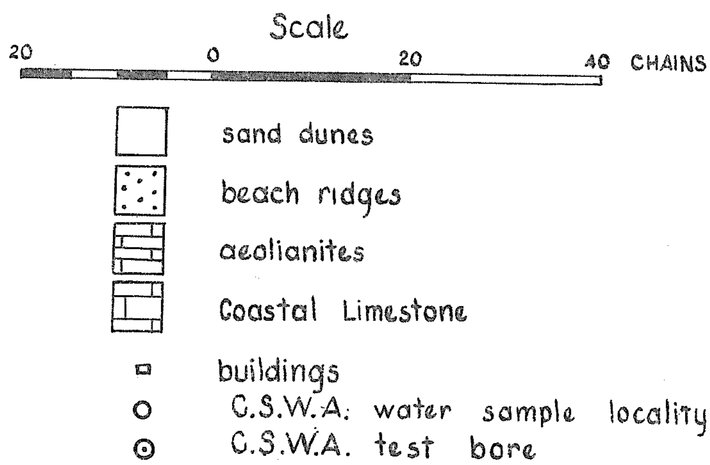
In the drilling area, the salinity to a depth of 70 feet is expected to average 400 p.p.m. total dissolved solids. Water of salinity greater than 1,000 p.p.m. total dissolved solids occurs below 70 feet in Bore No. 1 and below 90 feet in Bore No. 2B (Plate 4). Similar conditions are expected throughout the sand dune area, half a mile from the shore. The thickness of beds containing water of salinity less than 1,000 p.p.m. decreases rapidly towards the coast, whereas the zone of diffusion of brackish to saline water increases in thickness towards the coast.

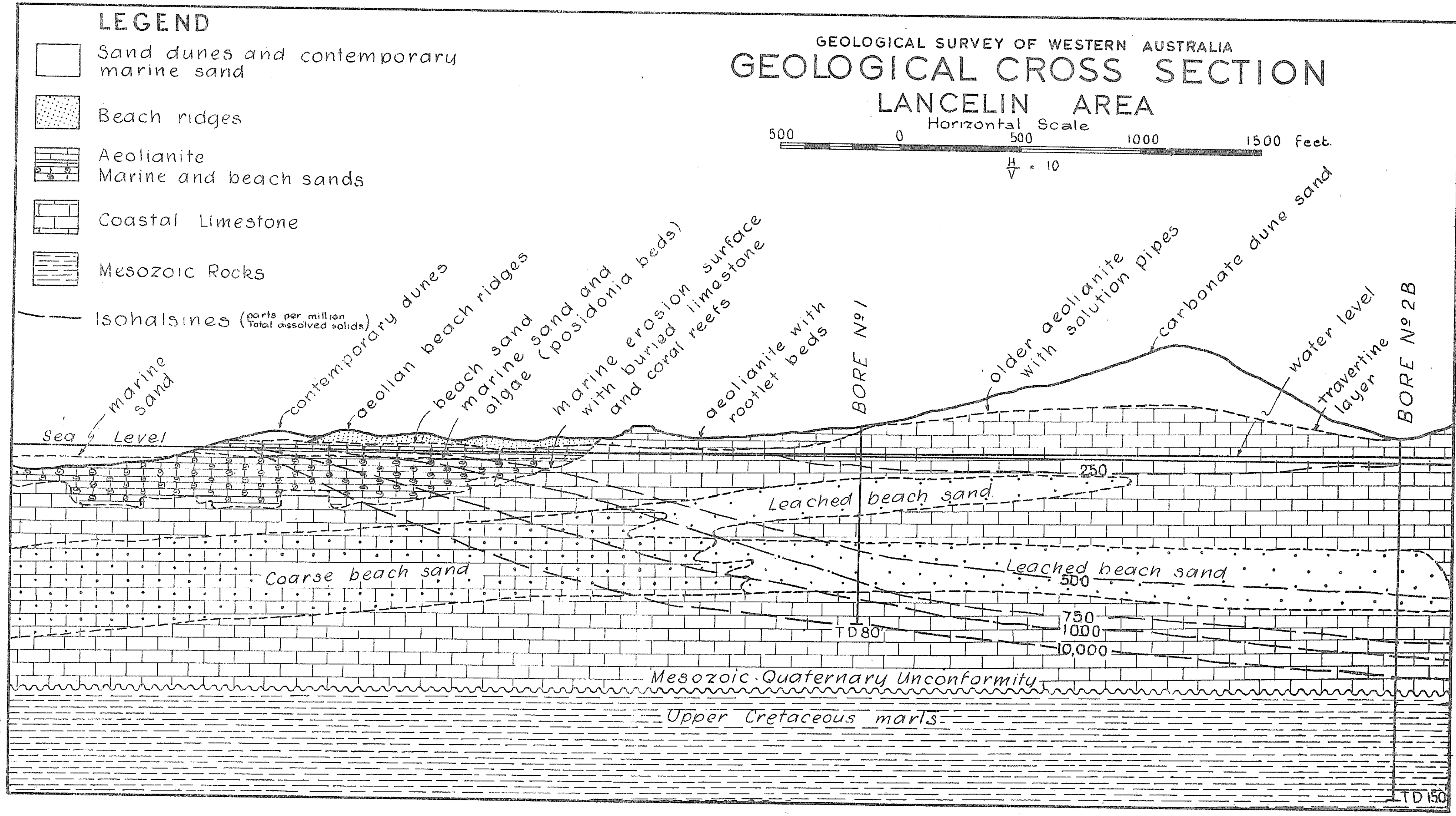
Assuming an average thickness of 30 feet of beds containing usable water and a specific yield of 20 per cent, there is probably available 1.5 million gallons per acre from water already in storage. An area of about 15 acres, if completely pumped out, would supply town needs for one year, and a square mile would last some 40 years, even if there was no recharge from rain.



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL SKETCH MAP OF LANCELIN AREA




LEGEND
Sand dunes and contemporary marine sand
Beach ridges
Aeolianite
Marine and beach sands
Coastal Limestone
Mesozoic Rocks
Isohalsines (parts per million Total dissolved solids)
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL CROSS SECTION
LANCELIN AREA
Horizontal Scale
500 0 500 1000 1500 Feet.
H/V = 10
marine sand
Sea Level
contemporary dunes
aeolian beach ridges
beach sand
marine sand and algae (posidonia beds)
marine erosion surface with buried limestone and coral reefs
aeolianite with rootlet beds
BORE No 1
older aeolianite with solution pipes
carbonate dune sand
water level
travertine layer
BORE No 2B
250
Leached beach sand
Leached beach sand
500
Coarse beach sand
750
1000
10,000
TD 80
Mesozoic Quaternary Unconformity
Upper Cretaceous marls
TD 150

An annual accretion of 3 inches of rain to the groundwater would provide about 68,000 gallons of recharge per acre per year. To balance the current requirement of 17.5 million gallons per year, an area of about 300 acres is needed.

That recharge does occur is apparent from the hydraulic gradient, which rises from mean sea level to about 2.1 feet higher at Bore No. 2B, a gradient of about 1 : 2,300. This gradient continues eastward and considerable recharge resulting from westward-moving groundwater would accur if the sand dune area was pumped.

The area of good quality groundwater probably exceeds the required 300 acres by a substantial margin, so that unless pumping rates in the future are much higher than expected, there appears to be an ample supply of groundwater available from the sand dune area east of the town.

Privately constructed bores in the town show that the shallow aquifer used at present has insufficient reserves for development, and production bores will have to be drilled a mile or so eastward and within the area recommended for development on the sketch map.

To spread the drawoff, and reduce the likelihood of saline waters rising from below and causing deterioration of water quality, it is suggested that more than one pumping bore be used.

REFERENCE

Edgell, H. S., 1964, The occurrence of Upper Cretaceous marine strata of Campanian age at Lancelin, Perth Basin: West. Australia Geol. Survey Ann. Rept. 1963.

APPENDIX 1

BORE COMPLETION REPORT LANCELIN No. 1

Location: Crown Reserve 22287, 40 chains east of Tropical Traders' Jetty, at the base of high drift sand dunes.

Drilled: October, 1963.

R.L. of Ground Surface: Approximately 20 feet.

Water Rest Level on Completion of Bore: 15 feet.

Total Depth: 80 feet.

SUMMARY OF LOG

		Strata	Water Samples	
			Depth (feet)	p.p.m./ t.d.s.
Coastal Limestone	Aeolianite	*Calcarenite* (0–20 feet): white to light yellow, fine to coarse grained stratified, friable calcarenite and marly calcarenite. Shell fragments common between 10–15 feet.	15 20	250 300
	Leached beach sand	*Interbedded coarse grained calcarenite and clean sand* (20–35 feet): light yellow, clean, medium to coarse grained, friable calcarenite interbedded with clean coarse grained quartz sand with carbonate grains.	25 30 35	305 310 320
		Poorly sorted calcarenite (35–55 feet): deep yellow to light yellow, medium grained, friable marly calcarenite. Moderate sorting between 50–55 feet.	40 45 50 55 60	335 450 510 540 570
		Limestone (55–80 feet): deep yellow to light yellow, hard calcarenite with a travertine layer between 55–60 feet.	65 70 75 80	610 680 2,950 4,300

APPENDIX 2

BORE COMPLETION REPORT LANCELIN No. 2

Location: In a valley in sand dues 70 chains east of Tropical Traders' Jetty.

Drilled: October-November, 1963.

R.L. Ground Surface: 10.2 feet.

Water First Encountered: Approximately 9 feet.

Water Level in Completed Bore: 8 feet.

Total Depth: 150 feet.

SUMMARY OF LOG

		Strata	Water Samples	
			Depth (feet)	p.p.m./ t.d.s.
Coastal Limestone	Travertine cap	*Boulder calcarenite*, 90% (0–25 feet): light yellow to cream, friable, medium to coarse grained calcarenite with abundant small shells and shell fragments, and boulders of deep yellow to grey travertine. Marly between 10–20 feet.	15 20 25	270 280 400
	Aeolianite	*Calcarenite* 90% (25–45 feet): light yellow to deep yellow, part cemented, friable, fine to medium grained calcarenite. Fine grained calcarenite. Fine grained and marly between 35–45 feet.	30 35 40 45	445 495 495 500
	Leached beach sand	*Quartz sand* 95% (45–70 feet): light yellow to yellow, mobile, well sorted, coarse and very coarse grained quartz sand with 5–10% carbonate-quartz sand accretions. Quartz grains are colourless to stained yellow with a rounded to highly rounded smooth to matt surface and an 0·4 to 0·6 sphericity.	50 55 60 65 70	275 300 440 500 620
		Limestone 90% (70–105 feet): light yellow to yellow, soft to hard, medium grained, quartz sandy limestone.	75 80 85 90 95 100	650 660 660 660 8,220 15,000
Upper Cretaceous	Lancelin Beds	*Marl* (105–150 feet+): green-grey marl, slightly micaceous to slightly sandy, with abundance of macrofossils including *Inoceramus* sp. and brachiopods.	105 110 115	19,000 19,000 16,000

GEOLOGICAL INVESTIGATIONS AT WUNGONG BROOK UPPER DAM SITE

by

F. R. Gordon and J. D. Wyatt

ABSTRACT

An earthfill dam 170 feet high, across Wungong Brook, and situated 70 miles south of Perth, is proposed on an alternative site to one previously investigated 2 miles downstream. Detailed investigation of the area included shallow auger holes; two diamond drill holes; plane table geological mapping; geophysical seismic traverses: with electric logging and water pressure tests of the completed drill holes.

The proposed dam will be located on a weathered granite gneiss complex of residual soils with minor alluvial material close to the stream channel. Outcrops of relatively fresh, open jointed granite gneiss are scattered throughout the foundation area along the river bed and valley slopes.

Four major dolerite dykes intrude the granite gneiss, one of which reaches a maximum width of 300 feet. Minor occurrences of a basic dyke or amphibolite lens were intersected during the drilling of the two diamond drill holes, which were sited close to the river near the proposed centreline of the dam. Thirty-three auger holes were drilled on both sides of the stream channel. The depth of the zone of decomposition ranged from 3 to 25 feet.

The weathering profile of granitic rocks in the Darling Range was investigated in detail because of the variable nature of materials available for use in the construction of the earthfill dam.

In order to restrict the passage of water through the abutments and foundation area of the dam, it is recommended that a cut-off wall be constructed down to impervious clays together with a grout curtain in the jointed granite gneiss.

INTRODUCTION

As an alternative to a gravity dam structure at the lower site on Wungong Brook, which has been under study for many years, design engineers of the Metropolitan Water Supply Board have proposed an earthfill dam 170 feet high, at a site 2 miles upstream.

This proposed "upper" dam site is approximately 30 miles by road from Perth. Access is by way of the South-Western Highway to Byford and thence east for 6 miles, along formed gravel roads and forest tracks.

The area is shown in Lands Lithograph No. 341 B/40 and is covered by Canning Location Nos. 618, 387, 124, 345, 462 and 373.

The section on "Geology" was contributed by J. D. Wyatt, who mapped the area at a scale of 100 feet to an inch using plane table and telescopic alidade traverses.

TOPOGRAPHY

The topography is rugged, and short intermittently-flowing streams have incised valleys to a depth of some 250 feet into the weathered Precambrian igneous complex of the Darling Peneplain. No active downcutting is taking place at the present time.

The Wungong stream course is rarely straight, and the dominant directions appear to be controlled both by major jointing patterns, which may be sheared, and the differential erosion of the various rock types.

The valley is asymmetric in cross-section: abundant steep-sided rock usually outcrops on the northern valley slope, and deeply-weathered gently-sloping residual soils on the opposite slope. The narrower sections suitable for damming are rarely continuous for more than a few hundred feet, but open out into small, alluvium-covered flats which are subject to winter flooding. These flats may conceal appreciable thicknesses of permeable gravels and sands.

GEOLOGY

ROCK TYPES

The local rocks consist dominantly of granite gneiss which is intruded by dykes of dolerite, pegmatite, and quartz, and veinlets of epidote. A weathered and lateritised mantle of varying thickness, consisting of lateritic soils on the valley slopes and massive laterite on the hill tops, approximately 650 feet above sea level, effectively obscures the crystalline parent rock.

Granite Gneiss

The granite gneiss is a medium to fine-grained acid rock, which is weakly gneissic in surface exposures. In size and extent, the outcrops range from extensive tabular exposures to isolated boulders which may or may not be in situ. In some instances where abundant outcrop exists on the steeper hill slopes, strong vertical jointing parallel to the river has allowed rock slide to occur in the larger boulders.

Abundant outcrop occurs within the foundation area of the proposed dam, especially in the vicinity of both upstream and downstream toes.

Dolerite Dykes

At last three and possibly four major dykes intrude the granite gneiss, but none of these appears to intersect the foundation area of the proposed dam. Where contact with the granite gneiss is visible, marginal chilling is evident in these otherwise coarse-grained dykes.

The smallest dyke mapped was 65 feet wide and could be traced for almost half a mile, while the largest was apparently 300 feet wide, although its marginal contacts were obscured by soil cover. All the dykes are frequently jointed, and on weathering are reduced to small blocky fragments ranging in size from 6 to 12 inches square. By contrast the granite gneiss outcrops tend to weather to conchoidal boulders showing only incipient jointing.

The dolerites strike in directions related to one or another of the major joint sets of the area, which suggests that emplacement was influenced by jointing.

Geophysical traverses using a seismic timer along three lines parallel to the proposed centreline of the dam, reveal the presence of a subsurface ridge, which has been interpreted as a dolerite dyke (Rowston, 1963). Examination of the area which has both a thick soil and vegetation cover has shown the existence of several small dolerite-type fragments. These fragments appear to be in a zone that strikes at 045°, but this alignment could be due entirely to debris slide and soil creep down slope, as there is no evidence of a dolerite dyke intersecting a bare granite gneiss outcrop only 150 feet away and along the strike. However, occasional basic pebbles having the appearance of dolerite are found further along the hill slope at the same elevation. This supports the idea that a dolerite dyke exists, although not exposed at the surface.

A comparison of the "dolerite" fragments from the left abutment with other pieces of basic rock found on the right bank of the Wungong Brook near Area 1 (Plate 5), suggests that the suspected dyke may prove to be a basic lens within the granite, with little lateral extension. This would explain the lack of evidence of a dolerite cutting the bare granite outcrop of Area 9 (Plate 5). Unfortunately the almost continuous blanket of soil cover makes confirmation by surface mapping difficult.

Pegmatite Dykes and Quartz Veinlets

In addition to the basic dolerite, minor acid intrusives in the form of pegmatite dykes and small quartz veinlets are evident.

The pegmatitic phase of the granite, which appears in several of the exposures, is most noticeable in an outcrop at the apex of the downstream toe of the proposed dam, where one dyke 5 feet wide was recorded.

The quartz veinlets are usually very small in size, being only 1 to 2 inches in width with random orientation. In two localities, closely-spaced parallel veinlets, sometimes showing slickensiding, suggest a possible shear zone.

Laterite

The massive laterite outcrop which forms a capping over all the rocks, irrespective of type, is generally found only above the 650 foot level, although floaters and scree fragments are found on the lower slopes. This capping shows a thickness of 3 to 5 feet, reaching the maximum higher up on the valley slopes above the top water level of the proposed dam.

JOINTING

A total of 133 joints was measured during the mapping of 11 major outcrop areas (see Plate 5) and from these it was possible to prepare a composite joint rosette containing seven major joint sets, which includes 74 per cent of the readings taken.

The two most abundant joint partings, due north and N 80° E, are parallel to local river direction changes, which would suggest a joint control for part of the river course.

Minor quartz-filled shears were also noted parallel to the predominant joint parting, which is aligned due north, and as this is also a common river channel direction, control by shearing is also possible.

The joint sets have influenced the emplacement of the dolerite dykes and minor quartz epidote veinlets, as veinlets can be directly related to one or another of the main joint sets.

An examination of the rosettes prepared for each major outcrop shows that all except one are similar, the exception being Area 5 (see Plate 5) which is singularly lacking in north-trending joints and also shows a preponderance of flat-lying planes. This exposure occurs as an isolated, large boulder in a small alluvial flat, suggesting that it may not be in situ, but is instead a talus block from an outcrop further upslope.

Several prominent, relatively flat-dipping exfoliation surfaces were noted dipping towards the river on both valley slopes, the majority of which occur on the right bank. One of these showed a small water seepage. As exfoliation joints are considered the result of expansion following the removal of overlying material, they tend to be roughly parallel to the topographic surface. The significance of these extensive surfaces is that they may act as passages for water under pressure.

SUMMARY

1. Shearing is probably at a minimum with only minor slickensiding and quartz vein intrusion.

2. The major rock types exposed in outcrop are homogeneous granite gneiss and dolerite which, although strongly jointed, show little surface evidence of crush zones or major shearing.

3. The large dolerite dykes appear to be confined to the area upstream of the dam.

4. A considerable portion of the river channel in the foundation area shows fresh granite outcrop.

5. There is no evidence of any thick alluvial deposits in the section chosen for the proposed dam, although deeper alluvial zones may occur both up and downstream.

EXPLORATION

AUGER DRILLING, 1962

In 1962 a soils investigation programme was undertaken by personnel of the Metropolitan Water Supply Board. Eleven auger holes were drilled, five of which were situated on Vardi Road, a forest track on the northeast or right bank of Wungong Brook, at an elevation of about 560 feet, and the remainder were on the southwest bank on a track at about 670 feet (Plate 6). The holes on both sides of the brook were about 100 feet apart, and were symmetrically disposed about the proposed centre line. The holes were drilled by a Gemco auger drill to "solid rock" or to a depth of 50 feet, whichever was less. The drill logs and some drive samples were made available to the Geological Survey, and these have proved valuable in a preliminary assessment of the state of rock weathering.

Hole No.	Depth to Rock	Nature of Overburden
	feet	
A1	22	Laterised weathered granite gneiss, very firm.
A2	18	Weathered granite gneiss.
A3	24 (?)	Decomposed dolerite clay and boulders.
A4	5	Alluvium, scree.
A5	18	Weathered granite gneiss, very firm.

The holes on the right bank were all about 20 feet above the level of the stream bottom, and in all holes except Hole A3, rock was encountered at comparatively shallow depths, with the overburden consisting of minor alluvials and residual granitic soils. Hole A3 was drilled into a weathered dolerite dyke and is of considerable engineering interest as there are practically no surface indications of the existence of such a zone of deep weathering or the presence of a different soil type. From the log and samples, five soil horizons can be distinguished:

A Horizon: Top soil with humus.

B Horizon: Residual grey clay, compact and dense.

C Horizon: Residual grey clay with rock structure, and small boulders of dolerite. There is a high voids ratio and permeability, and a high shear strength and resistance to compression where undisturbed.

D Horizon: Firm decomposed rock.

E Horizon: Fresh dolerite.

It is not certain that the hole bottomed on solid dolerite or on a boulder in the C Horizon. The soil samples from the B and C Horizons had very poor engineering properties, and knowledge of the extent and direction of this dyke would be desirable. It would be necessary to excavate at least as deep as firm dolerite where this dyke is exposed in the foundation area. Otherwise the auger drilling results are much as expected, with granite gneiss reasonably close to the surface.

The holes on the track on the western valley slope showed depths of over 40 feet before solid rock was encountered:

Hole No.	Depth to Rock	Nature of Overburden
	feet	
A6 and A7	Over 50	Clay sequence.
A8	Over 50	Sandy clays, " easy drilling in clays."
A9	44	" Easy drilling to 20 feet, then hardens."
A10	39	" Easy drilling in reddish clays."
A11	Over 50	" Easy drilling in clays."

From the samples taken from Holes A6 and A7 and knowledge gained from other sampling programmes, an in situ detailed weathering profile has been established and this is given in Table 1. The thickness of the weathered mantle is dependent largely on the mineral character and grain size of the bedrock, deeper weathering being found in areas where micaceous bands are prominent, and bedrock highs where quartzose gneiss is present.

GEOPHYSICAL TRAVERSES

Five seismic lines were traversed with a Dynametric R117 seismic timer (Rowston, 1963). Three parallel lines, 100 feet apart were centred on the proposed centre line and extended from Vardi Road, just above Wungong Brook on the northeast bank, to the forest track on the southwest bank. These lines were tied with a traverse parallel to the river on the southwest bank, and another traverse along Vardi Road. The differentiation made on the basis of velocity groups allows room for different interpretations as to the nature and origin of "sandy clays" in particular, and this point has been investigated by further auger holes.

The most interesting feature of the seismic results was the indication of the presence of a topographic ridge in the bedrock profile. This feature appears to strike about 120° which is parallel to the stream and it is no more than 35 feet wide. The suggestion has been made that it is a resistant dolerite dyke. This may be likely because two dolerite dykes south of the foundation area have a similar strike, which is also a major joint direction. Examination has revealed dolerite rubble in two places close to the inferred position of the dyke, but there are almost no other surface indications. An explanation of almost equal merit would be that the ridge is a more quartzose band in the gneissic sequence.

DIAMOND DRILLING

The geological problems associated with this site were mainly concerned with the presence in the river bed of dolerite dykes and associated fault zones, which transect the foundation at right angles in the left bank. Two diamond drill holes were proposed to resolve these questions as far as possible, and further auger drilling was programmed to supplement this work (Plate 6).

Diamond Drill Hole No. 1 was sited upstream of the proposed centre line on the left bank, at a depressed angle of 40° and a bearing of 004°M. It was laid out to cross under the stream bed at right angles. This would explore the possibility of river channel control by faulting or major jointing, and investigate the suspected presence of a dolerite dyke striking across the river from Gemco Hole A3. The second diamond drill hole was located close to No. 1, but was drilled in the opposite direction into the left abutment, in order to investigate the bedrock ridge suggested by the seismic timer traverses. The drilling was done by the Mines Department Drilling Section using a Mindrill A2000 machine.

Diamond Drill Hole No. 1 was drilled to 150 feet 6 inches in 9 days; it encountered 32 feet of silty clay overburden above 21 feet of highly jointed dolerite. Broken granite gneiss close to the dolerite contact was succeeded by a quartzose granite gneiss with a well developed joint system. There were three zones of core loss. One foot 3 inches was lost at 51 feet 3 inches hole depth at the dolerite-gneiss contact which was probably faulted; 9 inches of loss occurred between 60 and

61 feet, probably due to major joint intersections in a broken zone; and 6 inches of core was not recovered at 131 feet hole depth in a very coarse-grained quartz vein.

Diamond Drill Hole No. 2 was drilled at a depressed angle of 30°, and the target depth of 80 feet was reached in 4 days with 2 shifts operating. About 16 feet of weathered granitic soil was encountered, and the solid rock proved to be mainly pegmatite and quartzose granite gneiss. Following a zone of breakage at 62 feet, a core loss of 1½ feet coincided with a zone of complete loss of drilling water, and this probably indicates the presence of a shear zone. A band of dark green amphibolite schist about 4 feet across was intersected below the shear zone, followed by the granite sequence with pegmatite bands.

The shear zone and amphibolite schist were intersected near the position which had been anticipated for the ridge-forming rock from the geophysical traverses, but this material would undoubtedly be more easily weathered than the enclosing granite gneiss so the hole failed to resolve this problem.

ELECTRIC LOGGING

D.D.H.s 1 and 2 were electrically logged by D. L. Rowston with the Geological Survey's Widco well logger. Single point resistivity and self potential logs were recorded. In each case the correlation with the geological log was good, and furthermore, some features of the log were obviously diagnostic of open major joints as revealed by water pressure testing. As this was the first occasion in Western Australia that electrical logging had been used on engineering drilling exploration, the clarity of the results was encouraging. The major application of logging would be in areas of high core loss, and for this reason the indications of shearing shown in the relevant section of D.D.H. 2 was helpful in the final assessment of subsurface conditions.

The following correlations are tentative only and may be modified by further experience:

(1) Sharp, high point resistivity peak with sharp positive self potential peak is equated with zones of high water loss in open joints.

(2) Sharp negative self potential peak and sharp minimum point resistivity peak occurs in shear zones with schist filling.

(3) Minor negative facing peak in self potential and minor low facing point resistivity is correlated with pegmatite and quartz veins in granite gneiss.

(4) Granite gneiss has a positive self potential and high point resistivity as compared with dolerite.

WATER PRESSURE TESTING

The two diamond drill holes were tested for water leakage by engineers of the Metropolitan Water Supply Board. There were four zones of leakage in D.D.H. 1. The first was between 77 and 81½ feet hole depth, corresponding to a zone of breakage noted in the core, where five joints dipping between 65 degrees and 75 degrees show slaty faces and some slickensides. The main joint is open 1/10 inch, and is uneven and partly filled. The second was between 87 and 90 feet, where the water loss probably correlates with a group of three clay-faced joints that dip between 30 degrees and 45 degrees. The third was the main zone of water leakage between 106 and 109½ feet, where a system of four open joints between 106 feet and 107 feet is probably the reason. Openings of 1/5th to 1/10th inch show in the parallel joints that dip at 70 degrees to the core. Resolution of this plane with reference to foliation indicates joints striking due north and dipping at 45 degrees. The fourth, a further zone of water loss at 120½ to 123½ feet, is attributed to a zone of breakage associated with a 1 foot wide coarse-grained quartz vein.

The most surprising aspect of the water pressure tests in D.D.H. 1 was the fact that no significant water losses were recorded from the zone of heavy breakage between 32 and 62 feet. Most of the intensely jointed dolerite dyke between 32 and 50 feet was cased during drilling; the zone of core loss at the contact between dolerite and gneiss, and a sheared section that corresponded to a zone of drilling water loss, showed every indication of allowing water movement.

In D.D.H. 2 the fact that no significant water losses were recorded is surprising, as core loss, non-return of drilling water, and a shear zone on the electric logs, were recorded for the zone between 60 and 65 feet.

AUGER DRILLING 1964

The picture of the site gained from the initial investigations was general rather than complete, but the main problems were apparent. The right abutment had not been explored at all apart from the rather negative evidence gained from adjacent granite gneiss outcrops. On the lower slopes of this abutment and in the river bed, the presence of a dolerite dyke or dykes had been proved by auger hole A3 and D.D.H. 1, but the directions, width and full depth of weathering was not known with certainty. On the left side of the valley, the composition of the ridge which was shown on seismic traverses was not determined by diamond drilling, and it was possible this feature resulted from the presence of a dolerite dyke. The engineering significance of dolerite dykes is the fact that one or both of the margins is often faulted, and therefore broken and weathered, constituting a leakage path if cutting the earth dam.

A further Gemco auger drilling programme of 21 holes was devised in order to fill in the gaps in the knowledge of foundation conditions, and the results may be summarised:

(1) The bedrock ridge defined by seismic survey was proved to be a quartzose band in the granite gneiss (Holes B16, B17, and B18).

(2) The dolerite dyke originally intersected by Hole A3 on the right bank was approximately 40 feet wide. On the left bank definite intersections were made with dolerite in D.D.H. 1 and Hole B11.

(3) Palynological examination by H. S. Edgell (pers. comm.) of spores from samples from Holes B9 and B11 confirmed the samples as alluvials. The samples from above bedrock from Hole B11 showed dolerite but no in situ samples were recovered from the lower part of Hole B9. Alluvials were found above bedrock in Hole B13, in Hole B20 and in the upper part of Hole B12.

EMBANKMENT MATERIALS

The soils resulting from the in situ decomposition of granite gneiss vary widely in properties according to the depth of weathering and to the nature of the original rock. At the ground surface, a fairly uniform laterite residual shows few characteristics of the underlying rocks and the differences due to changes in rock types becomes more apparent at depth. The weathering profile is shown in detail in Table 1, and it is apparent that in an area where there is 60 feet of weathered material above bedrock a great variety of soil types with their own characteristic properties is present. This means that different combinations of soils may be incorporated into an enbankment, but it also means that field control of excavation and mixing must be efficient.

The three main soil types are:

(i) laterite, gravels and clays up to 8 feet thick

(ii) gibbsite-kaolin clays up to 20 feet thick

(iii) residual quartz and mica-quartz phases, up to 20 feet thick.

Table 1

WEATHERING PROFILE OF GRANITIC ROCKS, DARLING RANGE

Geological Material	Definition	Engineering Properties	General Classification
Slopewash, sand, soil	Clayey, silty or sandy soil with no rock texture, the surface layer often containing roots and humus	Undesirable as foundation or borrow material	Soil
Pisolitic laterite	Spherical ironstone pebbles lightly cemented together with a lighter coloured earthy matrix	Permeable. Excellent source of borrow material	
Massive laterite	Strongly cemented ironstone, massive and concretionary	Permeable. If too strongly cemented, may be unsuited as borrow material	Laterite
Laterite-gibbsite	Yellow silty clay, minor laterite nodules	Permeable. Good borrow material	
Kaolin clay phase	Complete decomposition of granite by in situ weathering. Micas absent, feldspars decomposed to clays, some residual quartz grains	Impermeable. Clay type borrow material	
Ferruginated zone	Zone of fluctuation of groundwater level. Iron deposition may form a 'hard pan'	Permeable. Reasonable type of borrow material	Highly weathered granite
Quartz residual phase	Largely consists of quartz grains and some decomposed feldspars. Disintegrates into a mass of clayey sand when immersed in water	Permeable. Sandy type of borrow material	
Mica-quartz residual phase	Found above schistose rocks, amphibolites or micaceous banded gneiss. Micas are slightly weathered and form about 50% of the rock	Permeable. Undesirable as borrow or foundation material	
Moderately weathered granite gneiss	All the mineral components are present but are considerably altered. Strength is such that pieces of NX core cannot be broken in the hands	Largely impermeable. Difficult to excavate readily	Moderately weathered granite
Slightly weathered granite gneiss	Granite distinctly weathered throughout the fabric of the rock as shown by slight limonite staining	Impermeable, water movement in some joints. Unsuited as borrow or rock-fill material	Slightly weathered granite
Fresh granite gneiss with limonite stained joints	Joint faces coated or stained with limonite, but the rock between is unweathered	Leakage through joints. Suitable as rock-fill material	Fresh granite, stained joints
Fresh granite gneiss	Unweathered granite. Possible joint coatings include chlorite, calcite, pyrites and clay	Leakage in joints. Suitable as rock-fill material	Fresh granite

As these may be regarded as layers largely parallel to the present land surface, they can be excavated either selectively and placed in different zones of the dam or excavated together and blended into a single material with intermediate properties. If the latter method is adopted then excavation of the borrow by means of inclined slices, or working borrow pits at different levels, will be necessary.

The only undesirable material of the laterite sequence is the cemented massive laterite that may be difficult to reduce to an acceptable size. The thickest development and strongest cementation of the laterite occurs on the valley slopes at the edge of the residual cover. In other words a borrow pit should not be sited on a valley slope but rather in the flatter interfluves or plateaux where the massive laterite layer is thin or even absent.

As well as the considerable vertical variations that exist in the soil types and their properties, the changing mineral character of the granite gneiss complex imposes differences in a lateral direction. The residual soils developed from a highly schistose or micaceous parent rock are of particular significance, as they are undesirable in every engineering aspect when in the mica-quartz residual phase (Table 1). These soils should not be used in embankment construction because they are usually semi pervious, often partially saturated, and of low cohesion caused by lubricated mica flakes.

SITE APPRAISAL

BEARING QUALITY OF THE FOUNDATION

The relatively narrow, asymmetric valley of Wungong Brook at the upper site is characteristic of river valleys in the Darling Range: the north-eastern bank shows the effects of physical weathering (exfoliation sheets) while the south-western bank is mantled with a residual soil sequence resulting from the chemical weathering of a gneissic complex. There has been some alluviation of the valley, but there is little active erosion or deposition at present because of the underfit nature of Wungong Brook.

The major complication of the site appears to be the presence of a deeply weathered dolerite dyke on the right bank and crossing the stream bed. This dyke is of importance as the cut off trench will have to be upstream at all locations to avoid differential settlement of the clay core. Furthermore the strike of the dyke through the foundation area is of interest as one margin may be faulted. If this feature transects the foundation, deep excavation will be necessary to prevent leakage.

PERMEABILITY CHARACTERISTICS

In the residual soil profiles that are developed on granitic rocks in the Darling Range there are two permeable zones. Close to present ground surface the saprolite (laterite) sequence often retains a quantity of water from rainfall and run-off. Deeper percolation is hindered by the underlying kaolin clay.

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Water movement is also possible beneath the kaolin clay layer, which forms the upper boundary of the fluctuating water table, with the top limits marked by a zone of deposition of iron minerals (Table 1). The completely weathered granite gneiss residual that forms the aquifer is mostly composed of quartz grains of sand size with minor kaolin and partly weathered feldspar minerals. Biotite, hornblende and feldspar have been largely broken down and removed by chemical and physical forces.

These two zones, which are usually separated by more than 20 feet of relatively impermeable clay, have considerable engineering signifiance for the construction of a dam at the Wungong Brook upper site. It is considered essential that the rolled earth core on either abutment should be founded below the laterite zones, in impermeable kaolin clay. On the lower valley slopes where the weathering sequence is less than 20 feet thick, the core zone should be founded on slightly weathered granite gneiss, below the clay and quartz residual zones.

In the relatively unweathered granite gneiss and dolerite rocks that will form the foundation in the valley bottom, water movement will be mainly controlled by a few major openings. This is because the rocks are impermeable and many of the joints are discontinuous, as shown by comparing the geological logs with the water pressure test results. This means that the stop grouting method, using a packer to isolate areas showing imperfections disclosed during drilling, would be advantageous, as the mix and pressure best adapted for connecting the particular fracture can be employed in each case. However, the possible presence in D.D.H. 1 of fractures that would allow the grout to bypass the packer means that the stop grouting method may not be completely effective. If the stage method was used the seams and joint filling materials in the weathered zone of the rock may not be sufficiently cleaned by pressure washing to provide a good grout bond, and the grout would break back through previously sealed seams. There would then be no certainty that the lower zones were subjected to full pressures. Accordingly a combination of the two methods may be most effective. This would include grouting to the full depth of the first zone by stage grouting methods, then cleaning the hole and drilling the first stage of the second zone, and grouting this stage with an expandable packer. When refusal is reached the packer is removed and a grout connection made to the grout nipple set as the surface of the core trench. This procedure, first employed at Folsom Dam, overcomes the problem of surface leakage, and allows full pressure to be applied at any depth.

RESERVOIR PERMEABILITY

Because of the confinement of the reservoir in the lower part of a deep valley, the place where leakage is most likely to occur is through the foundation area of the dam. Major joint systems, in particular exfoliation joints, and the sheared margins of dolerite or amphibolite 'dykes' are possible leakage channels. A grout curtain drilled from the floor of the core trench will be necessary to prevent water movement. It is recommended that on the northern valley slopes the grout holes should be drilled at right angles to the ground surface in order to intersect the exfoliation joints at minimum depth.

CONCLUSIONS

1. The final stage of investigation will involve the drilling of auger holes about 50 feet apart, along the cut-off line from one side of the valley to the other. This will complete the feasibility stage of exploration.

2. Adequate foundation for an earthfill dam should be readily obtainable at the upper site. The complications caused by the presence of dolerite dykes striking across Wungong Brook in the vicinity of the trial line and along the left bank can be overcome by shifting the cut-off wall upstream to clear the cross channel dyke.

3. All the older and recent alluvials in the valley bottom will need to be removed to allow a satisfactory cut-off to be obtained, and on the valley slopes the core trench should be taken down below any signs of lateritization.

4. A grouting programme should be designed to intersect a few water-bearing fractures of large capacity; it is recommended that a combination of stop and stage grouting methods should be employed, with the holes on both abutments directed at right angles to the ground surface.

5. Adequate supplies of borrow material are available in the immediate vicinity of the dam site. Care will be necessary in excavation of the borrow pits to ensure adequate mixing of the various types of weathered material making up the soil profile.

REFERENCE

Rowston, D. L., 1963, Wungong Brook upper dam site, geophysical investigations: West. Australia Geol. Survey Rec. 1963/16 (unpublished).

GEOLOGICAL INVESTIGATIONS AT THE ORD RIVER MAIN DAM SITE No. 2 IN 1964

By

F. R. Gordon

ABSTRACT

The most economic and sound engineering solution for a dam type at the Ord River Main Dam Site No. 2 is a rockfill dam, located about 250 feet downstream of the site of the concrete gravity dam, previously investigated in detail. The geological setting of the site was established by a special study of regional geology and tectonics. Detailed geological mapping of the site was basic to the investigations, and exploration consisted of five diamond drill holes, dozer costeans, hand trenches and auger drilling in the river bed.

In the foundation area the bedrock topography and the distribution of rock types, especially the location of a tectonically disturbed contact between quartzite and phyllite, was of critical importance to design work. Detailed information was also obtained from diamond drilling on joints, faults and permeability. The structure of the spillway area was established by mapping supplemented by drilling and trenching, thus allowing maximum stability to be achieved in shape and position.

The information obtained in 1964 completed the design stage of investigation.

INTRODUCTION

Three types of dam were considered possible at the No. 2 Dam Site on the Ord River:

(1) A rockfill embankment with a clay core and a saddle spillway.

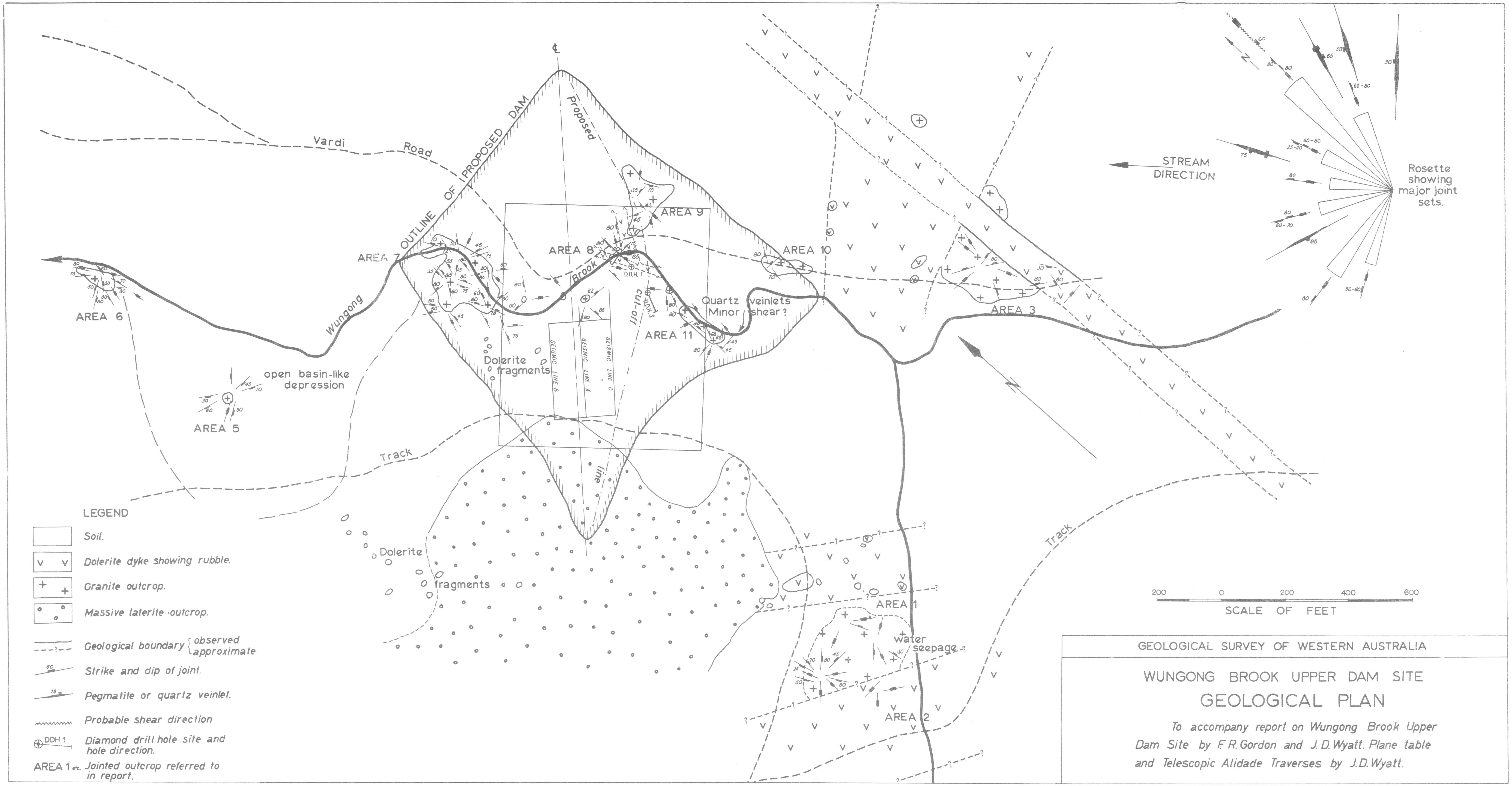
(2) A solid concrete gravity dam with a central ogee spillway.

(3) A hollow gravity dam.

Detailed engineering analysis has indicated that the most economical solution is a rockfill dam, 220 feet above lowest foundation, with a channel spillway 200 feet deep by 450 feet wide. Equally important, the serious problem of stability of the quartzite rock cap on the left abutment (Gordon, 1962) is lessened with a rockfill dam, as the clay core can be located downstream on phyllite underlying the quartzite capping (Lewis and Webster, 1964).

The final basis of investigation for feasibility of the structure concerned a rockfill dam with a centreline located 250 feet downstream of the centreline of the gravity dam investigated in considerable detail in 1961-63.

The change of location meant that further detailed geological mapping was necessary. Also, it was considered that subdivision of the quartzite succession would greatly assist analysis and design of a proposed underground power station. The entire area of the dam site was mapped by plane



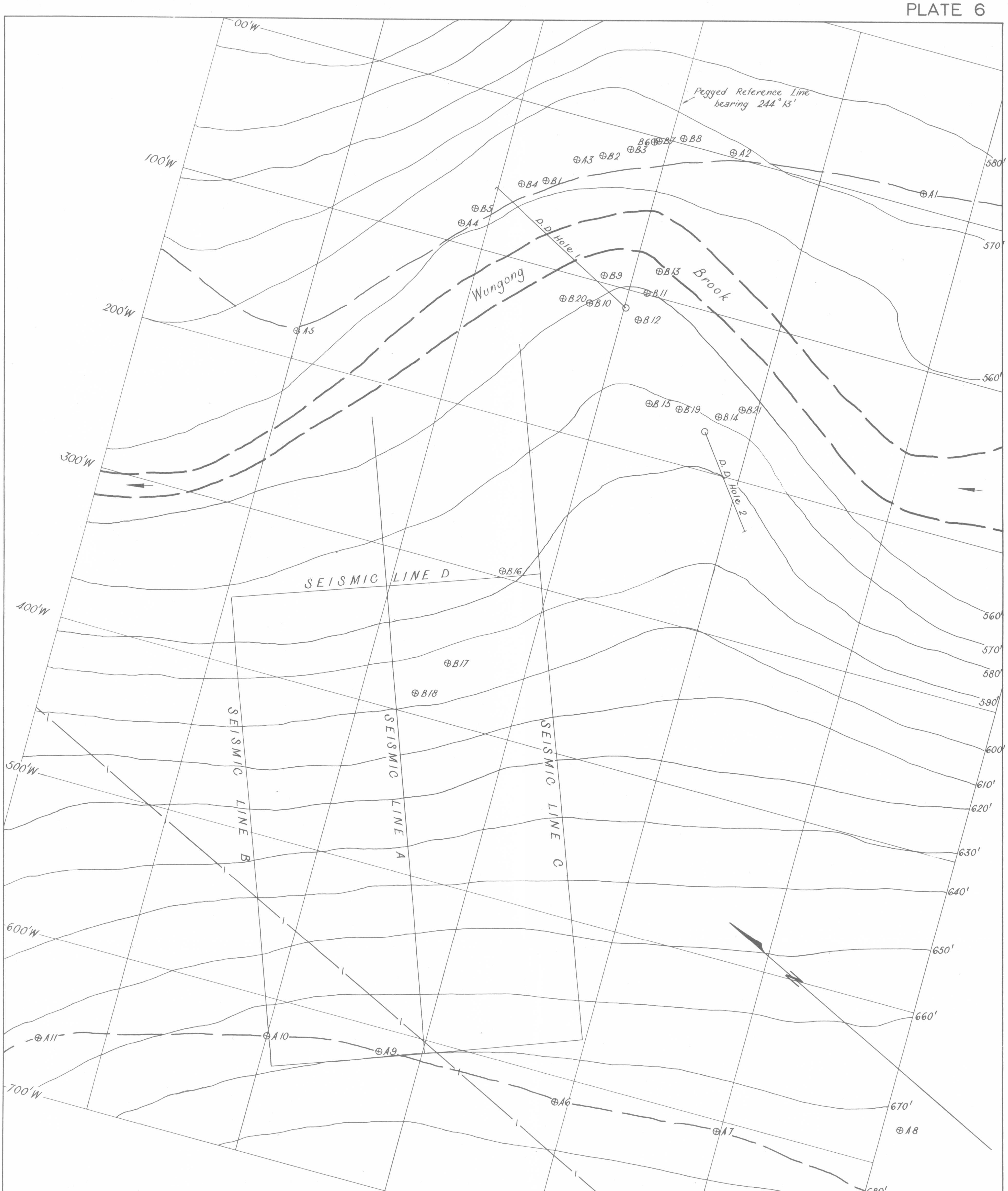
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

WUNGONG BROOK UPPER DAM SITE

GEOLOGICAL PLAN

To accompany report on Wungong Brook Upper Dam Site by F.R.Gordon and J.D.Wyatt. Plane table and Telescopic Alidade Traverses by J.D.Wyatt.

8379



REFERENCE

—/—/—	FENCE
○ D.D. hole 2	DIAMOND DRILL HOLE, INCLINED
⊕ A2	AUGER HOLES (1962)
⊕ B10	AUGER HOLES (1964)
— — — —	TRACKS

FEET 50 40 30 20 10 0 50 100 150 200 FEET

SCALE

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

WUNGONG BROOK UPPER DAM SITE

TOPOGRAPHY AND SITE EXPLORATION

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table and telescopic alidade traverses at a scale of 50 feet to an inch by J. D. Wyatt in the period May to August 1964 (Wyatt, 1965).

Although a geological setting to the scheme was available from the work of the joint Bureau of Mineral Resources/West Australian Geological Survey party on the Mt. Brooking 1-mile Sheet in 1963, a more detailed picture of the area surrounding the dam site was needed for the interpretation and evaluation of the tectonic features studied in close detail on the site. Accordingly in October 1964, R. C. Horwitz mapped the geology and tectonic features of an area of approximately six square miles centred on the main dam site (Horwitz, 1964).

Prior to 1964, 27 diamond drill holes and two adits had been used to obtain foundation data, but very little information was available from this exploration concerning the foundation area of the rockfill dam and the structure of the spillway channel. The investigations done in 1964 included three diamond drill holes in the river bed and two drill holes in the spillway area, along with dozer costeans and hand trenches in the same area (Plate 7). Shingle supplies in the river channel upstream of the dam site and core material in the flat, upstream of the dam site (Coolibah Pocket) were explored with dozer cuts. Supervision of the diamond drilling and allied investigations was provided by E. E. Swarbrick in the period August to November 1964 (Swarbrick, 1965 b).

DETAILED GEOLOGY

The geology of dam site area was mapped by J. D. Wyatt at a scale of 50 feet to an inch, and part of this work at a reduced scale is shown in Plate 7. A stratigraphic column showing the individual beds defined in the phyllite quartzite succession by Wyatt (1965) is given in Table 1. This division into beds of similar lithologic properties is artificial in that the rocks in the area belong to one cycle of deposition; boundaries are therefore not always clearly recognisable, and lateral and vertical variations in rock type occur. However, in the restricted area of the dam site, this division has allowed a more precise appreciation of the engineering properties of the rocks as applied to the various structures.

The basal beds of the cyclothem are an orthoquartzite with minor pebble horizons grading upwards into a sequence of variably bedded sandstone with minor siltstone layers. These pass transitionally into predominantly silty sandstone and then into siltstone beds with occasional sandy lenses. Metamorphism of these beds has produced the phyllitic quartzite sequence, as exposed on the northern abutment.

Table 1

STRATIGRAPHIC COLUMN—ORD RIVER MAIN DAM SITE No. 2

Age	Stratigraphy	Description	Thickness	Informal Name
QUATERNARY		Recent deposits of silt, sand and shingle. Poorly sorted, bedded, lenticular	feet Approx. 60	Alluvium
		Recent soil and talus material	10	Scree
UPPER PROTEROZOIC	LISSADELL FORMATION	Siltstone-sandstone sequence, fine-grained, grey to red-brown, thin-bedded, flaggy. Restricted mainly to the eastern side of Blind Gully Fault. Not studied in detail	Over 1,000	Coolibah Quartzite
		Silty sandstone, fine to medium-grained, red-brown thin-bedded. High silt-size content	150 to 180	Spillway Quartzite
		Sandstone with minor silty partings. Alternating thick and thin beds of sandstone with fine siltstone interbeds. Medium-grained, red-brown to grey. Beds generally thicker than underlying member	80 to 120	Hilltop Quartzite
		Sandstone with common thin-bedded silty sandstone beds. Fine to medium-grained, white to beige	90 to 105	Scree Slope Quartzite
		Sandstone with minor pebble bed horizons. Medium to coarse-grained, well-bedded, red to pink-brown. Altered to softer sandstone in upper section	100 to 120	Pebble Bed Quartzite
		Orthoquartzite, massive, medium to coarse-grained, white to fawn. Lateral transition into Pebble Bed Quartzite noted in some left abutment outcrops	50 to 260	Right Abutment Quartzite
	GOLDEN GATE SILTSTONE	Siltstone, thinly-bedded, fine-grained, red-brown to grey-green. Contains minor sand lenses. Outcrop form varies on either side of the Ord River	Over 250	Spillway Phyllite

Three major faults with throws in excess of 100 feet were recorded during the detailed mapping of the site:

1. *The Blind Gully Fault* is an arcuate, normal fault, with an apparent vertical throw of 1,000 feet maximum, east side down on a trend of 015°. It is arcuate because of later folding in places. No engineering structures are directly affected by this feature.

2. *The Spillway Fault* strikes about easterly and dips normally at 45° to the south. A throw of some 700 feet, south block down, has been measured. This fault strikes approximately along the centre line of the spillway channel at floor level, and is of dominant structural importancec.

3. *The Power Station Fault* has been postulated by J. D. Wyatt as having a vertical displacement of about 100 feet; it strikes easterly, with

a normal movement, and dips at 82° to the north. An alternative suggestion (Swarbrick, 1965b) that this is, in fact, a wrench fault, appears to offer a simpler explanation.

Numerous faults of small magnitude have resulted in considerable modifications to the topography of the dam site.

EXPLORATION

Two diamond drill holes were drilled in the river bed in order to close the gap left by previous investigations in the lowest part of the floor. In addition the holes were designed to determine the trend of the phyllite—quartzite contact, and to give an idea of the thickness of quartzite below the river bed. These objectives were achieved with D.D.H.s 28 and 29, and some implications of the drilling results are discussed separately in this Annual Report (Swarbrick, 1965b).

Jetting which failed to penetrate gravel layers, was followed by extensive drilling with a Gemco auger drill in the foundation area of the dam; this resulted in a complete modification of ideas on the depth of alluvium in the river bed and the configuration of bedrock. Depths of as much as 96 feet to solid rock were recorded, and even these figures may be increased if boulders are present, as is quite likely, in the deeper troughs. Plunge pool erosion in phyllite immediately downstream of a bar of massive quartzite is suggested to account for the abrupt changes in bedrock topography.

D.D.H. 33M was positioned near the centre of the proposed outdoor power station, and was drilled at a depression of 33° in an upstream direction to test the foundation rock and to determine the position and nature of the Power Station Fault zone. The power station will be founded on well laminated and bedded, red-brown and pink quartzite and sandstone with beds of hard blue quartzite. The rock is considerably broken by shears, minor crush zones, and open cavities, and a programme of consolidation grouting will be essential to prevent foundation settlement. Intersections with the Power Station Fault and probably with Fault No. 13 were obtained, and the nature of the brecciated zone in each case as well as the succession of rock types suggest that these faults are transcurrent. This reassessment of the Power Station Fault, previously considered normal, is of significance to the structural picture of the river bed.

Water pressure tests were carried out in all three river bed holes, using a Treifus packer. Tests were carried out at 10-foot intervals during drilling. Considerable and consistent water losses showed that the Right Abutment Quartzite contains numerous open fractures, and that an extensive grouting programme would be necessary to prevent seepage.

The production of a detailed geological map of the spillway area, especially the localization and estimation of dip of the Spillway Fault, allowed the placement of diamond drill holes in positions of maximum effectiveness. D.D.H. 32M was collared in Costean No. 2, and was designed to intersect the Spillway Fault close to spillway floor level. Micaceous flaggy siltstone with fine-grained muddy sandstone and minor pale green shale of the Spillway Quartzite were encountered down to 164 feet hole depth, and below the probable intersection of the Spillway Fault, dark grey-green to black mudstone and siltstone of the Spillway Phyllite were cored to the completion of the hole.

The second spillway hole (31M) which was drilled from the saddle, was located to make a shallow intersection with the Spillway Fault and to assess the physical condition of the rock in the spillway cutting. Intersection with the Spillway Fault and Fault No. 2 allowed a clear picture of the stability of the north side of the spillway.

Three dozer costeans were cut in the spillway area, and further hand trenching was carried out to extend these and to aid the mapping of geological boundaries.

The concentration of work in the spillway channel area was necessary because of the lack of results obtained from the earlier drilling (Holes 9M, 16M, 17M, 27M). The present concept of the spillway structure is of beds dipping to the north at about 20 degrees with a normal fault displacement of about 700 feet, south block down, on the Spillway Fault. Block gliding in the Right Abutment Quartzite in a southerly direction has meant displacement of the upper portions of the fault.

CONCLUSIONS

Because of a change in the location and type of dam, the extensive drilling investigations of previous years were not of direct relevance to the present proposed rockfill dam.

Detailed geologic mapping, set within a defined regional framework of geology and tectonics, was of value in locating the drill holes of a limited drilling programme.

Previous concepts concerning the topography of the river bed were considerably revised after the use of a Gemco drill in place of water jetting. The accurate definition of the shape and nature of the river bed will not be known however until alluvium has been removed during construction. The contact between massive quartzite and phyllite, which in places is marked by mechanical breakdown of the phyllite, is of importance in the foundation area of the dam. The unconformable contact has been studied in some detail and is explained by the mechanism of gravitational gliding (Swarbrick, 1965a).

Water pressure testing of the diamond drill holes in the river bed has confirmed previous ideas as to the need for a full grouting programme.

The exploration of the spillway channel has produced a rational picture that previously was lacking, and will allow the spillway to be positioned in a setting of maximum stability.

The 1964 investigations have completed the feasibility stage and much of the design stage of exploration. If the scheme is not proceeded with, it will not be for lack of foundation data.

REFERENCES

Gordon, F. R., 1963, Engineering geology of the Ord River main dam site No. 2, Kimberley Division: West. Australia Geol. Survey Ann. Report. 1962.

Gordon, F. R., 1964, Ord River main dam site No. 2, rockfill dam proposal, investigations 1963: West. Australia Geol. Survey Rec. 1964/4 (unpublished).

Horwitz, R. C., 1964, The geology of the region surrounding the Ord River main dam site, Western Australia; West. Australia Geol. Survey Rec. 1964/18 (unpublished).

Lewis, J. G. and Webster, K. C., 1964, Report of engineering investigations, Ord irrigation project: Public Works Department, West. Australia (unpublished).

Swarbrick, E. E., 1965a, Gravitational gliding tectonics at the Ord River main dam site No. 2: West. Australa Geol. Survey Ann. Rept. 1964.

Swarbrick, E. E., 1965b, Ord River main dam site No. 2, drilling programme 1964, completion report: West. Australia Geol. Survey Rec. 1965/7 (unpublished).

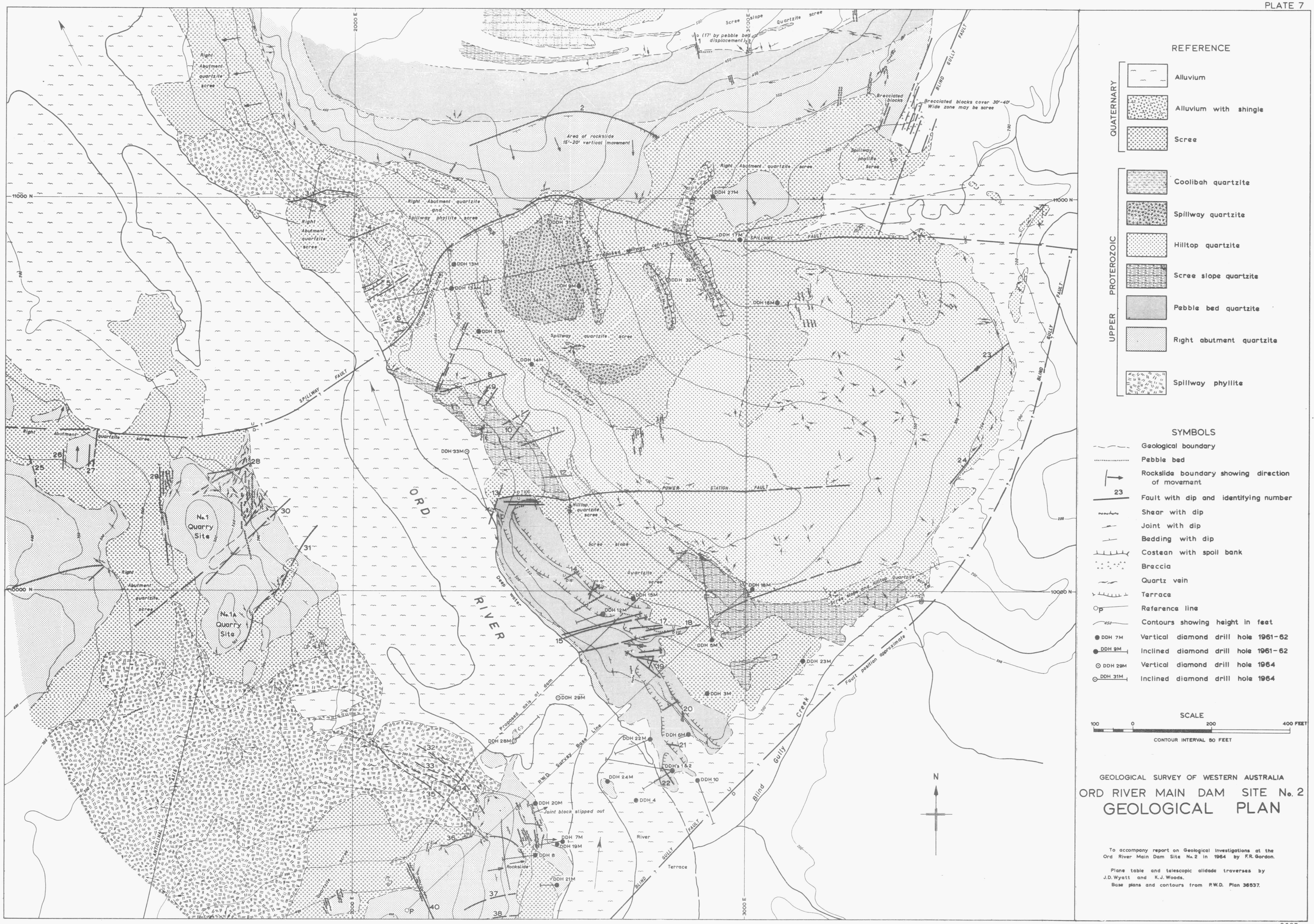
Wyatt, J. D., 1965, Ord River main dam site No. 2, detailed geology: West. Australia Geol. Survey Rec. 1965/5 (unpublished).

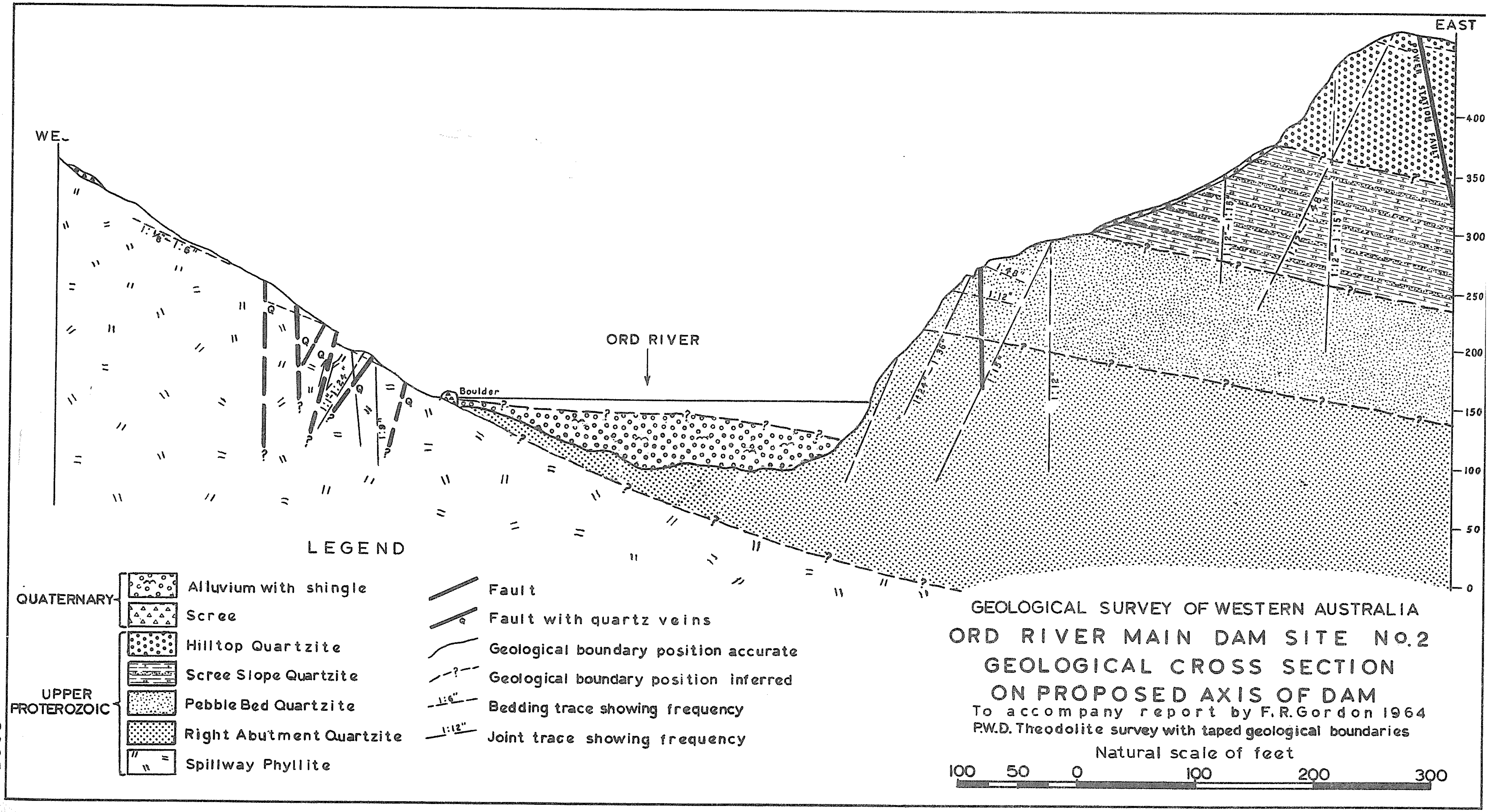
GRAVITATIONAL GLIDING TECTONICS AT THE ORD RIVER MAIN DAM SITE No. 2

by E. E. Swarbrick

ABSTRACT

Gravitational gliding in Proterozoic sediments is suggested to explain certain structures in the area of the Ord River Main Dam Site No. 2. Evidence is presented which supports a theory that movement has occurred between a thick quartzite sequence and a mudstone—siltstone succession. Considerable movement within the quartzite is also demonstrated. The origin of the movement is believed to lie in normal fault movement and differential erosion, in association with major wrench faulting.


REFERENCE
QUATERNARY
Alluvium
Alluvium with shingle
Scree
UPPER PROTEROZOIC
Coolibah quartzite
Spillway quartzite
Hilltop quartzite
Scree slope quartzite
Pebble bed quartzite
Right abutment quartzite
Spillway phyllite
SYMBOLS
Geological boundary
Pebble bed
Rockslide boundary showing direction of movement
Fault with dip and identifying number
Shear with dip
Joint with dip
Bedding with dip
Costean with spoil bank
Breccia
Quartz vein
Terrace
Reference line
Contours showing height in feet
Vertical diamond drill hole 1961-62
Inclined diamond drill hole 1961-62
Vertical diamond drill hole 1964
Inclined diamond drill hole 1964
SCALE
100 0 200 400 FEET
CONTOUR INTERVAL 50 FEET
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
ORD RIVER MAIN DAM SITE No. 2
GEOLOGICAL PLAN
To accompany report on Geological Investigations at the Ord River Main Dam Site No. 2 in 1964 by F.R. Gordon.
Plane table and telescopic alidade traverses by J.D. Wyatt and K.J. Woods.
Base plans and contours from P.W.D. Plan 36537.
N
ORD RIVER
SPILLWAY FAULT
POWER STATION FAULT
BLIND GULLY FAULT
Blind Gully Creek
Proposed spillway centre line
Proposed axis of dam
P.W.D. Survey Base Line
No. 1 Quarry Site
No. 1A Quarry Site
Area of rocksilde 15'-20' vertical movement
Brecciated blocks cover 30'-40' Wide zone may be scree
Deep water
Joint block slipped out
Rockslide
River Terrace
Fault position approximate
11000 N
10000 N
2000 E
3000 E


WEST
EAST
ORD RIVER
Boulder
POWER STATION FAULT
400
350
300
250
200
150
100
50
0
LEGEND
QUATERNARY
Alluvium with shingle
Scree
UPPER PROTEROZOIC
Hilltop Quartzite
Scree Slope Quartzite
Pebble Bed Quartzite
Right Abutment Quartzite
Spillway Phyllite
Fault
Fault with quartz veins
Geological boundary position accurate
Geological boundary position inferred
Bedding trace showing frequency
Joint trace showing frequency
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
ORD RIVER MAIN DAM SITE No.2
GEOLOGICAL CROSS SECTION
ON PROPOSED AXIS OF DAM
To accompany report by F.R.Gordon 1964
P.W.D. Theodolite survey with taped geological boundaries
Natural scale of feet
100 50 0 100 200 300

8285

INTRODUCTION

The information presented in this report represents part of the work carried out during geological investigations at the Ord River Main Dam Site No. 2 in 1964. Further details of the geology are given by Wyatt (1965).

The dam site lies 30 miles upstream from the township of Kununurra and approximately 10 miles west of the junction of the main roads from Darwin and Nicholson Station to Kununurra. The surrounding area is one of variable relief, with fairly deep gorges downstream from the dam site and high level alluvial plains upstream.

In the dam site area Proterozoic sediments overlie quartz porphyries of the Whitewater Volcanics and porphyritic granite of the Lamboo Complex (Dunnett and Plumb, 1964). The Proterozoic sequence is given below:

Dunnett and Plumb (1964)	*Wyatt (1965)*
Lissadell Formation	Coolibah Quartzite Spillway Quartzite Hilltop Quartzite Scree Slope Quartzite Pebble Bed Quartzite Right Abutment Quartzite
minor unconformity	
Golden Gate Siltstone	Spillway Phyllite*

Subdivisions of part of the Lissadell Formation erected by Wyatt (1965) are not formal names. The sequence has been subdivided on a lithological basis for the purposes only of the work on the dam site. The names have been capitalised to avoid confusion with various features of the dam site which have similar names.

The Right Abutment Quartzite is a massive orthoquartzite up to 250 feet thick. Succeeding quartzite units have an increasing proportion of fine-grained material, and show a general tendency towards fine grain and thin bedding. Between the Right Abutment Quartzite and the Spillway Phyllite there is a minor unconformity which probably originated as a hiatus in sedimentation, but has since been complicated by gliding movement.

Structurally the area around the dam site is fairly simple. Folding is minor and is not considered pertinent to the subject of this report. There is a general dip to the northeast. Faulting is extensively developed, characteristically of a generally competent succession, and shows both normal and wrench movement. A tectonic map of the area is given in Plate 9.

Two major faults dominate the structural pattern of the area. The Blind Gully Fault (Plate 9) trends north-northeast along the eastern edge of the area and has a maximum displacement down to the east of 1,000 feet. This is considered to be the oldest fault in the area and is parallel to an ancient major lineament (the Halls Creek Mobile Zone) which occurs 4 to 5 miles to the east. Cutting and displacing the Blind Gully Fault is the Spillway Fault which trends east-northeast. This also is a normal fault with a maximum throw down to the south of 800 feet, although as will be shown later, it was initially a major wrench fault. Numerous other faults are present but are not considered relevant to the particular subject under discussion (see Plate 7).

GRAVITATIONAL GLIDING OF THE LISSADELL FORMATION

Evidence will be brought to indicate that the nature of the Right Abutment Quartzite/Spillway Phyllite interface should be considered in terms of what De Sitter (1956) calls "Gravitational Gliding Tectonics." Bedding plane slip is a commonly observed phenomenon in most layered sequences which are folded or tilted. There is considerable evidence however, to suggest that between the Spillway Phyllite and Right Abutment Quartzite, and also between different units of the Right Abutment Quartzite, there has been gravity-induced movement totalling hundreds of feet.

EVIDENCE OF MOVEMENT

The various points of evidence are grouped by occurrence within a particular structure or stratigraphical unit (Spillway Phyllite, Blind Gully Fault Zone, etc.). For ease of reference to locality of occurrence the various points are numbered consecutively with small Roman numerals irrespective of groupings. Corresponding numerals are shown in the appropriate locality on Plate 9.

Structural Features of the Quartzite/Phyllite Interface

North of the Spillway Fault the quartzite/phyllite interface dips approximately east of 10° to 25°. The dip of the rock units above and below the interface is approximately the same, but the strikes of the two units frequently differ, that of the quartzite being consistently 5° to 20° farther to the east than that of the phyllite. The interface is rarely seen as a plane, but more usually as a gap up to 12 inches wide separating the two units probably as a result of selective weathering.

On the left abutment the unconformity varies locally in nature, probably as a result of complication by movement similar to gravitational sliding. The interface is well exposed on the downstream edge of the block and can be followed continuously from near river level to the summit of the left abutment (Wyatt, 1962, fig. 6). Various structures are seen at the interface as one follows it up the hill.

(i) A quartzite fold, 36 inches in amplitude and 4 to 12 inches in wave-length protrudes down into the underlying Spillway Phyllite (see Plate 10a). The axial plane of the fold is parallel to the quartzite/phyllite interface and dips at 45° on a bearing of 095°. The fold is in the form of a tight syncline overturned to the west. Between the fold and the overlying quartzite the phyllite is tightly folded and plastically deformed.

(ii) Close to the fold is a large lenticular quartz vein in Spillway Phyllite up to 3 feet long and 4 inches thick. Phyllite laminae are dragged into and truncated by the vein. The vein generally dips at 20° on a bearing of 140° but approaching the interface changes to a steeper dip.

(iii) The interface immediately east of the fold is locally vertical, with the quartzite apparently gouging into the phyllite. In such cases the quartzite is brecciated, partly recrystallised, and striated parallel to the dip of the interface.

(iv) Farther up the hill, two blocks of massive quartzite are separated by a 4-inch wide gap which opens downwards into the interface (see Plate 10b). The gap is filled with thin-bedded, intensely sheared quartzite and mudstone.

Structures within the Spillway Phyllite

The intensity of deformation of the phyllite is closely related to that of the interface and lowest horizons of the quartzite. Thus north of the Spillway Fault the only structures in the phyllite are occasional small-scale symmetrical similar folds and minor box folds with basal shear, all with northerly trends. In the left abutment the phyllite is deformed into a series of small drag folds generally overturned to the east (Wyatt, 1962, fig. 5). In Quarry Site No. 1 (see Plate 9) the interface is not exposed. The lowest units of the Right Abutment Quartzite are intensely deformed (see below), and the phyllite close to the probable position of the interface is isoclinally folded on north-south axes, with axial planes dipping west.

Structures within the Right Abutment Quartzite

(v) The most distinctive structures in the quartzite are planes here called planes of detachment (Gordon, 1963, figs. 1, 4). These are highly polished and, although occasionally parallel to the bedding, generally cut across it at low angles.

* The use of the term "phyllite" by Wyatt is petrologically incorrect, but on this project has become accepted by usage, and will be used here for ease of definition. The sequence to which it is applied is in fact, a sequence of mudstone and siltstone with some thin quartzite near the top.

Furthermore, the dip is generally 5 degrees to 10 degrees farther to the east than that of the bedding. The planes dip at angles ranging from 10 degrees to 45 degrees, and show numerous and often rapid changes of dip. Occasionally the unit above the plane has in it a cavity up to 24 inches high immediately above the plane, which is probably caused by weathering of the intensely jointed quartzite (Wyatt, 1962, fig. 7). The planes of detachment are considered to result from movement of the quartzite above them down the dip of the plane. These planes are often parallel to the ground surface and could be interpreted as exfoliation planes. They are not typical of such planes in that (a) they are highly polished and (b) they control the other joint and fracture system of the quartzite. Exfoliation planes are usually a late phenomenon and as such are frequently controlled by other jointing.

(vi) A characteristic feature of the quartzite is the development of a major sheet-jointing which dips consistently west at angles from 50 degrees to 85 degrees. Typically the sheeting is best developed above the planes of detachment occurring in the quartzite (Wyatt, 1962, fig. 7). The dip and strike of the sheeting appears to be more closely related to the attitude of the planes described later than to bedding.

(vii) The lowest horizons of the quartzite south of the Spillway Fault are often intensely deformed, and accompanied by well developed quartz veining. Quartz veining is common throughout the Lissadell Formation and usually shows a cause-and-effect relationship with the joint pattern in having a controlled frequency and orientation. The basal units of the quartzite in Quarry Site No. 1 however, show quartz veins developed to a degree that is uncharacteristic. The veining forms an anastomosing system with random orientation, in which the quartzite appears as rounded to subrounded masses in a vein-quartz matrix (Plate 10c). Similarly extensive development of vein quartz is found in various outcrops of the basal quartzite units.

(viii) In the extreme southwest of the dam site area, the quartzite outcrop is crossed by a zone of intense deformation. Extensive sheets of quartzite, with a northerly strike, are probably bedding units which have been lifted into near-vertical attitudes, and sharply flexed on horizontal axes (Plate 10d). These folds closely resemble the "cascade" folding described in association with gravitational gliding by Harrison and Falcon (1936) and are probably caused by steepening of the glide plane to the west. Cutting the whole sequence is a well developed series of vertical northerly-trending shear planes in a zone which is approximately 250 feet wide and is gently arcuate. The zone is not seen in the Spillway Phyllite outcrop, but the trend of the zone is continuous with a long narrow gully which also trends north-south, and passes immediately west of Quarry Site No. 1 (Plate 9). Quarry Site No. 1, as described earlier, is a zone of intensive deformation of the quartzite. Furthermore the western side of the outcrop has well developed sheet jointing and shear zone systems. This all suggests that the zone of deformation to the south was once continuous northwards. Across the phyllite outcrop the zone is expressed physiographically by the gully.

Structures Within the Blind Gully Fault Zone

Various structures associated with the Blind Gully Fault cannot be explained by invoking the normal movement of the fault. Such structures are considered to be more easily understood relative to a west to east compressive movement resulting from gliding on a bearing of approximately 070°. The close association of such structures with the fault suggests that the movement of the faulting and that of the gliding were intimately associated. The various structures associated with the fault and relevant to the gliding theory are described below.

(ix) Immediately west (upthrow side) of the Blind Gully Fault north of the Spillway Fault (Plate 9) a zone of intensely brecciated quartzite extends to the west for 100 feet. Some of the brecciation, notably that occurring on planes or in units dipping east at 70° to 80°, is considered to be directly related to the fault movement. Other units of breccia are obviously more directly related to planes of detachment occurring within the quartzite. One such example is shown in plate 10c. The brecciated unit which is roughly 3 feet thick, lies above part of the plane of detachment which can be traced westwards for a considerable distance. At its western end the plane dips east at 35° to 40°. To the east this dip decreased to 10° to 15° then rapidly increases once more to 35° to 40° beneath the breccia. The western end of the unit (i.e. above the flat-lying part of the plane of detachment) is completely brecciated, as far as the point of flexure of the plane of detachment. At this point the degree of brecciation decreases by stages; thus the quartzite above that part of the plane which dips at 35° to 40° shows only intense sheet jointing which dips west and closely resembles the sheet jointing in the Right Abutment Quartzite as described earlier. The lowest part of the most intensely brecciated section of the unit is locally absent, the resulting cavity being clay-filled.

(x) Beds on the eastern (downthrow) side of the fault are overturned to the east parallel to the fault. South from the Spillway Fault the Blind Gully Fault can be traced to the east of the Right Abutment Block, thence southwards along the left bank of the river between outcrops of Right Abutment Quartzite to the west, and Spillway (?Coolibah) Quartzite to the east. These latter thin bedded sediments frequently show steepening and overturning of bedding. All the available evidence indicates that the Blind Gully Fault is a normal fault with an easterly throw and an easterly dipping fault plane. The youngest sediments occur consistently to the east and there is no evidence that the fault is a thrust or reverse fault. Movement on this fault therefore is unlikely to cause steepening of bedding to verticality and overturning without invoking cylindrical fault planes or cylindrical joint systems. It is far more likely that the overturning is the result of intense compressive movement from west to east. No evidence of regional compressive folding of the nature exists, and it is considered that the structures result from gravitational gliding. Immediately west of the fault in these areas, the Spillway Phyllite is isoclinally folded, the westerly dipping axial planes also indicating west to east movement (Plate 10f).

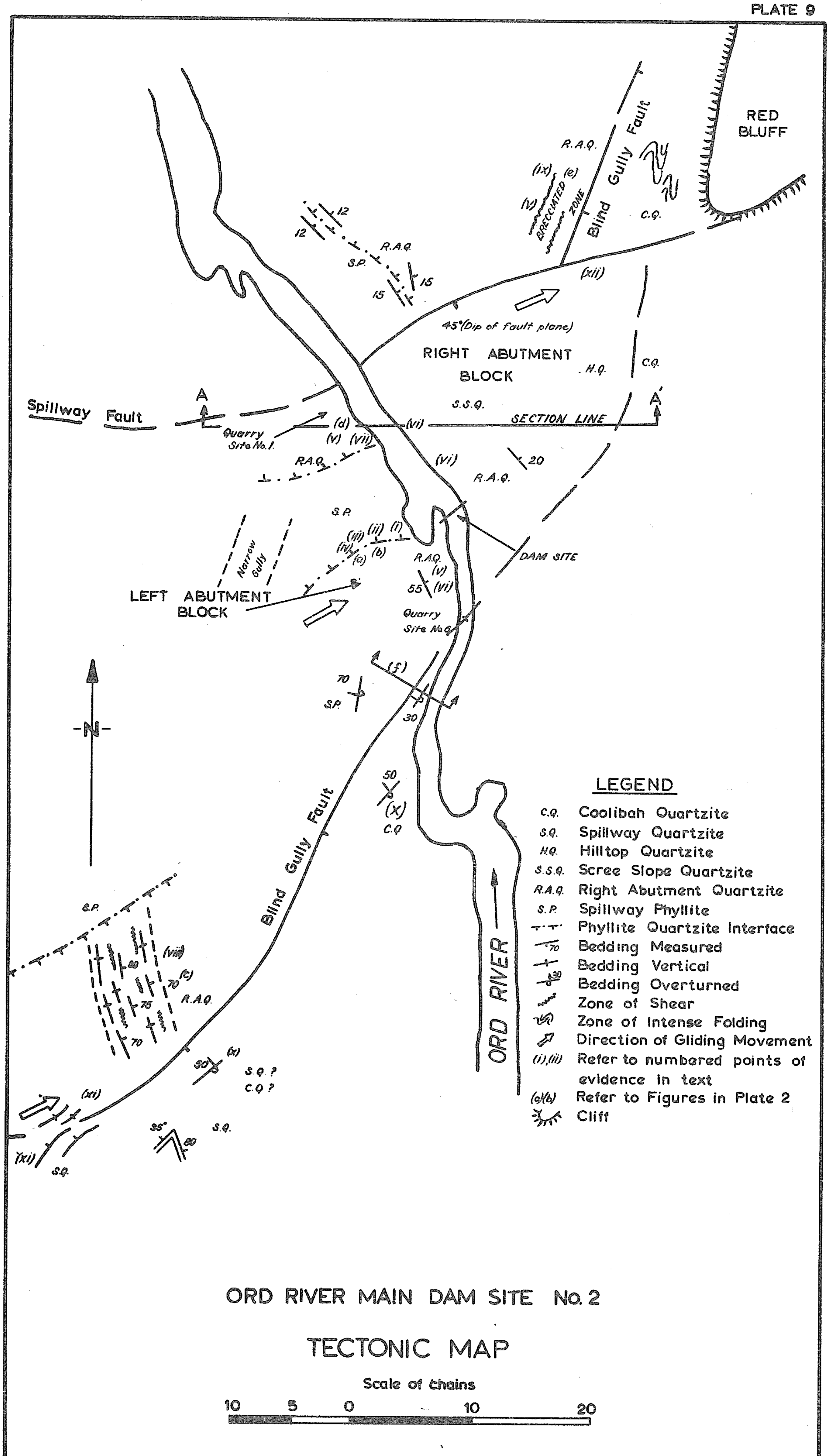
(xi) Bedding strikes are often fault controlled. In the extreme southwest of the area the Blind Gully Fault turns west, and bedding strikes in the Spillway Phyllite and Spillway Quartzite are dragged into the plane of the Blind Gully Fault, in a manner consistent with a dextral wrench movement on the fault (see Plate 9). The evidence suggests that in this area the fault plane is near-vertical, which is also consistent with wrench movement.

(xii) The Blind Gully Fault is anomalously displaced by the Spillway Fault. As stated above, the Blind Gully Fault is a normal fault dipping east, and the Spillway Fault is a normal fault dipping south. Any displacement of the Blind Gully Fault by the Spillway Fault therefore should be in a dextral sense. The displacement however, is some 500 feet to the east, which is a sinistral movement (Plate 9). It is therefore suggested that the Blind Gully Fault has been displaced by the Spillway Fault both laterally and vertically.

ORIGIN AND NATURE OF THE GLIDING MOVEMENT

The easterly direction of gliding means that the movement was triggered in the eastern part of the area, and suggests it was related to movement on the Blind Gully Fault. The idea is supported by the intimate association of the fault with structures described earlier which are related to the fault but resulted from the gliding movement.

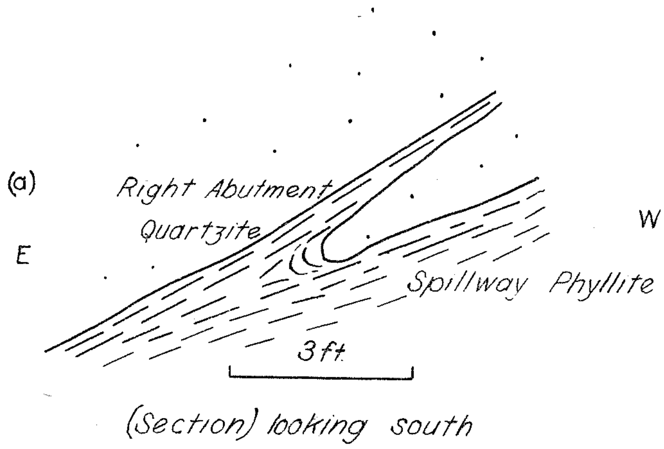
The trend and magnitude of the Blind Gully Fault are such that the easterly displacement would place the thin bedded Coolibah and Spillway Quartzites in juxtaposition with the massive Right Abutment Quartzite over a considerable length of the fault. Differential erosion would



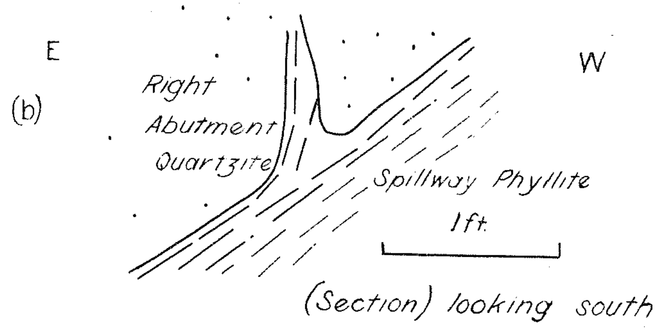
ORD RIVER MAIN DAM SITE No. 2

TECTONIC MAP

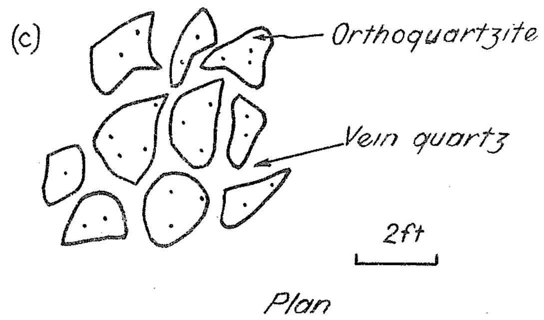
8653



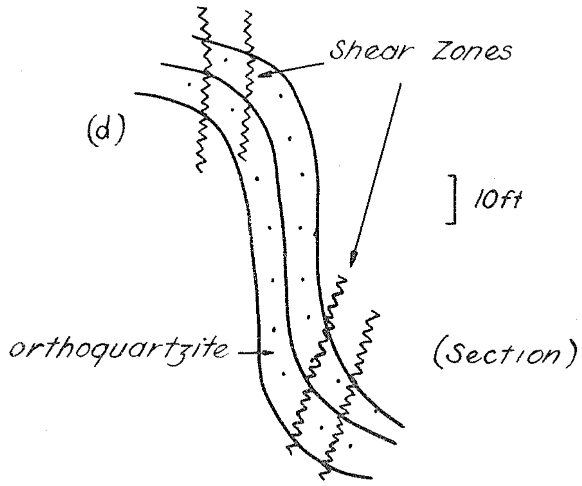
(a) Orthoquartzite fold in Spillway Phyllite



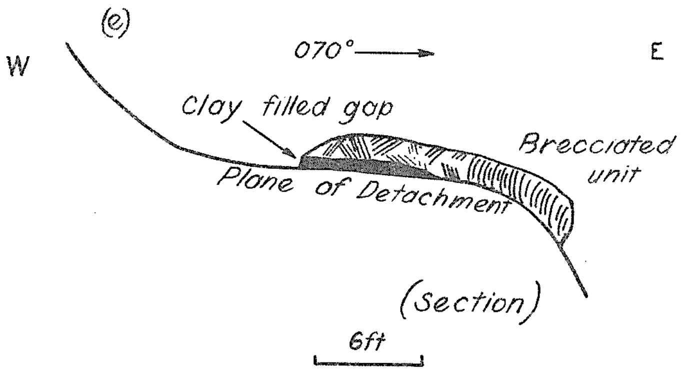
(b) Spillway Phyllite injected into orthoquartzite



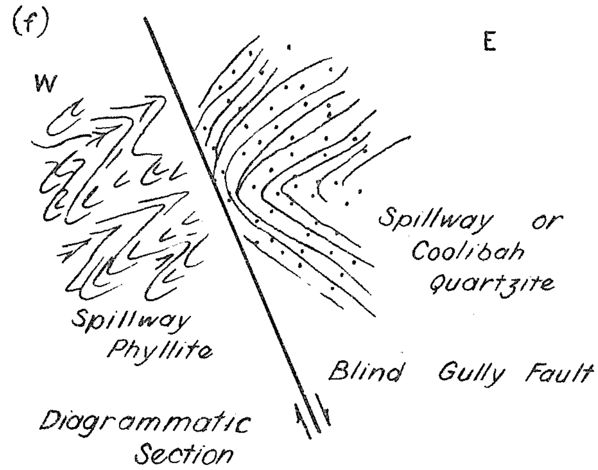
(c) Isolated masses of orthoquartzite in vein quartz



(d) Cascade folding and vertical to near vertical shear in Orthoquartzite



(e) Brecciated orthoquartzite above a flexured plane of detachment

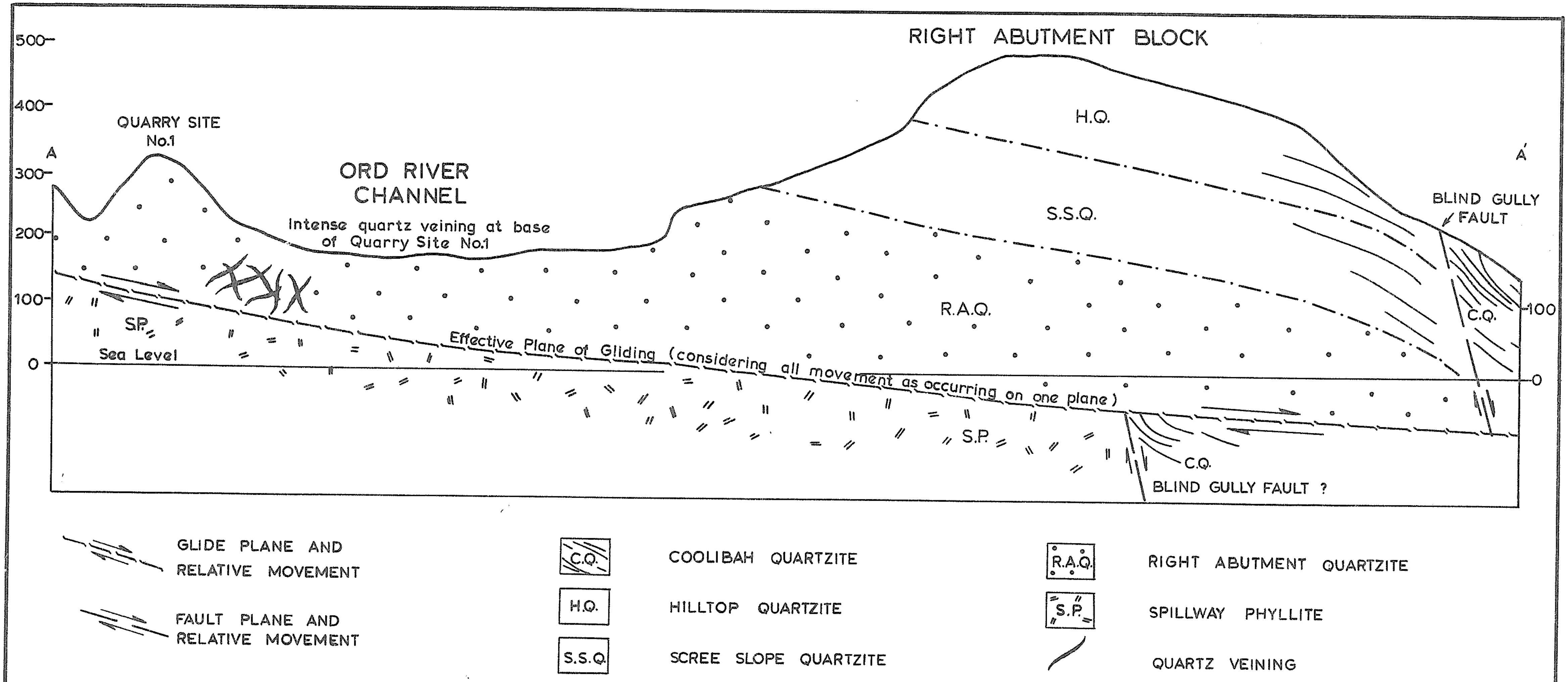


(f) Isoclinal folding and overturning adjacent to the Blind Gully Fault

ORD RIVER MAIN DAM SITE No 2

SKETCHES (a-f) SHOWING OBSERVED GEOLOGICAL FEATURES

8654



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

ORD RIVER MAIN DAM SITE No.2

GEOLOGICAL SECTION A - A'

Scale of feet

200 0 200 400

$\frac{H}{V}=1$

8655

PLATE 11

then tend to remove the thin bedded younger sediments, leaving the quartzite upstanding and unsupported on the western side of the fault. This situation coupled with the easterly regional dip was ideal for the promotion of gravitational gliding.

The Spillway Phyllite/Right Abutment Quartzite interface would be the most likely plane on which movement would be initiated. Certainly some movement has taken place on that plane, as shown by the structures on the interface and small-scale folding of the phyllite below the interface. The amount of movement indicated by the intensity and preservation of these structures however, is not consistent with the observed lateral displacement of at least 500 feet of the Blind Gully Fault. It is possible that wrench movement has taken place on the Spillway Fault independently of the gliding movement, but even so there is incontrovertible evidence that a certain amount of movement took place purely within the Right Abutment Quartzite. Why planes of weakness (planes of detachment) should develop independently of bedding, so close to the supposedly weak quartzite/phyllite interface, is not clear. It is possible that the quartzite beds at the top of the Spillway Phyllite gave sufficient resistance to the phyllite sequence. Whatever mechanism operated, considerable movement took place on each plane of detachment. As a result the planes became highly polished and the units above the planes were intensely sheet jointed. One of the more spectacular results of the movement within the quartzite is the zone of cascade folding and vertical shear occurring 1½ to 2 miles southwest of the dam site as described earlier.

The Blind Gully Fault is virtually the easterly limit of the gliding movement. In the Right Abutment Block however, that part of the fault above the glide plane or planes has been carried eastwards. Thus below the glide plane the Blind Gully Fault continues with its original trend subject only to relatively minor displacement by the vertical throw of the Spillway Fault (Plate 11).

Much of the relief of stress was taken up by the wrench movement of the Spillway Fault, and also of the southerly part of the Blind Gully Fault. These two faults therefore define the major part of the glide mass and are virtually its northerly and southerly limits. North of the Spillway Fault the quartzite has not moved very far to the east, possibly because of the presence of a resistant sandstone mass known as the Red Bluff. (It may be significant to the location and origin of the Spillway Fault, that the easterly extension of the fault passes close to the southern end of the Red Bluff). However, although very little movement occurred north of the fault, the compressive forces operating were similar to those in areas to the south. This is shown by intense folding of the Coolibah Quartzite between the fault and the Red Bluff. As no relief of stress could be obtained by movement therefore, the area became one of intense brecciation. The parts most intensely brecciated would be those underlain by a flat-lying plane of detachment. Some movement would occur, but insufficient for the relief of stress, and the result would be intense brecciation. Where the plane of detachment dipped fairly steeply to the east however, the unit above would be protected to a certain extent, and the intensity of deformation thus relatively decreased (see Plate 10e).

Following its initial wrench movement, which was in response to the gliding movement, the Spillway Fault became the focal plane for the relief of stress set up by later movement, and which resulted in a southerly downthrow in a vertical sense. This final vertical movement is documented by the presence on the fault plane of striae which dip parallel to the dip of the fault plane.

CONCLUSIONS

It is considered that the various structures described from the area of the dam site are the result of a gravitational gliding movement from west to east initiated by movement on the Blind Gully Fault. The gliding was not limited to a single plane but occurred on a number of planes within the quartzite and also at the quartzite/phyllite interface. One of the major effects of the movement was to displace the Blind Gully Fault to the east, mainly along the Spillway Fault. Beneath the lower limit of the glide block therefore, the Blind Gully Fault should be found more or less in its original position, only slightly displaced by the vertical movement on the Spillway Fault (Plate 11). This portion of the fault, below the glide block could be uncovered to the west of its present mapped position when the dam site is excavated.

REFERENCES

De Sitter, L. U., 1956, Structural Geology: London, McGraw Hill.

Dunnett, D. and Plumb, K. A., 1964, Explanatory notes on the Lissadell 1: 250,000 Geological Sheet SE/52-2 Western Australia: Bur. Min. Resour. Aust. Rec. 1964/70 (unpublished).

Gordon, F. R., 1963, Engineering geology of the Ord River main dam site No. 2, Kimberley Division: West. Australia Geol. Survey Ann. Rept. 1962.

Harrison, J. V. and Falcon, N. L., 1936, Gravity collapse structures and mountain ranges as exemplified in South-Western Iran: Geol. Soc. London Quart. Jour., v. 92, p. 91-102.

Horwitz, R. C., 1964, The geology of the region surrounding the Ord River dam site, Western Australia: West. Australia Geol. Survey Rec. 1964/18 (unpublished).

Wyatt, J. D., 1962, Final report on the diamond drill exploration of the Ord River No. 2 main dam site, East Kimberley Division: West. Australia Geol. Survey Ann. Rept. 1961.

Wyatt, J. D., 1965, Ord River main dam site No. 2, detailed geology: West Australia Geol. Survey Rec. 1965/5 (unpublished).

THE SEARCH FOR OIL IN WESTERN AUSTRALIA IN 1964

by P. E. Playford

INTRODUCTION

The most important developments in the search for oil in Western Australia since the Rough Range oil strike in 1953 occurred during 1964. Oil and gas were discovered at Yardarino in the Perth Basin and at Barrow Island in the Carnarvon Basin. The commercial potential of each of these fields was still being evaluated at the end of the year. One oil and gas well and another gas well had been completed at Yardarino and three oil and gas wells at Barrow Island.

The amount of geophysical work and test drilling increased considerably in 1964 as compared with 1963, and exploratory work was carried out in all sedimentary basins except for the Ord Basin. Six oil-test wells were completed in the Carnarvon Basin, five in the Perth Basin, and two in the Bonaparte Gulf Basin. At the end of the year one oil-test well, Barrow No. 4, was still being drilled in the Carnarvon Basin, and another, Gingin No. 1, in the Perth Basin.

Two stratigraphic wells were drilled in the Perth Basin and another in the Eucla Basin. Geophysical operations totalling some 60 party months of seismic work (including 1.7 months of marine seismic surveys), and 39 party months of gravity work were conducted in the Perth, Carnarvon, Canning, Bonaparte Gulf and Officer Basins. Surface geological mapping was undertaken in the Perth, Carnarvon, Canning and Officer Basins.

OIL HOLDINGS

The positions of Permits to Explore and Licenses to Prospect in Western Australia at the end of 1964 are shown on Plate 12. Details regarding each permit and license are shown on the following table:

OIL HOLDINGS IN WESTERN AUSTRALIA ON 31/12/64

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	31/12/65
28H	do. do. do.	30,750	31/12/65
30H	do. do. do.	140,200	31/12/65
106H	Westralian Oil Ltd.	11,800	28/9/65
127H	Alliance Oil Development Australia N.L.	13,800	28/3/65
134H	Exoil Pty. Ltd. and Hunt Petroleum Corporation	12,600	Appln. pending
135H	do. do. do.	12,600	do.
136H	do. do. do.	12,450	do.
142H	Hawkstone Oil Co. Ltd.	5,200	8/4/65
147H	Hunt Oil Co. and Placid Oil Co.	12,850	16/8/65
148H	do. do. do.	12,600	16/8/65
151H	Hackathorn Oils Pty. Ltd.	14,200	7/2/65
152H	do. do.	11,650	7/2/65
153H	do. do.	13,050	7/2/65
156H	Hunt Oil Co. and Placid Oil Co.	12,450	10/7/65
157H	do. do. do.	12,600	10/7/65
158H	do. do. do.	12,800	10/7/65
159H	do. do. do.	12,800	10/7/65
161H	do. do. do.	12,900	24/8/65
172H	Alliance Petroleum Australia N.L.	6,150	30/7/65
173H	do. do. do.	12,250	30/7/65
174H	do. do. do.	6,100	30/7/65
175H	do. do. do.	6,050	30/7/65
177H	do. do. do.	6,050	30/7/65
178H	Australian Oil Corporation	12,300	28/2/65
193H	Hawkstone Oil Co. Ltd.	2,750	5/8/65
199H	Pilbara Exploration N.L.	11,950	15/2/65
205H	Alliance Petroleum Australia N.L.	16,700	17/9/66
206H	do. do. do.	12,950	17/9/66
207H	do. do. do.	13,000	17/9/66
209H	Australian Oil Corporation	12,200	28/2/65
210H	do. do.	12,050	28/2/65
211H	do. do.	5,975	28/2/65
213H	Woodside (Lakes Entrance) Oil Co. N.L.; B.O.C. of Aust. Ltd.; Shell Development (Aust.) Pty. Ltd.	103,700	20/6/65
216H	Pilbara Exploration N.L.	13,200	10/4/65
217H	West Australian Petroleum Pty. Ltd.	17,600	30/5/65
221H	Australian Aquitaine Petroleum Pty. Ltd.; Arco Ltd.	44,000	28/7/66
225H	West Australian Petroleum Pty. Ltd.	7,500	20/7/66
226H	do. do. do.	34,700	6/4/66
227H	do. do. do.	11,400	6/4/66
228H	do. do. do.	2,900	13/5/66
231H	Great Southern Oil Co. Pty. Ltd.	15,376	9/10/66
232H	Victorian Oil N.L.	3,000	10/9/66
233H	West Australian Petroleum Pty. Ltd.	34,650	17/12/66
235H	Tasman Oil Pty. Ltd.	29,500	17/12/66
236H	Abrolhos Oil N.L.; British Petroleum Co. of Aust.	2,300	17/12/66
237H	West Australian Petroleum Pty. Ltd.	8,950	Appln. pending

Licenses to Prospect

No.	Name of Holder	Area in Square Miles	Date of Expiry of Current Tenure
66H	West Australian Petroleum Pty. Ltd.	200	18/1/65
67H	do. do. do.	199·4	20/4/65
74H	do. do. do.	186	17/5/65
75H	do. do. do.	190·8	17/5/65
76H	do. do. do.	192·9	17/5/65
77H	do. do. do.	196·2	17/5/65
78H	do. do. do.	189·7	17/5/65
79H	do. do. do.	198·8	17/5/65
80H	do. do. do.	188·9	17/5/65
81H	do. do. do.	193·4	17/5/65
82H	do. do. do.	198·1	17/5/65
83H	do. do. do.	193·1	17/5/65
84H	do. do. do.	187·4	17/11/65
85H	do. do. do.	187	17/5/65
86H	do. do. do.	189	17/5/65
87H	do. do. do.	189	5/1/65
88H	Hawkstone Oil Co. Ltd.	189	28/2/65
90H	West Australian Petroleum Pty. Ltd.	160·5	27/2/65
91H	do. do. do.	133·8	27/8/65
94H	do. do. do.	186·5	27/2/65
96H	do. do. do.	100	18/9/65
97H	do. do. do.	191·4	26/7/65
99H	do. do. do.	190·5	4/12/65
101H	do. do. do.	193·6	17/12/65
102H	do. do. do.	195·6	13/1/65
103H	do. do. do.	200	20/5/65
104H	do. do. do.	197·9	6/6/65
105H	do. do. do.	196	14/8/65
106H	do. do. do.	200	11/9/65
107H	do. do. do.	200	25/2/66
108H	do. do. do.	200 (excl. Lyndon Loc. 42)	22/1/66
109H	do. do. do.	200	Appln. pending
111H	do. do. do.	150	4/6/66
113H	do. do. do.	200	10/5/66
114H	Alliance Oil Development Australia N.L.	67	27/10/65

Licenses to Prospect—*continued.*

No.	Name of Holder	Area in Square Miles	Date of Expiry of Current Tenure
115H	West Australian Petroleum Pty. Ltd.	200	5/11/66
117H	do. do. do.	200	10/9/66
118H	do. do. do.	120	29/9/66
119H	do. do. do.	200	Appln. pending
120H	Westralian Oil Ltd.	196	30/11/66
121H	Associated Freney Oil Fields N.L.	120	Appln. pending
122H	do. do. do.	113·4	do.
123H	do. do. do.	113·2	do.
124H	do. do. do.	112·5	do.
125H	do. do. do.	112·5	do.
126H	West Australian Petroleum Pty. Ltd.	200	do.
127H	do. do. do.	200	do.

During the year the following farm-out agreements were made: West Australian Petroleum Pty. Ltd. farmed out Permits 226H and 227H to Continental Oil Co. of Australia Ltd. and Australian Sun Oil Ltd., and Permit 228H to French Petroleum Co. (Australia) Pty. Ltd. and Australian Aquitaine Petroleum Pty. Ltd.; Alliance Petroleum Australia N.L. farmed out Permits 172H-177H to Outback Oil Co. N.L.; Hackathorn Oils Pty. Ltd. farmed out Permits 151H and 152H to Geosurveys of Australia Pty. Ltd.; Abrolhos Oil N.L. farmed out Permit 193H to B.P. Petroleum Development Australia Ltd.; Alliance Oil Development Australia N.L. farmed out Permit 127H to Anacapa Corp. and Tasman Oil Pty. Ltd.; and Woodside (Lakes Entrance) Oil Co. N. L. farmed out Permit 213H to B.O.C. of Australia Ltd., Shell Development (Australia) Pty. Ltd., California Asiatic Oil Co., and Mid-Eastern Oil N.L.

DRILLING

The positions of all wells drilled for petroleum exploration in Western Australia to the end of 1964 are shown on Plate 13. The following wells were drilled during the year:

PERMIT TO EXPLORE 27H

Permit to Explore 27H is held by West Australia Petroleum Pty. Ltd. and covers part of the Perth Basin. The company completed five oil-test wells (Wicherina No. 1 and Yardarino Nos. 1-4) in this permit area during 1964. Another test well, Gingin No. 1, was being drilled at the end of the year.

The first significant petroleum discovery in the Perth Basin was made in Yardarino No. 1 during 1964. It yielded flows of dry gas amounting to as much as 15 million cubic feet per day and small quantities of oil. Yardarino Nos. 2 and 4 produced only salt water, but Yardarino No. 3, situated ¼ mile south of the discovery well, produced up to 2,000 barrels of oil per day.

Details of the wells drilled during the year in this permit area are as follows:

Gingin No. 1

Type: Oil test.

License to Prospect: 115H.

Latitude and Longitude: 31° 08′ 32″ S., 115° 49′ 35″ E.

Elevation: Ground 649 feet, rotary table 665 feet.

Date commenced: November 16th, 1964.

Status: Drilling ahead at 9,270 feet on 31st December, 1964.

Mt. Hill No. 1

Type: Stratigraphic.

Latitude and Longitude: 29° 04′ 05″ S., 114° 58′ 53″ E.

Elevation: Ground 378 feet, Kelly bushing 383 feet.

Date commenced: November 8th, 1964.

Date completed: November 21st, 1964.

Total depth: 1,858 feeet.

Bottomed in: Lower Triassic.

Mungarra No. 1
Type: Stratigraphic.
License to Prospect: 119H.
Latitude and Longitude: 28° 51′ 02″ S., 115° 06′ 55″ E.
Elevation: Ground 625 feet, Kelly bushing 630 feet.
Date commenced: October 3rd, 1964.
Date completed: November 4th, 1964.
Total depth: 1,998 feet.
Bottomed in: Lower Permian.

Wicherina No. 1
Type: Oil test.
License to Prospect: 107H.
Latitude and Longitude: 28° 49′ 53″ S., 115° 14′ 19″ E.
Elevation: Ground 862 feet, derrick floor 874 feet.
Date commenced: February 14th, 1964.
Date completed: March 6th, 1964.
Total depth: 5,530 feet.
Bottomed in: Lower Permian.
Remarks: Dry.

Yardarino No. 1
Type: Oil test.
License to Prospect: 111H.
Latitude and Longitude: 29° 13′ 13″ S., 115° 03′ 10″ E.
Elevation: Ground 142 feet, derrick floor 154 feet.
Date commenced: April 7th, 1964.
Date completed: June 16th, 1964 (suspended).
Total depth: 7,800 feet.
Bottomed in: Lower Permian.
Remarks: Test of interval 7,485-7,526 feet Wagina Sandstone (Upper Permian) produced gas at a maximum rate of 15.31 MMCF/day. The gas consists of 97% methane with traces of higher saturated hydrocarbons and quantities of oil condensate (A.P.I. gravity 44 deg.) A production test of the perforated interval 7,558-7,568 feet through a ¼-inch choke yielded 2-3 MMCF/day of gas with slugs of oil and water.

Yardarino No. 2
Type: Oil test.
License to Prospect: 111H.
Location: 1 mile north, ½ mile east of Yardarino No. 1.
Latitude and Longitude: 29° 12′ 22″ S., 115° 03′ 38″ E.
Elevation: Ground 289.6 feet, derrick floor 301.6 feet.
Date commenced: July 8th, 1964.
Date completed: September 20th, 1964.
Total depth: 10,090 feet.
Bottomed in: Lower Permian.
Remarks: Showings of oil and gas recorded from the Wagina Sandstone, but testing produced only salt water with traces of oil and gas.

Yardarina No. 3
Type: Oil test.
License to Prospect: 111H.
Location: ¼ mile south of Yardarino No. 1.
Latitude and Longitude: 29° 13′ 27″ S., 115° 03′ 10″ E.
Elevation: Ground 136 feet, derrick floor 148 feet.
Date commenced: October 8th, 1964.
Date completed: November 27th, 1964.
Total depth: 8,857 feet.
Bottomed in: Lower Permian.
Remarks: Testing of the interval 7,514-7,544 feet in the Wagina Sandstone produced oil (A.P.I. gravity 35 deg.) through a ½-inch choke at a rate of 1,300 barrels/day. Later testing of the perforated interval 7,526-7546 feet through a ⅝-inch choke yielded oil at up to 2,000 barrels/day with varying amounts of gas and water. However, the oil flow declined substantially with prolonged testing, to less than 100 barrels/day.

Yardarino No. 4
Type: Oil test.
License to Prospect: 111H.
Location: ½ mile west, ¼ mile north of Yardarino No. 1.
Latitude and Longitude: 29° 13′ 03″ S., 115° 02′ 39″ E.
Elevation: Ground 131 feet, derrick floor 144.5 feet.
Date commenced: December 4th, 1964.
Date completed: December 30th, 1964.
Total depth: 8,168 feet.
Bottomed in: Lower Permian.
Remarks: Dry; minor showings of oil and gas.

PERMIT TO EXPLORE 28H

Permit to explore 28H is held by West Australian Petroleum Pty. Ltd. and covers the north-central part of the Carnarvon Basin. The company completed three dry oil-test wells (Learmonth No. 2, Paterson No. 1 and Quail No. 1) in this permit area during the year. Details of these are as follows:

Learmonth No. 2
Type: Oil test.
License to Prospect: 108H.
Latitude and Longitude: 22° 17′ 35″ S., 114° 03′ 48″ E.
Elevation: Ground 72 feet, derrick floor 83 feet.
Date commenced: January 22nd, 1964.
Date completed: March 5th, 1964.
Total depth: 6,137 feet.
Bottomed in: Upper Triassic.
Remarks: Dry; traces of gas observed in the Cretaceous sequence. This well encountered the first Triassic rocks to be found in the Carnarvon Basin.

Paterson No. 1
Type: Oil test.
License to Prospect: 85H.
Latitude and Longitude: 22° 27′ 34″ S., 113° 55′ 56″ E.
Elevation: Ground 320 feet, derrick floor 331 feet.
Date commenced: November 8th, 1963.
Date completed: January 16th, 1964.
Total depth: 7,500 feet.
Bottomed in: Jurassic.
Remarks: Dry; traces of gas and minor fluorescence observed in the Jurassic sequence.

Quail No. 1
Type: Oil test.
License to Prospect: 103H.
Latitude and Longitude: 23° 57′ 04″ S., 114° 29′ 57″ E.
Elevation: Ground 376 feet, derrick floor 388 feet.
Date commenced: May 19th, 1963.
Date completed: January 20th, 1964.
Total depth: 11,747 feet.
Bottomed in: Tumblagooda Sandstone (?Lower Silurian).
Remarks: Dry.

PERMIT TO EXPLORE 217H

Permit to Explore 217H is held by West Australian Petroleum Pty. Ltd. and covers the northern part of the Carnarvon Basin and the southwestern extremity of the Canning Basin. Most of the permit area lies offshore. During the year the first test wells were drilled in this area, on Barrow Island. This island is situated in the northern Carnarvon Basin on the crest of a large anticlinal structure developed in Tertiary limestones. The company completed three test wells on the island during the year and all were successful in finding oil and gas. The best flows were obtained from Barrow No. 1, which yielded up to 11 million cubic feet per day of wet gas with condensate and up to 985 barrels per day of oil. Barrow No. 4 was drilling ahead at the end of the year at a depth of 5,156 feet.

Details of the wells are as follows:

Barrow No. 1

Type: Oil test.

License to Prospect: 113H.

Latitude and Longitude: 20° 49′ 06″ S., 115° 38′ 38″ E.

Elevation: Ground 170 feet, derrick floor 181 feet.

Date commenced: May 7th, 1964.

Date completed: August 27th, 1964.

Total depth: 9,785 feet.

Bottomed in: Upper Jurassic.

Remarks: The following are the important test results from this well: Interval 6,176-6,206 feet produced up to 11 MMCF/day of wet gas with quantities of distillate (A.P.I. gravity 50.1°). Interval, 6,759-6,740 feet produced up to 460 barrels/day of oil (A.P.I. gravity 37.3°) through a ½-inch choke. Interval, 6,750-6,783 feet through perforations produced up to 985 barrels/day of oil (A.P.I. gravity 38.1°) through a ½-inch choke. Small amounts of oil were recovered along with large volumes of salt water from the interval 7,490-7,580 feet, tested through perforations. The oil and gas in the above tests was produced from Upper Jurassic sediments. Showings of oil and gas were also observed in the overlying Cretaceous sequence.

Barrow No. 2

Type: Oil test.

License to Prospect: 113H.

Location: ½ mile south, ½ mile west of Barrow No. 1.

Latitude and Longitude: 20° 49′ 40″ S., 115° 23′ 07″ E.

Elevation: Ground 154 feet, derrick floor 165 feet.

Date commenced: August 30th, 1964.

Date completed: October 31st, 1964.

Total depth: 7,640 feet.

Bottomed in: Upper Jurassic.

Remarks: The following are the important test results from this well: Interval 6,124-6,167 feet produced up to 10 MMCF/day of wet gas with some condensate (A.P.I. gravity 44.8°) through a ½-inch choke. Interval 6,196-6,205 feet produced 120 barrels/day of oil (A.P.I. gravity 38.2°) with 440 MCF/day of gas. Interval 6,198-6,210 feet produced 337 barrels/day of oil (A.P.I. gravity 36.1°) with 1.14 MMCF/day of gas and 2.28 barrels/day of fresh water.

Barrow No. 3

Type: Oil test.

License to Prospect: 113H.

Location: ½ mile south of Barrow No. 1.

Latitude and Longitude: 20° 49′ 22″ S., 115° 23′ 11″ E.

Elevation: Ground 154 feet, derrick floor 165 feet.

Date commenced: November 4th, 1964.

Date completed: December 11th, 1964.

Total depth: 7,250 feet.

Bottomed in: Upper Jurassic.

Remarks: The following are the important test results from this well: Interval 6,792-6,798 feet (through perforations) produced a mixture of 90% oil (A.P.I. gravity 44.3°) and 10% water at 300-400 barrels/day with a flow of gas amounting to 1.5-2.8 MMCF/day. Interval 6,738-6,748 feet (through perforations) produced up to 240 barrels/day of oil (A.P.I. gravity 39°) with a trace of water and 800 MCF/day of gas through a ⅜-inch choke.

Barrow No. 4

Type: Oil test.

License to Prospect: 113H.

Location: 1 mile south, ½ mile east of Barrow No. 3.

Latitude and Longitude: 20° 50′ 32″ S., 115° 23′ 05″ E.

Elevation: Ground 101 feet, derrick floor 112 feet.

Date commenced: December 15th, 1964.

Status: Drilling ahead at 5,156 feet in Cretaceous sediments on 31st December, 1964.

PERMIT TO EXPLORE 127H

Permit to Explore 127H is held by Alliance Oil Development Australia N. L. and covers the Western Australian part of the Bonaparte Gulf Basin. Two test wells were completed in this permit area during 1964. The second of these, Bonaparte No. 2, obtained the first flow of hydrocarbons in the basin. It yielded up to 1.54 million cubic feet per day of methane with small amounts of higher saturated hydrocarbons from the Lower Carboniferous Milligans Beds. Details of the two wells are as follows:

Bonaparte No. 1

Type: Stratigraphic test.

Latitude and Longitude: 15° 01′ 00″ S., 128° 44′ 30″ E.

Elevation: Ground 339 feet, Kelly bushing 355 feet.

Date commenced: July 18th, 1963.

Date completed: June 6th, 1964.

Total depth: 10,530 feet.

Bottomed in: Upper Devonian.

Remarks: Dry hole.

Bonaparte No. 2

Type: Stratigraphic.

License to Prospect: 114H.

Latitude and Longitude: 15° 05′ 07″ S., 128° 43′ 16″ E.

Elevation: Ground 383 feet, Kelly bushing 400 feet.

Date commenced: July 27th, 1964.

Date completed: October 15th, 1964.

Total depth: 7,008 feet.

Bottomed in: Lower Carboniferous.

Remarks: The following important drill-stem tests were run in the hole: Interval 4,712-4,819 feet yielded a maximum gas flow of 1.54 MMCF/day. Interval 4,694-4,760 feet yielded a maximum gas flow of 1.15 MMCF/day.

PERMIT TO EXPLORE 173H

Permit to Explore 173H is held by Alliance Petroleum Australia N. L. and covers part of the Eucla Basin adjacent to the South Australian border. The company drilled a stratigraphic well, Eucla No. 1, in this area during 1964. Details are as follows:

Eucla No. 1

Type: Stratigraphic.

Latitude and Longitude: 31° 52′ 15″ S., 128° 13′ 21″ E. (approx.).

Elevation: Ground 40 feet (approx.)

Date commenced: January 21st, 1964.

Date completed: February 24th, 1964.

Total depth: 728 feet.

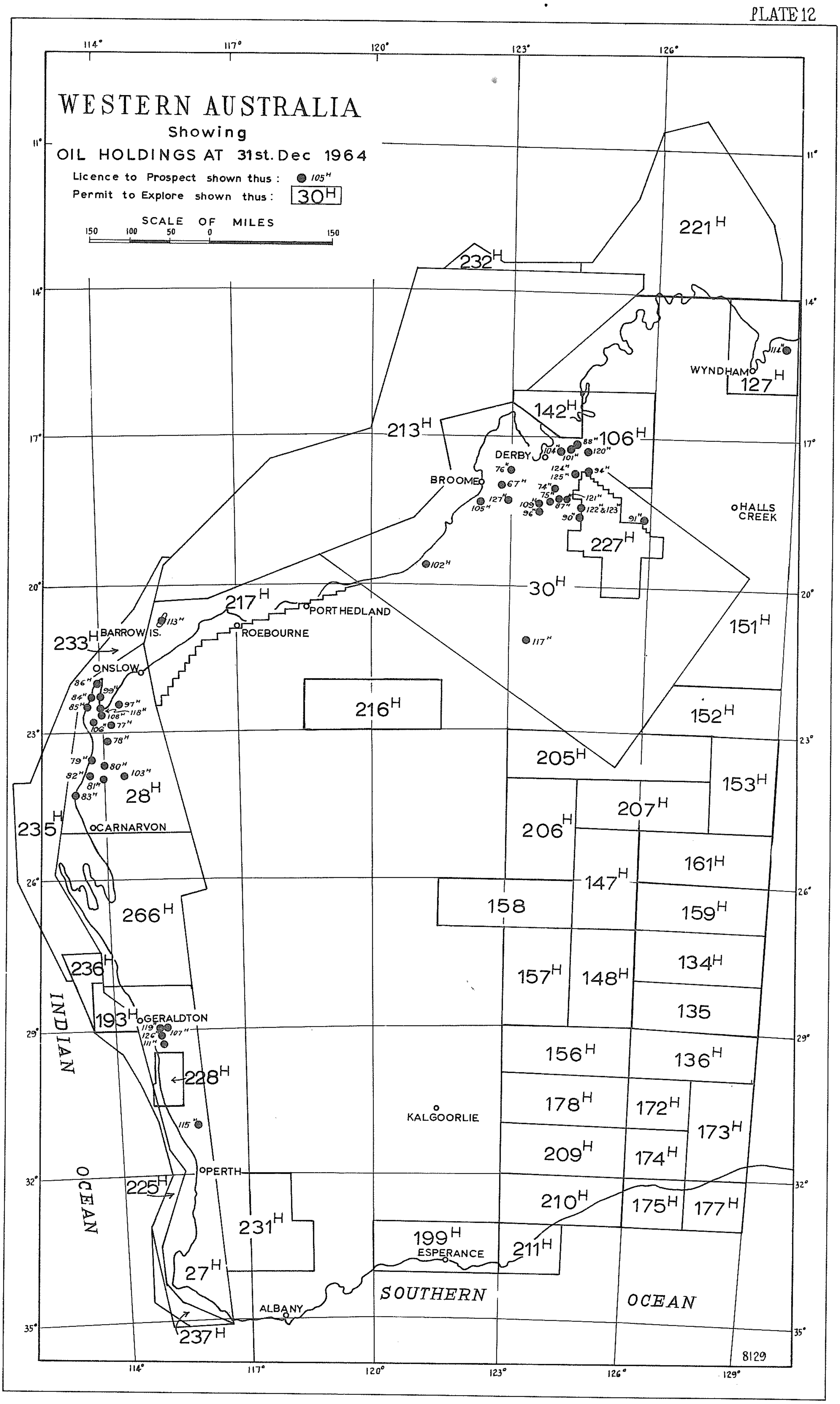
Bottomed in: Precambrian granitic rocks.

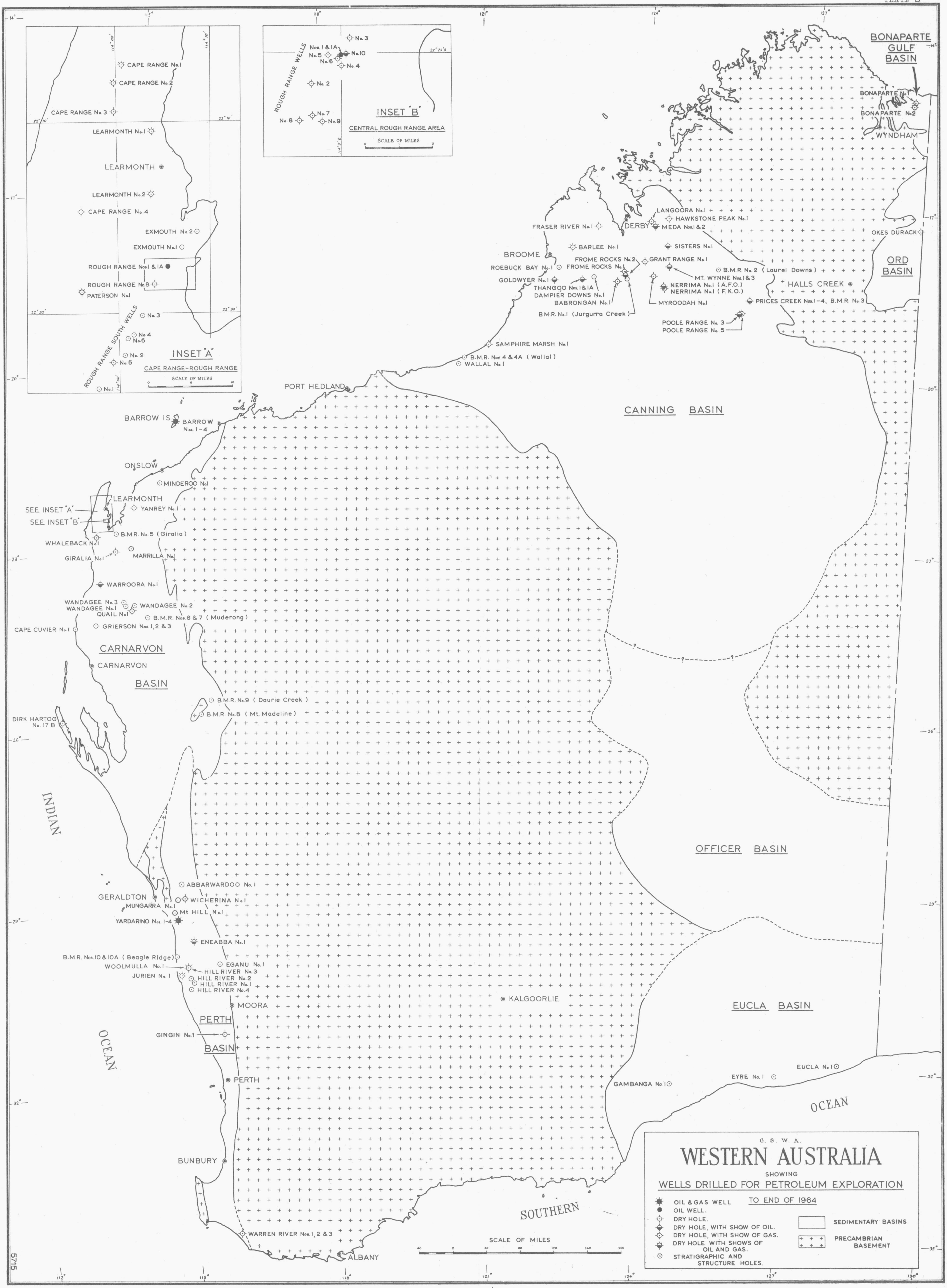
GEOPHYSICAL OPERATIONS

SEISMIC

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

Company	Permit	Basin	Party Months
West Australian Petroleum Pty. Ltd.	27H	Perth	17·8
Do. do. do.	30H	Canning	13·8
Do. do. do.	217H	Carnarvon	6·25
Continental Oil Co. of Australia Ltd.	226H	Carnarvon	6·5
Do. do. do.	227H	Canning	3·65
French Petroleum Co. (Aust.) Pty. Ltd.	228H	Perth	4·0
B.O.C. of Australia Ltd.	213H	Canning-Carnarvon (offshore)	1·7
Alliance Oil Development N.L.	127H	Bonaparte Gulf	2·5
Hunt Oil Co.	147H, 159H	Officer	4·0


WESTERN AUSTRALIA
Showing
OIL HOLDINGS AT 31st. Dec 1964
Licence to Prospect shown thus : 105H
Permit to Explore shown thus : 30H
SCALE OF MILES
150 100 50 0 150
INDIAN OCEAN
SOUTHERN OCEAN
WYNDHAM
DERBY
BROOME
HALLS CREEK
PORT HEDLAND
ROEBOURNE
BARROW IS.
ONSLOW
CARNARVON
GERALDTON
PERTH
KALGOORLIE
ESPERANCE
ALBANY
8129


G. S. W. A.
WESTERN AUSTRALIA
SHOWING
WELLS DRILLED FOR PETROLEUM EXPLORATION
TO END OF 1964
OIL & GAS WELL
OIL WELL.
DRY HOLE.
DRY HOLE, WITH SHOW OF OIL.
DRY HOLE, WITH SHOW OF GAS.
DRY HOLE WITH SHOWS OF OIL AND GAS.
STRATIGRAPHIC AND STRUCTURE HOLES.
SEDIMENTARY BASINS
PRECAMBRIAN BASEMENT
SCALE OF MILES
INSET "A"
CAPE RANGE-ROUGH RANGE
SCALE OF MILES
CAPE RANGE No.1
CAPE RANGE No.2
CAPE RANGE No.3
LEARMONTH No.1
LEARMONTH
LEARMONTH No.2
CAPE RANGE No.4
EXMOUTH No.2
EXMOUTH No.1
ROUGH RANGE Nos.1 & 1A
ROUGH RANGE No.8
PATERSON No.1
ROUGH RANGE SOUTH WELLS
INSET "B"
CENTRAL ROUGH RANGE AREA
SCALE OF MILES
ROUGH RANGE WELLS
BONAPARTE GULF BASIN
BONAPARTE No.1
BONAPARTE No.2
WYNDHAM
LANGOORA No.1
HAWKSTONE PEAK No.1
DERBY
MEDA Nos.1 & 2
FRASER RIVER No.1
OKES DURACK
BARLEE No.1
SISTERS No.1
BROOME
FROME ROCKS No.2
FROME ROCKS No.1
GRANT RANGE No.1
ROEBUCK BAY No.1
B.M.R. No.2 (Laurel Downs)
ORD BASIN
MT. WYNNE Nos.1 & 3
GOLDWYER No.1
THANGOO Nos.1 & 1A
DAMPIER DOWNS No.1
BABRONGAN No.1
NERRIMA No.1 (A.F.O.)
NERRIMA No.1 (F.K.O.)
HALLS CREEK
MYROODAH No.1
PRICES CREEK Nos.1-4, B.M.R. No.3
B.M.R. No.1 (Jurgurra Creek)
POOLE RANGE No.3
POOLE RANGE No.5
SAMPHIRE MARSH No.1
B.M.R. Nos.4 & 4A (Wallal)
WALLAL No.1
PORT HEDLAND
CANNING BASIN
BARROW IS.
BARROW Nos.1-4
ONSLOW
MINDEROO No.1
SEE INSET "A"
SEE INSET "B"
LEARMONTH
YANREY No.1
B.M.R. No.5 (Giralia)
WHALEBACK No.1
GIRALIA No.1
MARRILLA No.1
WARROORA No.1
WANDAGEE No.3
WANDAGEE No.1
QUAIL No.1
WANDAGEE No.2
B.M.R. Nos.6 & 7 (Muderong)
GRIERSON Nos.1, 2 & 3
CAPE CUVIER No.1
CARNARVON BASIN
CARNARVON
B.M.R. No.9 (Daurie Creek)
B.M.R. No.8 (Mt. Madeline)
DIRK HARTOG No.17 B
INDIAN OCEAN
OFFICER BASIN
ABBARWARDOO No.1
GERALDTON
WICHERINA No.1
MUNGARRA No.1
Mt HILL No.1
YARDARINO Nos.1-4
ENEABBA No.1
B.M.R. Nos.10 & 10A (Beagle Ridge)
WOOLMULLA No.1
EGANU No.1
HILL RIVER No.3
JURIEN No.1
HILL RIVER No.2
HILL RIVER No.1
HILL RIVER No.4
KALGOORLIE
MOORA
EUCLA BASIN
PERTH BASIN
GINGIN No.1
EUCLA No.1
EYRE No.1
GAMBANGA No.1
PERTH
OCEAN
BUNBURY
SOUTHERN
WARREN RIVER Nos.1, 2 & 3
ALBANY
5715

GRAVITY

Gravity surveys were conducted during 1964 in the Canning and Officer Basins. They were distributed as follows:

Company	Permit	Basin	Party Months
West Australian Petroleum Pty. Ltd.	30H	Canning	3·2
Hunt Oil Co.	147H, 148H, 134–136H, 159H	Officer	34·0
Geosurveys of Australia Pty. Ltd.	151H	Canning	2·0 (helicopter)

GEOLOGICAL OPERATIONS

Geological field investigations played a relatively small part in the exploration programmes of companies searching for oil in Western Australia during 1964, though the amount was greater than in 1963. Field investigations were carried out in the Canning, Carnarvon, Perth and Officer Basins. They were distributed as follows:

Company	Permit	Basin	Geologist Months
Continental Oil Co. of Australia Ltd.	227H	Canning	17
Do. do. do.	226H	Carnarvon	2
West Australian Petroleum Pty. Ltd.	28H	Carnarvon	4
Do. do. do.	30H	Canning	2
French Petroleum Company (Aust.) Pty. Ltd.	228H	Perth	4
Alliance Petroleum (Aust.) N.L.	205H–207H	Canning-Officer	9
Hunt Oil Co.	134–136H, 147–148H, 157–159H	Officer	4
Geosurveys of Australia Pty. Ltd.	151–152H	Canning	2½

The Geological Survey continued its mapping programme in the southern half of the Perth Basin, and this occupied two geologists for three months. In addition a geological reconnaissance of the northern Officer Basin-southern Canning Basin occupied one geologist for one month. One geologist also spent three weeks in mapping on the Lennard Shelf (northern Canning Basin).

Other geological work connected with the search for oil in this State during 1964 was mainly concerned with the review of information obtained previously and its application to the results of exploratory wells and geophysical investigations. Several companies also carried out photogeological studies.

DRILLING FOR COAL IN THE MUJA FORMATION, COLLIE MINERAL FIELD

by G. H. Low

ABSTRACT

In 1964 the Geological Survey supervised a drilling programme in the Muja Depression, 14 miles southeast of Collie, to obtain more information about the structure and coal reserves in a potential open-cut area. Seventeen boreholes were drilled in the programme, which was financed by the State Electricity Commission.

The Muja Formation, the youngest of the three formations in the depression, contains some 90 million tons of coal in 8 seams. The seams from top to bottom (with the average thickness of each shown in brackets) are: Ate (4 ft.), Bellona (8 ft.), Ceres (8 ft.), Diana (4 ft.), Eos (9 ft.), Flora (7 ft.), Galatea (9 ft.), and Hebe (38 ft.) Seams. The coal reserves consist of 14 million tons in the Western Collieries lease, and 76 million tons in the Griffin Co. leases.

Analyses of numerous samples show that all the coal seams are of commercial grade, the best being the Hebe Seam.

The Muja Formation is not as strongly faulted as was expected. The only important fault encountered during the drilling was already known to occur along the eastern side of the Hebe Colliery. Steep dips along the margins of the area are now thought to be due to differential compaction. The coal seams dip as high as 45° in at least one place on the southwestern side of the area, but the average dip of the seams throughout most of the area is only 10° to 15°.

More drilling may be necessary to check the structure and the thickness of the seams in some areas.

INTRODUCTION

A drilling programme was carried out between March and October, 1964 to elucidate the structure and coal reserves of the potential open-cut area centred about 2 miles southwest of the Muja railway siding near Collie. The State Electricity Commission financed the project which was directed by the Geological Survey.

Most of the area is in leases held by the Griffin Coal Mining Company which is already working an open-cut and a colliery at the southern end of the area. Initially a programme of 10 boreholes was decided upon by the Company and the Geological Survey but subsequently seven more boreholes were added to the original programme; six of these were selected by the Geological Survey, and the seventh by the Company to check conditions ahead of the Hebe Colliery. One of the additional boreholes was located on a lease at the northern end of the area held by Western Collieries Ltd.

The 17 boreholes (S1-S17) involved 7,804 feet of drilling. This does not include footage in some sections which were redrilled because an original borehole had to be abandoned due to drilling difficulties. Detailed logs for all the boreholes are held on File 169/64 at the Geological Survey, and summarized logs are given in Low (1964).

Previous geological work in the Muja area has been carried out by J. H. Lord, officers of the Griffin Co. and myself. Lord (1953) first described the geology of the area and named the seams. In 1958, after completion of the Mines Department exploratory drilling programme, I estimated the quantity of coal available in the potential open-cut areas as being 86 million tons (Low, 1958). It was believed at this time that the area was bounded on at least two sides by strong faulting. However subsequent company drilling showed that this structural interpretation was not entirely correct, and it was desirable to check on the structure in more detail.

The drilling was carried out by Geophysical Service International, contractors to the State Electricity Commission, using a Mayhew 1000 truck-mounted drilling rig. A 10-foot core barrel was used, fitted with a hard formation bit and a stationary inner-tube.

Electric logging was carried out in the last borehole drilled (S17) to determine if such logging methods could be used to determine the true thickness and depth of the coal seams. The results from the point-resistivity and self-potential logs were very encouraging, but unfortunately the borehole was too narrow for the gamma-ray probe (Rowston, 1964).

During the drilling valuable assistance was received from various officers of the State Electricity Commission, especially Mr. G. Rich, site engineer at Muja, and Mr. D. Saunders, chief chemist at the East Perth power station, and this is gratefully acknowledged. I am also indebted to Messrs. R. Fowler and B. Stronach of the Griffin Co., and Mr. W. Hille of Western Collieries Ltd for many interesting discussions concerning the drilling.

GEOLOGY

The Muja Depression is a deep trough filled with Permian sediments more than 2,000 feet thick. The trough is believed to have been scoured out by ice action during the Lower Permian glaciation. Strong post-depositional compaction occurred in the Permian sediments, resulting in the basin structure, and in the development of some normal faults.

The coal seams occur in the Muja Formation, the youngest of the three coal-bearing formations in the Muja Depression. It is correlated with the Cardiff Formation of the main Collie Basin and is of Upper Permian age. The coal seams are on the western side of the Muja Depression, adjacent to a ridge of granite which, in a structural sense, divides the coal field into two unequal parts. The broad structure of the Muja Formation is an elliptical basin, the long axis of which trends northwest.

The coal seams are not exposed at the surface, but are covered by a unit of sand, clay, and conglomerate called the "Lake Beds" (Lord, 1952). The thickness of the unit in this area ranges from about 20 feet at the southern end, to about 120 feet at the northern end. In some places the top 6 feet or so are strongly lateritised forming a tough capping which may itself be covered by a thin layer of sand.

Sandstone and minor developments of shale, claystone, and siltstone are interbedded with the coal seams. Much of these sediments are weakly lithified and give poor core recovery. The core recovered, excepting the coal removed for analysis, has been stored in the Geological Survey's core shed in Wittenoom Street, Collie.

The top of the coal measures is an uneven surface due mainly to erosion before the deposition of the "Lake Beds". Although in most places the seams do not rise higher than an elevation of 700 feet, there are instances, e.g., in boreholes S3 and P257, where they rise to about 730 feet above sea level. The part of a coal seam in contact with the base of the overlying "Lake Beds" is called its "blind outcrop". The positions of the blind outcrops, estimated from borehole data, are shown on Plate 14.

Post-depositional compaction of the coal and other sediments of the Muja Formation and of the underlying formations has affected the structure of the area. Most compaction took place in the deepest part of the depression so that the dip of the beds (including the coal seams) becomes quite steep towards the edges of the formation, especially on the side adjacent to the granite ridge. This steep turning-up of the coal seams towards the blind outcrops had previously been interpreted as being due to faulting. Dips are variable, even in one borehole, but the average in the central part of the area is between 10 degrees and 15 degrees, whereas the steepest dips are found along the southwestern margin. In borehole S13 in lease 537 the Diana, Eos, and Flora Seams dip at about 45 degrees, and in borehole S15 in lease 425 the Hebe Seam dips at 37 degrees. The angle of dip of the seams between boreholes P257 and P268 at the northeastern end of section 1 is 30 degrees, and this steeply dipping structure is expected to continue around most of the blind outcrop of the Hebe Seam in lease 425. The general effect of the steepening of dip towards blind outcrops is illustrated in the geological sections on Plate 15.

The thickest penetration of the Muja Formation was made in Failing borehole 9 where the base of the deepest important seam was at 701 feet. The top of the highest seam was at 232 feet, so that the section containing the significant seams in this borehole is 469 feet thick. The thickness of the sediment interbedded between adjacent coal seams is variable and it is not practicable with the available data to draw up an accurate isopach map. However contours on the base of the Hebe Seam have been drawn (Plate 14).

There are eight major coal seams, and an average thickness for each has been calculated using the borelogs of most of the boreholes which have made complete intersections. In order of occurrence from top to bottom, with the average thickness of each in brackets, the coal seams are: Ate (4 ft.), Bellona (8 ft.), Ceres (8 ft.), Diana (4 ft.), Eos (9 ft.), Flora (7 ft.), Galatea (9 ft.), and Hebe (38 ft.) Seams. The variation in the thickness of these seams in 40 boreholes is shown in Table 1.

Table 1

THICKNESS OF COAL SEAMS

Bore	Coal Seam Thickness (in feet)							
	Ate	Bell-ona	Ceres	Diana	Eos	Flora	Gala-tea	Hebe
F6	....	....	....	....	....	....	....	35
F7	....	....	....	....	....	5	9	32
78	8	13	9	....	....	....	....	....
G83	....	....	....	....	....	....	....	40
S12	4	8	9	2	11	9	15	45
S2	3	9	10	3	11	8	12	43
188	2	11	9	4	10	6	11	40
S1/1A	....	....	....	4	11	6	12	33
P248	....	....	....	....	....	....	9	42
P252	....	....	....	....	....	....	....	40
P258	....	....	....	....	....	....	13	40
P260	....	....	....	....	....	6	12	41
S4	6	10	6	2	8	11	7	40
F9	2	5	7	5	12	5	11	44
P272	3	6	9	....	....	....	....	....
74	6	11	9	4	10	....	....	....
P273	....	....	....	4	10	9	10	41
S3	....	....	....	....	9	6	8	35
P270	2	6	10	....	....	....	....	....
P271	....	....	....	4	4	7	....	....
S16	4	11	11	3	3	7	9	35
P273	....	....	....	4	10	9	10	41
S17	6	7	7	4	8	8	8	38
S13	....	....	9	5	12	6	6	39
S7	2	8	6	3	8	....	11	38
S11	3	6	7	....	....	....	....	....
S6	5	6	7	3	....	....	5	28
S14	....	5	6	4	8	7	7	....
P234	....	....	....	....	....	7	5	31
P242	....	....	....	5	8	6	6	....
S8	....	....	....	4	10	7	8	37
79	3	9	7	3	10	6	10	39
"D"	....	....	....	4	6	6	10	37
P257	....	....	....	4	9	8	....	26
S10	3	9	10	4	11	8	12	41
Wc70	3	10	7	3	....	....	....	....
F16	....	....	....	2	9	7	8	40
S15	....	....	....	....	....	....	....	40
N3	....	....	....	....	15	6	11	40
N4	....	....	....	....	....	16	7	40
Average Thickness	4	8	8	4	9	7	9	38

In some places the coal seams are considerably below average thickness (for example in boreholes S6 and S14) and the lateral extent of this thinning is not known. Borehole S6 is particularly important because the Hebe and Galatea Seams are reduced to 28 and 5 feet respectively, and the Flora and Eos Seams are absent altogether. This borehole does not appear to have intersected any faults which could explain these anomalies. Some of the seams show substantial thinning near their blind outcrops. This applies especially to the Hebe Seam which is considerably reduced in P236 and S9 at the southwestern end of section 1 (Plate 15), and in P268 at the northwestern end of the same section. The sediments of the Muja Formation are sufficiently incompetent in most places to have reacted to compaction by folding and bedding-plane slip rather than by faulting. An exception however is the fault which has been touched at a number of places along the eastern side of the Hebe Colliery, and which has been traced by boreholes as far north as S14.

The fault is downthrown to the southwest, and appears to have an average dip of 75°. On section 4 (Plate 15) it has a throw of about 170 feet, but it appears to die out some 15 chains north of S14. If this is so then probably the lower five seams of the formation will be found to continue uninterrupted around the eastern side of the fault up to the eastern end of section 1 (Plate 15). This could provide quite a good area of relatively shallow coal.

Borehole S14 appears to have entered the fault zone somewhere below the Galatea Seam and above the Hebe Seam, because only 11 feet of coal was intersected at the depth at which the Hebe Seam was expected. Judging by the angle of the shale-coal contact at the top of the seam, the dip is nearly vertical. This section of coal probably represents part of the Hebe Seam.

There are few boreholes in Western Collieries Lease (M.L. 425) at the northern end of the area. However borehole S15 in lease 425 reached the bottom of the Hebe Seam at a depth of 205 feet and, although bedding dips as high as 37° were found in the core, there was no sign of faulting other than some bedding-plane slip. It appears therefore that structural conditions in this area are similar to those existing further south, and on this assumption the seam limits have been drawn as shown on Plate 14.

COAL RESERVES

For the purpose of estimating reserves, an average thickness has been calculated for each of the eight major seams from thicknesses measured in boreholes throughout the area. The average thicknesses are shown in Table 1. The Ate and Diana Seams, which were not included in the 1958 estimates, have now been included because the drilling has shown them to be more consistent in thickness and quality than was previously realized. They account for 5 million tons of the total reserves.

For convenience the whole area has been divided into four blocks as shown on Plate 14. The outlines of the present open-cut area and the Hebe Colliery are not shown, but allowance has been made for the coal produced from them in calculating the remaining reserves.

It should be noted that indicated and inferred categories are used because of inexact knowledge of the structure and grade of the coal in some areas. The assumptions made in the estimation of quantity are considered conservative, and no doubt is felt that the 90 million tons of coal is present within the 20% range of accuracy allowable under measured reserves.

A factor of 27 cubic feet to the ton has been used in making the calculations. Details of the estimates are given in Table 2.

Table 2

COAL RESERVES ESTIMATES

(The four areas are shown on Plate 14.)

Seam	Area (acres)	Average Thickness (feet)	Tons
AREA "A": INFERRED COAL—14 million tons			
Hebe	129	38	8,000,000
Galatea	99	9	1,400,000
Flora	92	7	1,000,000
Eos	88	9	1,300,000
Diana	83	4	500,000
Ceres	58	8	700,000
Bellona	45	8	800,000
Ate	38	4	200,000
AREA "B": INDICATED COAL—20 million tons			
Hebe	173	38	11,000,000
Galatea	154	9	2,200,000
Flora	145	7	1,600,000
Eos	138	9	2,000,000
Diana	130	4	800,000
Ceres	98	8	1,300,000
Bellona	80	8	1,000,000
Ate	61	4	400,000
AREA "C": INDICATED COAL—26 million tons			
Hebe	217	38	13,000,000
Galatea	199	9	2,900,000
Flora	189	7	2,100,000
Eos	179	9	2,600,000
Diana	165	4	1,100,000
Ceres	141	8	1,800,000
Bellona	128	8	1,700,000
Ate	108	4	700,000
AREA "D": INDICATED COAL—30 million tons			
Hebe	305	38	17,000,000
Galatea	247	9	3,600,000
Flora	215	7	2,400,000
Eos	180	9	2,600,000
Diana	173	4	1,100,000
Ceres	107	8	1,400,000
Bellona	93	8	1,200,000
Ate	78	4	500,000
TOTAL: INFERRED COAL: 14 million tons			
INDICATED COAL: 76 million tons			

COAL ANALYSES

Samples were taken from all the major coal seams intersected during the drilling programme. These were sealed in airtight plastic bags and placed inside cans as soon as possible after being withdrawn from the borehole, usually within 10 minutes.

All the coal recovered from the main seams was analysed, and where there was sufficient core recovery the analyses represent 3 or 4 foot sections. However where core recovery was poor the coal recovered has been taken to represent thicker sections. Separate samples were analysed for poor quality coal or shaly bands in a seam.

The samples were analysed by the proximate method at the State Electricity Commission power station in East Perth. The results are consistent with earlier analyses of the coal seams in this formation. The best quality coal is in the Hebe Seam, but all the seams are of commercial quality. A table of coal sample analyses is given by Low (1964).

OPEN-CUT MINING

The difficulties involved in the open-cut extraction of coal from the Muja Formation are increased by the fact that several seams are to be worked. The thick seam at the bottom (Hebe Seam) can be extracted with economic coal-overburden ratios for a considerable distance along the strike, especially around the southern and southeastern limits of the formation; but as the cut is developed down-dip, the extraction of the overlying seven seams will be necessary in order to maintain economic ratios. The extraction of coal from the Hebe Seam by deep mining in the Hebe Colliery will cause problems when the open-cut is extended to this area.

An estimate has been made of the coal/overburden ratios for each borehole that intersected significant thicknesses of coal. This has been done for 43 boreholes as shown in Table 3. To arrive at ratios including all the seams it has been necessary to assume the thickness and depth of some of the lower seams in 11 boreholes which were not carried down to intersect the base of the Muja Formation. An allowance was made for the dip of the seams so that the true thicknesses are used in the calculations. These ratios are shown on Plate 14.

Table 3

COAL/OVERBURDEN RATIOS

Bore	Seam(s)	Dip	Thickness (A = assumed)	Thickness Corrected	Base of Hebe Seam	Ratio Coal/Overburden
			feet		feet	
F6	Hebe	7°	35	35	80	1/1·3
F7	Flora-Hebe	32°	46	41	238	1/4·7
78	Ate-Hebe	6°	A 101	101	465	1/3·6
G83	Hebe	10°	40	39	65	1/0·6
S12	Ate-Hebe	10°/20°/30°	103	96	513	1/4·3
S2	Ate-Hebe	7°	99	97	665	1/5·8
188	Ate-Hebe	7°	A 92	90	590	1/5·6
S1/S1A	Diana-Hebe	5°	66	66	280	1/3·2
P248	Galatea-Hebe....	17°	51	48	158	1/2·3
P252	Hebe	17°	40	38	101	1/1·6
P258	Galatea-Hebe....	17°	53	50	182	1/2·6
P260	Flora-Hebe	17°	59	56	231	1/3·1
S4	Ate-Hebe	10°	90	88	662	1/6·5
F9	Ate-Hebe	5°	91	91	701	1/6·7
P272	Ate-Hebe	7°	A 89	87	670	1/6·5
74	Ate-Hebe	10°	A 97	94	620	1/5·6
P273	Diana-Hebe	5°	74	74	359	1/3·9
S3	Eos-Hebe	25°	58	50	213	1/3·3
P270	Ate-Hebe	7°	A 89	87	670	1/6·7
P271	Diana-Hebe	5°	A 62	62	356	1/4·8
S16	Ate-Hebe	10°	80	78	538	1/5·6
P273	Ate-Hebe	5°	74	74	359	1/3·9
S17	Ate-Hebe	5°	86	86	705	1/7·2
S13	Ceres-Hebe	20°	77	73	484	1/5·6
S7	Ate-Hebe	20°	76	72	561	1/6·8
S11	Ate-Hebe	10°	A 85	83	550	1/5·6
S6	Ate-Hebe	10°	54	52	501	1/8·6
S14	Bellona-Hebe....	10°/40°	A 67	50	410	1/7·2
P236	Hebe	30°	7	7	118	1/16
S9	Hebe	30°	13	10	193	1/16·6
P234	Flora-Hebe	20°	43	41	277	1/5·8
P242	Diana-Hebe	20°	59	56	350	1/5·2
S8	Diana-Hebe	10°	66	64	477	1/6·5
79	Ate-Hebe	5°	87	87	502	1/4·8
D	Diana-Hebe	10°	63	60	454	1/6·6
P257	Diana-Hebe	20°	47	44	368	1/7·3
P268	Diana-Hebe	30°	46	40	274	1/5·8
S10	Ate-Hebe	5°	98	98	629	1/5·4
Wc70	Ate-Hebe	20°	A 86	81	550	1/5·8
F16	Diana-Hebe	20°	66	63	480	1/6·6
S15	Hebe	30°	40	35	204	1/4·8
N3	Eos-Hebe	10°	A 72	70	380	1/4·4
N4	Flora-Hebe	30°	A 63	55	360	1/5·5

The coal/overburden ratios for the boreholes in the Griffin Co. leases in Table 3 suggest that 76 million tons of coal is available at an average

ratio of 1 to 5.6. Better-than-average ratios are present near the southern and southeastern margins of the formation due mainly to the gentler dips and thinner "Lake Beds" in these places.

The discovery that the lateral limits of the formation are unfaulted eases the open-cut problems considerably. Nevertheless the steep dip of the Hebe Seam near its blind outcrop on the southwestern, northern, and northeastern sides will make coal extraction difficult in those places.

As far as can be judged from the drill core none of the material in the coal measures will be any more difficult to remove by ripping than that already extracted from the open-cut. The toughest rock encountered during drilling occurred in bands a few inches thick cemented by either marcasite (iron sulphide) or silica. However these thin bands are discontinuous and should present no problems in extraction. Some moderately hard sandstone was found in the fault shear-zone in borehole S14, and more of this can be expected elsewhere along the fault; but this rock is strongly jointed and this should facilitate extraction.

The laterite at the top of the "Lake Beds" is tough and massive in places, and this may pose some problems especially towards the northern end of the area.

Difficulty was experienced in maintaining mud circulation in some uncased boreholes at the level of the Diana and Galatea Seams, and near the top of the Hebe Seam. In these places the sandstone (actually sand) was sufficiently coarse-grained, loose and permeable to allow the drilling fluid to escape. No artesian or sub-artesian water pressures were recorded during drilling but it is realized that the weight of the drilling mud could have kept back water under moderate pressure if any was in fact encountered. However percussion holes throughout the area (although not generally as deep as the rotary holes) have not intersected any significant pressure-water aquifers and it is not expected that pressure-water will pose any major problems during open-cut operations.

RECOMMENDATIONS

Although the drilling done since the last report of the Geological Survey (Low, 1958) is sufficient to show that the Muja Formation is not as severely affected by faulting as was previously expected, there are still many places where details of the structure are uncertain. The drilling validates the estimates made in 1958, but the estimates cannot yet be raised above the "indicated" and "inferred" categories because of inexact knowledge of the structure and grade of the coal in some areas. More drilling may be necessary for efficient planning of the open-cut and if so it should be directed toward clarification of the following points:

1. Location of the blind outcrops and the dip of the coal seams, especially the Hebe Seam, on the southwestern, northern, and northeastern sides of the area.

2. Extent of thinning of the coal seams around borehole S6.

3. Northward extent of the major fault on the eastern side of the area.

4. Coal/overburden ratios in sufficient detail throughout the area to permit compilation of accurate isopach maps.

It is also recommended that a detailed surface contour map of the entire area should be prepared before any further detailed investigations are carried out.

In any future coal drilling programme further experimental electric logging should be carried out on one of the first holes drilled. The minimum diameter of the hole would need to be 5½ inches so that the gamma-ray log could be run as well as the resistivity and self-potential logs. If the experiment is successful rotary holes could be drilled without coring unless coal samples are required. This would result in considerable savings in time and expense.

REFERENCES

Lord, J. H., 1952, Collie Mineral Field: West. Australia Geol. Survey Bull. 105, pt. 1.

——1953, Report on the geology of the Muja Depression: Private report to the Griffin Coal Mining Co.: West. Australia Geol. Survey File 15/1952 (unpublished).

Low, G. H., 1958, Collie Mineral Field: West. Australia Geol. Survey Bull. 105, pt. 2.

——1964, Coal drilling in the Muja Formation near Collie, 1964: West. Australia Geol. Survey Rec. 1964/30 (unpublished).

Rowston, D. L., 1964, Well logging report 12/64, Collie Coal bore No. S17: West. Australia Geol. Survey File 169/64 (unpublished).

DRILLING OF UPPER CRETACEOUS GLAUCONITE DEPOSITS AT DANDARAGAN, GINGIN AND BULLSBROOK

by G. H. Low

ABSTRACT

Upper Cretaceous greensands north of Perth were drilled by 13 auger holes to assess quantity, potash content and attitude of the beds.

At Dandaragan, glauconite reserves are estimated at 3.5 million tons containing 5.4% K_2O overlain by 6 million tons containing 2.3% K_2O. Data in other areas is insufficient to estimate reserves.

At Dandaragan and Gingin the greensands dip at about 1° to the east and southeast, and at Bullsbrook they dip to the west at about 1¾°.

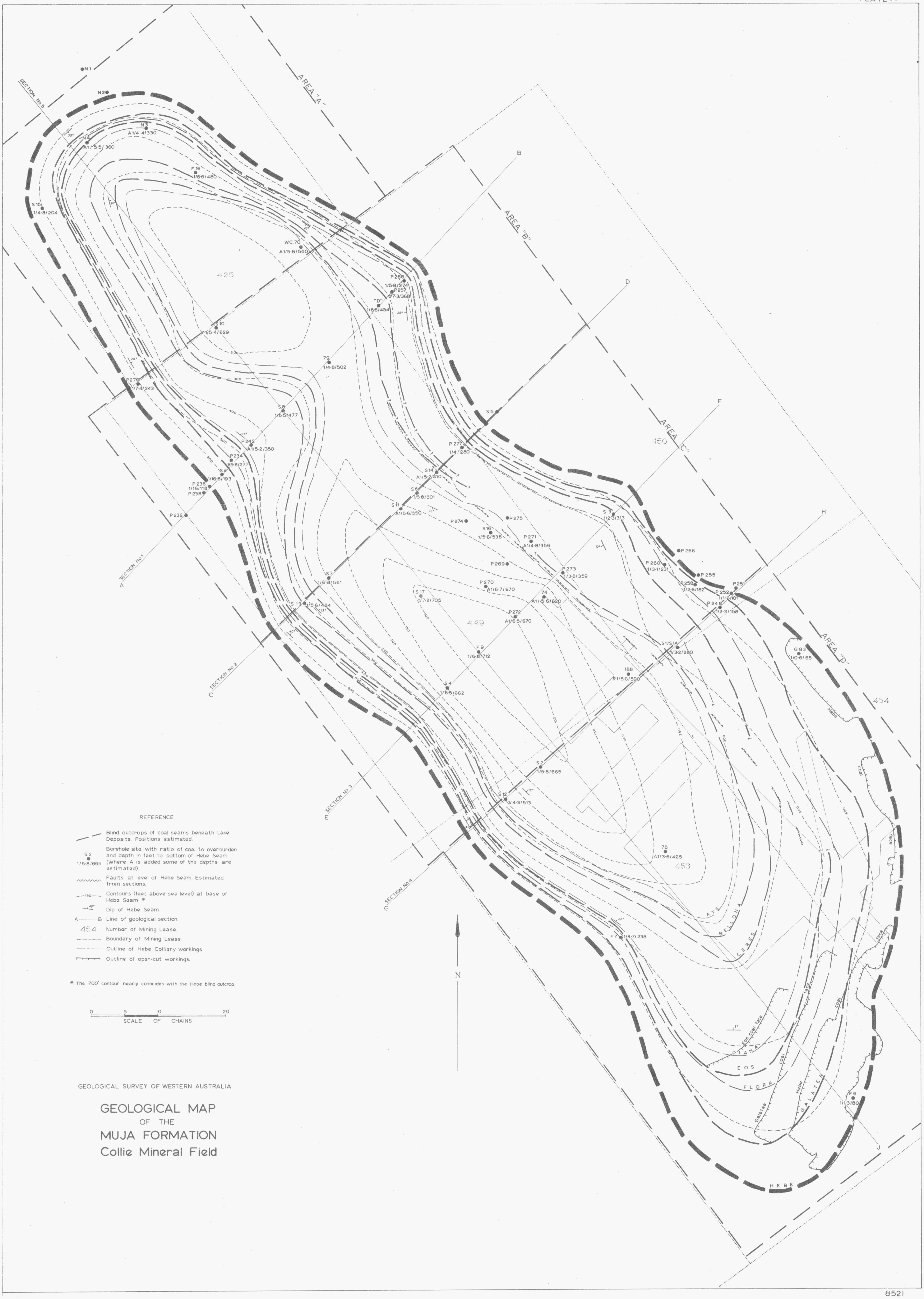
INTRODUCTION

A programme of 13 auger holes was drilled by the Geological Survey to obtain glauconite samples and stratigraphic information from Upper Cretaceous greensands in the Dandaragan, Gingin and Bullsbrook areas. This was done at the request of W. E. Ewers, officer in charge of the C.S.I.R.O. Secondary Industries Laboratory in Perth, to assist the appraisal of the greensands as a source of potash for agricultural and industrial use.

The best-known and most accessible occurrences of greensand in the Perth Basin occur around Dandaragan and Gingin, small farming district towns 85 and 43 miles respectively north of Perth. The glauconite in these two areas occurs in two formations: the Poison Hill Greensand (upper greensand) and the Molecap Greensand (lower greensand).

Three holes were drilled through the Poison Hill Greensand and three through the Molecap Greensand in both the Gingin and Dandaragan areas. The holes were widely spaced to obtain information on any facies variation in the greensands. The final hole was drilled at Bullsbrook where a greensand occurrence was known (Metropolitan Survey File 1951/52), from two water wells 23 miles northeast of Perth on the slopes of the Darling Range. The logs for the 13 holes are summarised in Low (1965), and the locations are shown on Plate 16.

The holes were drilled using a Mines Department Gemco rig fitted with an auger bit. Drilling commenced at Dandaragan on 5th December 1963 and was completed at Bullsbrook on 6th April, 1964.



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL MAP OF THE MUJA FORMATION Collie Mineral Field


SECTION N°1
S.W.
N.E.
A
B
SECTION N°2
C
D
SECTION N°3
E
F
SECTION N°4
G
H
SECTION N°5 (Part I)
N.W.
S.E.
I
SECTION N°5 (Part 2)
J
700' above sea level
West boundary M.L.449
East boundary M.L.449
West boundary ML 453
East boundary ML 453
ATE
BELLONA
CERES
DIANA
EOS
FLORA
GALATEA
HEBE
Part of the Chicken Creek Horizon
Hebe colliery workings
Face N°2 Left Hebe Colliery
Face N°3 Left Hebe Colliery
Face N°4 Left Hebe Colliery
2 chains N.E. of section
Back filled
REFERENCE
Approximate surface
Coal seams projected between boreholes or workings
Faults estimated from sections
Granite-gneiss (part of basement)
Borehole with depth and coal seams intersected (to nearest foot)
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL SECTIONS N^os. 1 to 5
THROUGH PARTS OF THE MUJA FORMATION
Collie Mineral Field
SCALE OF CHAINS
0
5
10
20
V/H = 1
G.H.Low 1964

A preliminary laboratory report by C. E. S. Davis of the C.S.I.R.O. on the composition of greensand samples provided the chemical data used in this report.

GEOLOGY

Scattered exposures of the Upper Cretaceous Poison Hill and Molecap Greensands occur in a zone of variable width which trends north-northwest from about 7 miles south-southeast of Gingin to about 20 miles past Dandaragan. South of Moore River this zone forms an eroded escarpment along the western edge of an elevated sand and laterite-covered plain which extends eastward to the Darling Fault. East of the fault is the granite-gneiss complex of the Western Australian Precambrian Shield. North of the Moore River the escarpment is less distinct, giving way to rounded slopes and some isolated hills with abrupt breakaway faces. The zone of greensand exposures attains a maximum width of about 12 miles at Dandaragan.

The Poison Hill and Molecap Greensands, which are separated by the Gingin Chalk, appear in outcrop as ferruginised red-brown clayey sandstones. They are glauconitic in some areas but there are no unweathered natural exposures.

The greensands presumably extend eastwards to the Darling Fault beneath the superficial cover, but this has not been checked by sub-surface exploration. To the west, between the escarpment and the coast, the underlying Lower Cretaceous and Jurassic rocks are obscured by Pleistocene and Recent sand and limestone.

The two water wells which encountered greensand of the Osborne Formation at Bullsbrook are near the 350-foot contour level on the lower slopes of the Darling Range. They were sunk through a surface cover of gravelly loam about ½ mile west of an outcrop of laterite developed over gneiss, which is the closest exposure of the Precambrian rocks. No outcrops of the Osborne Formation have been seen, and the areal extent of the formation in this area is not known.

STRATIGRAPHY

Table 1 shows the thickness of the various formations and other units in each hole. In the table and the following text, Dandaragan glauconite holes are abbreviated to DGH, Gingin glauconite holes to GGH, and Bullsbrook glauconite holes to BGH.

Sand and Laterite

Alluvial sand occurs on the elevated plain, east of the escarpment, in broad shallow drainage channels and in pockets on the slopes of the escarpment. However most of the sand occurring on the plain and covering the Upper Cretaceous formations is residual, forming part of the normal lateritic profile.

Thicknesses of 30 and 20 feet of sand were penetrated in DGH 6 and GGH 6 respectively. Most of this sand is loose or only very weakly lithified but it contains an increasing proportion of clay and hard nodular ferruginous sandstone towards the base.

Laterite is widely developed over the greensands in the Dandaragan and Gingin areas, and some of the drilling commenced in either pisolitic or massive laterite. The maximum surface concentration of iron is in DGH 5 where Fe_2O_3 was found to average 48.9% in the top 15 feet. Other results were 30.3% down to 5 feet in DGH 1, 36.8% down to 10 feet in DGH 4, and 45.0% down to 5 feet in GGH 1.

A lateritic hardpan was found near the water table in some holes. In DGH 1 samples between 75 and 90 feet average 21% Fe_2O_3, and in DGH 2 a sample from 40 to 45 feet gave 24.3% Fe_2O_3.

The full thickness of the sand, laterite and strongly ferruginised layers is not known but it may be as much as 50 feet in the plain country to the east.

Table 1

THICKNESS OF FORMATIONS IN AUGER HOLES (in feet)

Hole	Sand	Poison Hill Greensand	Gingin Chalk	Molecap Greensand	Dandaragan Sandstone	South Perth Formation	Approximate Depth of Weathering
			DANDARAGAN				
DGH 1	....	135	6	....	....	....	95
DGH 2	....	120	5	....	....	....	70
DGH 3	....	....	10	20	82	....	30
DGH 4	....	....	....	54	1	....	55
DGH 5	....	....	....	46	2	....	48
DGH 6	30	120	....	....	....	....	110
			GINGIN				
GGH 1	....	....	....	44	6	....	35
GGH 2	....	135	....	....	....	....	95
GGH 3	....	....	45	5	3	22	....
GGH 4	....	....	5	91	1	3	55
GGH 5	....	....	15	35	10	....	....
GGH 6	20	73	....	....	....	....	93
			BULLSBROOK				
				Osborne Formation			
BGH 1	....	....	....	138	....	17	12

Poison Hill Greensand

The Poison Hill Greensand consists of weakly lithified clayey glauconitic sandstone and carbonaceous glauconitic claystone, with some thin shaley bands. In DGH 1, DGH 2, DGH 6, and GGH 2, there are 30, 39, 40, and at least 55 feet respectively of dark grey-green to black glauconitic clay immediately above the Gingin Chalk. This is unweathered greensand and it is considerably richer in potash than the overlying material.

The maximum thickness of the Poison Hill Greensand was encountered in GGH 2 at Poison Hill, where the type section for the formation is located. The hole penetrated 135 feet of Poison Hill Greensand before it was abandoned due to drilling difficulties. From 130 to 135 feet the CaO content was 3.1%, which may be due to interfingering with the Gingin Chalk but is more likely to be due to the presence of calcareous fossils in the greensand.

Weathering in the Poison Hill Greensand extends to a maximum depth of 95 feet (DGH 1 and GGH 2) and this has resulted in a leaching of potash and enrichment in iron. In places the weathered greensand is a brown ferruginous sandstone.

The Poison Hill Greensand has been dated by H. S. Edgell (pers. comm.) as Campanian to Upper (?) Santonian in age from the study of samples collected during the drilling. It rests conformably on the Gingin Chalk, and in some places there may be some minor interfingering between the two formations.

Gingin Chalk

The Gingin Chalk is a grey to white, richly fossiliferous chalk, which is somewhat glauconitic at the top and the base. It is Santonian in age.

The maximum penetration of the formation was 45 feet in GGH 3. At this site the top of the Chalk is eroded but the hole penetrated the base of the formation. Its maximum thickness in outcrop is 70 feet in McIntyre Gully, 2 miles north of the Gingin Railway Station (Feldtmann, 1963). However it is a lenticular formation and can be expected to vary considerably in thickness between Gingin and Dandaragan; it may even be absent in some places. Some apparent interfingering with the underlying Molecap Greensand may be seen in the northern face of the Molecap Quarry, but it has been suggested by P. E. Playford (pers. comm.) that the thin chalky layers in the greensand are due to slumping or precipitation of lime from ground waters.

Molecap Greensand

The Molecap Greensand rests conformably beneath the Gingin Chalk, and it is apparently conformable on the Dandaragan Sandstone below. The formation is 91 feet thick in GGH 4, and this is the thickest section recorded to date.

In the Dandaragan area two well-developed phosphatic beds, each about 2 feet thick, lie at the top and the base of the formation. Matheson (1948) states that the phosphate is present as collophanite in nodules and replacing pieces of wood, and as the iron phosphates dufrenite and vivianite in the greensand matrix. The phosphate beds do not appear to be so well developed in the Gingin area, although Feldtmann (1963) records that at Molecap Hill a thin band with phosphate nodules is said to have been found at the base of the formation during quarrying operations, and that a band 3 to 30 inches thick of dark red-brown ferruginous material at the top of the formation carries phosphatic nodules up to 8 inches in diameter.

Phosphate was determined in a few of the samples from the drilling, and the best results were 3.1% P_2O_5 at the base of the Molecap Greensand in DGH 3 and 2.0% P_2O_5 between 10 and 15 feet at the base of the Gingin Chalk in GGH 5 at Molecap Hill. DGH 4 at the "Hole in the Wall" phosphate deposit, and DGH 5 at the "Caves" phosphate deposit, two of the occurrences described in some detail by Matheson (1948), showed only 0.3% and 1.2% P_2O_5 respectively. However too much reliance should not be placed on these results because auger sampling methods are not very satisfactory where the phosphate is mainly in nodular form.

The Molecap Greensand is deeply weathered except where overlain by the Gingin Chalk. It usually contains less glauconite than the Poison Hill Greensand and is somewhat richer in glauconite at Gingin than at Dandaragan.

The Molecap Greensand has been dated as Upper Cretaceous (Santonian) in age by H. S. Edgell (pers. comm.)

Osborne Formation

Palaeontological examinations by H. S. Edgell (pers. comm.) show that the 138 feet of glauconitic clay and sand in BGH 1 is part of the Upper Cretaceous (Cenomanian) Osborne Formation. The material penetrated is a yellow, red-brown, and green-grey clayey glauconitic sandstone, with some brown argillaceous siltstone. The top 12 feet is somewhat weathered, showing slight ferruginisation. This section averaged 2.3% K_2O, and the next 100 feet averaged 3.0% K_2O. The top 50 feet averaged 3.1% K_2O, which is a better near-surface percentage than in any other hole.

It appears that the Osborne Formation overlies 17 feet of South Perth Formation in this hole, but the nature of the contact is not known.

Dandaragan Sandstone

The thickest section of Dandaragan Sandstone penetrated during the drilling programme is in DGH 3 where it is 82 feet thick, but the base was not reached. It is a cross-bedded or massive, coarse to very coarse-grained, feldspathic sandstone, conglomeratic in places. It is apparently conformable beneath the Molecap Greensand and rests with angular unconformity on the Yarragadee Formation (Dandaragan area) or on the South Perth Formation (Gingin area). Analyses of samples from GGH 3, 4, and 5 showed more potash (probably as sericite) in the Dandaragan Sandstone than in the green sand just above.

Although no diagnostic fossils have been found in the Dandaragan Sandstone, it is probably Upper Cretaceous in age (McWhae and others, 1958).

South Perth Formation

A few feet of orange and purple, sandy siltstone was penetrated near the bases of GGH 3, GGH 4, and BGH 1. This section is correlated with the Lower Cretaceous (Aptian-Neocomian) South Perth Formation by H. S. Edgell (pers. comm.), and it is regarded as being laterally equivalent to the upper part of the Yarragadee Formation.

STRUCTURE

In the Dandaragan area the limited exposures indicate that the Upper Cretaceous rocks dip at 1° to 4° to the southeast, with occasional reversals of dip which suggest gentle warping (Matheson, 1948). The altitudes of the holes are only known approximately, but from DGH 3, 4, and 5 it is estimated that the dip of the Molecap Greensand in the area is only 0° 45′ to the east-southeast. The base of the Poison Hill Greensand drops only about 130 feet between DGH 1 and 6, a distance of almost 14 miles.

At Gingin the dips of the top and the base of the Molecap Greensand, estimated from GGH 3, 4, and 5, are to the east and the west respectively, both being less than 1 degree. The base of the Molecap Greensand is only about 200 feet lower at Gingin than at Dandaragan.

At Bullsbrook the base of the Osborne Formation was cut at about 212 feet above sea level in BGH 1, whereas in the No. 3 Pearce aerodrome bore, 2.7 miles to the west, it occurs at about 250 feet below sea level, a difference in elevation of approximately 460 feet. This difference is thought to be due to a westerly dip of about 1¾ degrees rather than to faulting. Seismic work has shown a possible reversal from the regional easterly dip in deeper formations in this area (Walker and Raitt, 1964).

RESERVES

Because of insufficient outcrops, deep weathering, and inadequate sub-surface exploration (by drilling or pits), it is not possible to make satisfactory estimates of reserves for most of the areas in which the greensands occur.

An exception is in the vicinity of DGH 2 in the Dandaragan area where the nature of the outcrop and topography permits a minimum estimate to be made. Using a density of 15 cubic feet to the ton, it is estimated that there is 6 million tons of weathered Poison Hill Greensand carrying 2.3 per cent. K_2O, overlying 3.5 million tons of fresh Poison Hill Greensand carrying 5.4 per cent K_2O. The weathered material is 70 feet thick and the fresh material is 40 feet thick.

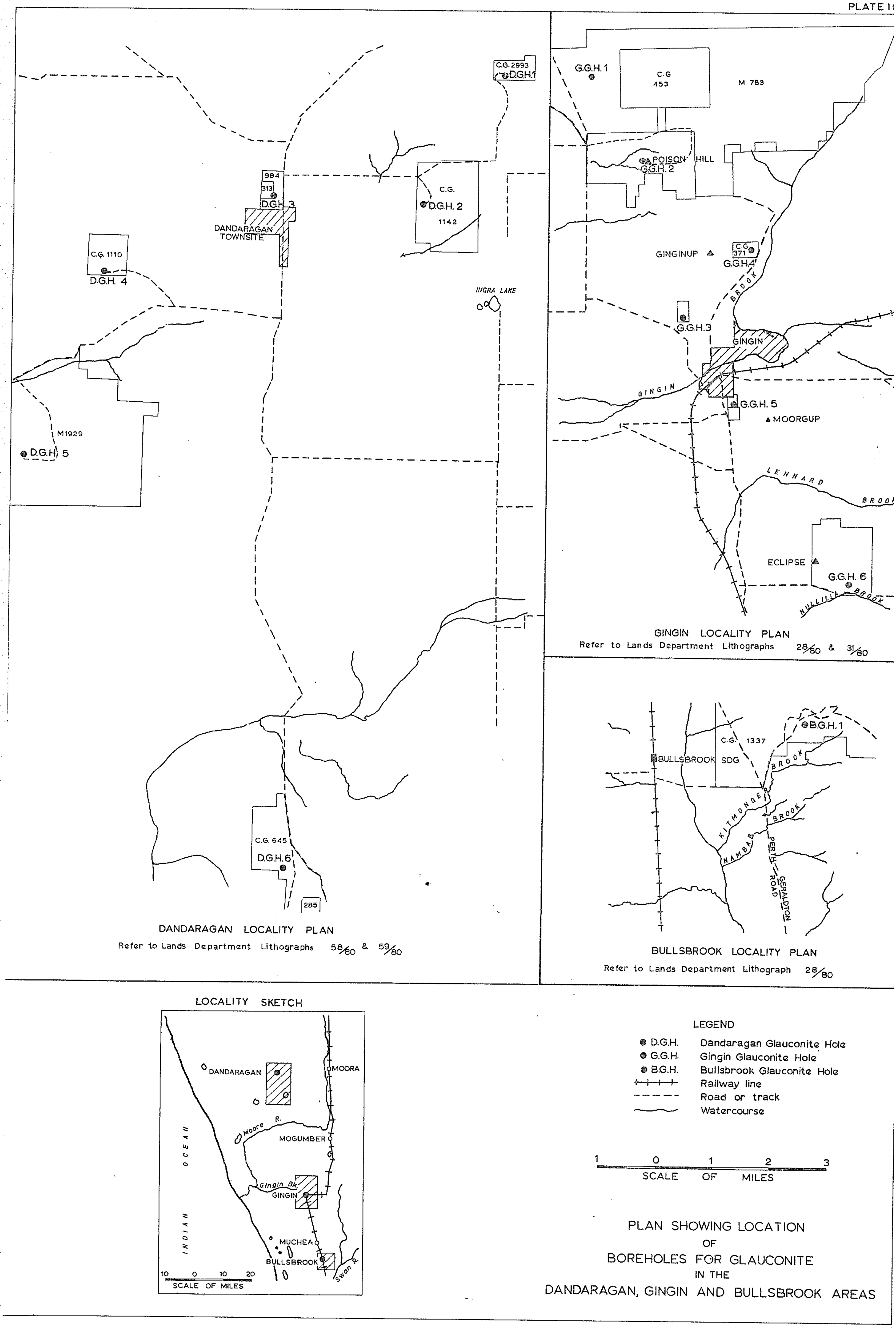
CONCLUSIONS

The Poison Hill Greensand was found to be strongly weathered down to a maximum depth of 110 feet. Below the weathered greensand in DGH 2, DGH 6, and GGH 2, sections of unweathered grey-green to black glauconitic clay, ranging in thickness from 30 to 55 feet, were found to contain 4½ to 5½ per cent K_2O. The highest potash percentage (average 5.4 per cent. K_2O between 70 and 110 feet) was found in DGH 2.

The Molecap Greensand was tested in DGH 3, 4, and 5, and GGH 1, 3, 4, and 5. It contains less glauconite (maximum of 3.6 per cent K_2O in GGH 1 and 5) than the best sections of the Poison Hill Greensand, but the thickness of the weathered material over the Molecap Greensand is generally thinner than is the case with the Poison Hill Greensand.

The greensand unit at Bullsbrook (the Osborne Formation) is topographically suited to a detailed investigation by drilling, and may prove suitable for quarrying. The potash percentage (2.3 per cent to 12 feet below the surface and 3.0 per cent. from 12 to 112 feet) is less than for the best sections in the Poison Hill and Molecap Greensands, but the relatively high near-surface potash content at the Bullsbrook locality and its convenient location are factors in its favour.

The planning of future investigations by drilling of the glauconite deposits depends upon the results of current potash extraction experiments being made by the C.S.I.R.O. Boreholes may be sited to prove reserves of the near-surface lower grade material in the Molecap or Osborne Formations, or reserves in the deeper but higher grade sections of the Poison Hill Greensand.



PLAN SHOWING LOCATION
OF
BOREHOLES FOR GLAUCONITE
IN THE
DANDARAGAN, GINGIN AND BULLSBROOK AREAS

REFERENCES

Feldtmann, F. R., 1963, Some pelecypods from the Cretaceous Gingin Chalk, Western Australia, together with some descriptions of the principal chalk exposures: Royal Soc. West. Australia Jour., v. 46, p. 101-125.

Low, G. H., 1965, Drilling of Upper Cretaceous glauconite deposits at Dandaragan, Gingin and Bullsbrook: West. Australia Geol. Survey Rec. 1965/6 (unpublished).

McWhae, J. R. H., Playford, P. E., Lindner, A. W., Glenister, B. F., and Balme, B. E., 1958 The stratigraphy of Western Australia: Geol. Soc. Australia Jour., v. 4, pt. 2.

Matheson, R. S., 1948, The Dandaragan phosphate deposits: West. Australia Mines Dept. Min. Res. Bull. 4.

Walker, D. J. and Raitt, J. S., 1964, Bullsbrook (Perth Basin) seismic survey: Bur. Min. Resour. Aust. Rec. 1964/155 (unpublished).

PROTEROZOIC GRANITES OF THE ASHBURTON REGION, NORTH-WEST DIVISION

by J. L. Daniels

ABSTRACT

Four Proterozoic granites from the Ashburton Region are discussed. Their petrography, contact effects and structural setting are described and their economic possibilities outlined.

INTRODUCTION

Granitic rocks have long been known in the northwest of Western Australia. Early descriptions of granitic rocks from the region between Nanutarra and Maroonah are given by Talbot (1926), who also states (p. 61, 62) "the granite on the Gascoyne near Lockier Range, described by Mr. Maitland in Bulletin No. 33 (1909), is probably an extension of the same belt." Probably part of the same suite are the granites to the north of Nanutarra and extending intermittently to Peedamullah; those just west of Parry Range, Mt. Alexander and Uaroo; and those near Lyndon. The approximate distribution of these masses is given on the Tectonic Map of Australia (published 1960).

An airborne magnetic and radiometric survey of the Carnarvon Basin was made by the Bureau of Mineral Resources between 1956 and 1961 (Spence, 1962). This survey extended a short distance into the Precambrian and located several radiometric anomalies, some of which were associated with granitic rocks.

Recent mapping of the Wyloo 1 : 250,000 Sheet (SF/50-10) by the Geological Survey has delineated the boundaries of the following granitic masses (Plate 17):

Mt. Danvers Granodiorite
Wongida Creek Granodiorite
Boolaloo Granodiorite
Kilba Granite.

This report is a summary of the available knowledge concerning samples from individual granitic bodies, some of their contact regions and the asssociated rocks.

AGE

All the granitic rocks in the northern part of the area intrude metamorphosed sediments of the Wyloo Group (Halligan and Daniels, 1964). This is probably also the case further south in the Edmund and Minilya Sheet areas. In the Henry River region, the granites are unconformably overlain by the Bangemall Group.

Their relationship to the Bresnahan Group is not definitely known, but tourmaline-rich schists occur as pebbles and boulders in the Cherrybooka Conglomerate (the lower formation of the Bresnahan Group). These could be related to the abundant examples of tourmaline-impregnated schists of the Wyloo Group, seen in the Wongida Creek Granodiorite, and suggest that the emplacement of one or more of the granites may have taken place before the Bresnahan Group was deposited. In the Wyloo and Yarraloola Sheet areas there are several isolated outliers of sandstone, quartzite and conglomerate which are tentatively correlated with the Bresnahan Group. They overlie the Ashburton Formation and are unconformably overlain in one place by Bangemall Group sediments. They are not known to contain any granite pebbles and, along the western face of the Parry Range, are intruded by granite. This particular granite is not well exposed but may be a continuation of the Kilba Granite.

One age determination on the Boolaloo Granodiorite (Leggo and others, 1965) indicates an age of 1,720 million years.

Some of the granitic rocks show the effects of shearing while others are structurally homogeneous, probably indicating that intrusion took place over an interval of time during the waning phases of the Ophthalmian Fold Period (Halligan and Daniels, 1964).

STRUCTURAL SETTING

The central and southern sections of the Hamersley Range show a strong development of easterly trending fold structures (MacLeod and others, 1963; Halligan and Daniels, 1964). Followed to the west, these structures gradually swing to a northerly trend. It is in this northerly trending zone that the granitic rocks are intruded and is here also where the highest grade of regional metamorphism is attained.

Near Kooline homestead, 14 miles south of Mt. de Courcey, the Ashburton Formation shows the effects of dynamic metamorphism, with production of strong cleavages. No regional metamorphic consequences have been noted and the local fold axes show a general westerly trend. Some 36 miles to the northwest, near Mt. Danvers, mica schists are common. Minor fold axes in this area have a northwesterly trend. Between Mt. Alexander and the Parry Range minor fold axes generally show a northwesterly to northerly trend. Near Mt. Alexander very coarse mica schist and plagioclase amphibolite are abundant.

GENERAL CHARACTERISTICS

The granites generally give rise either to low sandy plains with isolated monadocks or to slightly undulating ground, strewn with granite boulders.

Fresh surfaces are white or light grey, but they weather to pale yellow-brown. Some of the granite of Black Hill, and of the small hills to the west and southwest of Mt. Hubert is anomalous in that it weathers to very dark brown, or almost black. This is caused by a thin coating, possibly of an iron mineral, associated with jointing. Between this dark outer layer and the unweathered granite is a bleached zone up to a quarter of an inch wide. The staining and the associated bleaching may have been caused by late hydrothermal activity.

The Boolaloo body frequently occurs as accumulations of boulders which show only a very thin skin of weathered material. In the Kilba Granite the depth of weathering varies widely; some areas show deep weathering producing a very friable granite crust and jagged hills whereas elsewhere in the same granite exfoliation commonly exposes fresh granite and gives rise to smooth rounded dome-shaped hills.

DESCRIPTIONS OF INDIVIDUAL INTRUSIONS

Mt. Danvers Granodiorite

Some 4 miles southeast of Mt. Danvers is a small oval outcrop of granitic rock occupying an area of approximately 14 square miles (Plate 17). It has a maximum length of 8 miles. It intrudes cleaved shale and mica schist of the Ashburton Formation and is unconformably overlain in the

(3)—95166

southwest by the Bangemall Group. Fresh dolerite dykes cut the granite and also extend into the Bangemall Group. Along the line of the unconformity, faulting accompanied by intense shearing has affected the mass, with the consequent production of a zone of granitic gneiss some 50 yards wide.

The main mass is composed of quartz, plagioclase, microcline and biotite with accessory iron oxide, zircon, sphene, apatite, epidote, chlorite and possible prehnite. It may be termed a granodiorite (Table 1, No. 3). The quartz, as a mosaic of small crystals, forms irregularly shaped "pools". It also occurs as fine-grained inclusions in plagioclase and to a lesser extent in the biotite. The plagioclase is sericitised and saussuritised andesine (An_{35}), with rare remaining fresh areas showing albite twinning or, rarely, albite-carlsbad combinations. Some crystals are zoned. Several crystals show moderately fresh, thin rims, probably preserved on account of their more albitic composition allowing less secondary alteration. The biotite, green-brown and strongly pleochroic, possesses ragged terminations and carries inclusions of opaques, quartz and zircon, the latter surrounded by very strongly pleochroic haloes. Slight replacement of the biotite by epidote, chlorite and possible prehnite was noted. Frequently the biotite and iron oxide forms aggregates with associated fine-grained quartz and relatively fresh, fine-grained andesine (An_{35}).

Table 1

MODAL ANALYSES OF THE GRANITIC ROCKS

	1	2	3	4	5
Quartz	39·7	35·9	38·2	27·0	31·2
Plagioclase	36·1	31·4	33·4	39·8	38·5
Potash Feldspar	5·9	10·7	8·8	25·4	20·3
Biotite	17·1	20·6	19·1	4·5	1·0
Muscovite	....	0·2	0·1	2·7	8·4
Tourmaline	0·6	....	....	....	0·1
Opaques	0·2	....	....	....	....
Apatite	....	0·1	0·3	0·3	0·1
Zircon	0·1	....	....	....	Trace
Epidote	0·2	1·1	....	....	....
Calcite	....	....	....	0·3	0·3
Total	99·9	100·0	99·9	100·0	99·9
Plagioclase anorthite percentage	35–40	10–15	35	10	7

1. Boolaloo Granodiorite
2. Wongida Creek Granodiorite
3. Mt. Danvers Granodiorite
4. Kilba Granite
5. Kilba Granite

Rare quartz veins cut the granodiorite. They carry traces of muscovite and abundant trails of minute liquid inclusions with gas bubbles.

The granodiorite is slightly xenolithic, the xenoliths being of the order of one or two inches in diameter, and well rounded. One example consists of a fine-grained aggregate of ragged flakes of green-brown biotite and evenly disseminated subhedral magnetite in a groundmass of plagioclase laths and a small amount of fine-grained anhedral quartz. The texture and petrography would suggest that the original rock was a medium-grained igneous rock of intermediate composition.

Wongida Creek Granodiorite

A granitic mass intrusive into metamorphosed sediments of the Ashburton Formation occupies an area of approximately 34 square miles, just west of Wongida Creek, and is unconformably overlain by the Bangemall Group. Wongida Creek flows along the line of the unconformity on the eastern margin of the mass.

The granite is locally gneissose, and many pegmatite and aplite dykes cut the body. Xenoliths are present.

In thin section the rock is composed of quartz, microcline microperthite, plagioclase and biotite with accessory opaques, chlorite, epidote, sphene, apatite and zircon (Table 1, No. 2). The microcline is usually fresh and shows cross-hatched albite-pericline twinning either alone or combined with simple carlsbad twinning. It is subordinate to the plagioclase (andesine) which has been almost completely sericitised and saussuritised and rarely shows unaltered relics. The biotite is dark brown and carries inclusions of, or is closely associated with, opaques, epidote and sphene. It is largely replaced by green chlorite showing anomalous green and brown interference colours.

Towards the western margin of the intrusion, near the Henry River, there is a muscovite-rich tourmaline granite facies.

In contrast to the highly altered host rock are the fresh aplite veins. They consist of a fine-grained mosaic of quartz, microcline, plagioclase and muscovite with traces of iron oxide, garnet, apatite and very rare epidote and chlorite. The plagioclase has a composition of An_{10-15} and occasionally shows very slight sericitisation.

Thin pegmatites are locally abundant and consist of quartz and white feldspar, often in graphic intergrowth, abundant tourmaline and some muscovite.

Some of the large schist xenoliths show abundant tourmaline, and in some instances almost complete replacement by tourmaline has taken place. A typical thin section of the altered rocks shows an association of tourmaline and quartz with accessory muscovite, iron oxide, apatite and biotite. The tourmaline shows strong pleochroism from pale pink to very dark olive green. Most of the grains show very dark blue-green cores and are generally riddled with quartz inclusions.

Boolaloo Granodiorite

The Boolaloo Granodiorite is an irregularly shaped body with an outcrop of approximately 255 square miles. It is the largest of the granitic masses in the Wyloo Sheet area but may eventually prove to be smaller than the Kilba body when the latter is fully mapped.

In hand specimen the rock is grey-white and speckled with biotite flakes. The quartz is generally a light grey and the feldspar a pale yellow-green.

A typical sample consists of quartz, plagioclase, microcline and biotite with accessory muscovite, apatite, zircon, tourmaline and secondary chlorite, epidote and sericite. Strain extinction is commonly developed in the quartz, which frequently has crystallised into a mosaic of small grains. The microcline is fresh and slightly perthitic, and is subordinate to the plagioclase. The latter has a composition of An_{35-40} and is largely replaced by a fine-grained aggregate of sericite and granular epidote. The biotite is a dark brown to red-brown variety frequently with abundant inclusions of sphene and zircon, surrounded by pleochroic haloes. It almost always shows various degrees of chloritisation. Epidote is often closely associated with the biotite suggesting that the former is replacing the latter. The rock may be termed a biotite granodiorite.

Variations in the microcline/plagioclase ratio occur. It is not known if these are local variations due to differentiation in the granite or if they represent discrete intrusions.

One example shows included half inch areas of a medium to fine-grained assemblage of plagioclase, muscovite and biotite with very rare quartz. It may represent a small syenitic differentiate.

Other larger areas of unknown extent include a tonalite and a nearby adamellite. Apart from the ratio of potash feldspar to plagioclase, the mineralogy of the rock types is similar.

The effects of shearing are often in evidence. An example of a sheared granodiorite occurs towards the western margin of the body some 10 miles northwest of Boolaloo Homestead. The rock shows a pronounced orientation of the biotite and a tendency towards differentiation of the constituent minerals into monomineralic bands.

Occasional aplite veins cut the granodiorite. These carry quartz, fresh microcline and variable tourmaline, partially chloritised biotite and traces of muscovite, apatite and opaques. Plagioclase is rare or absent. The tourmaline is very dark olive-green with blue-green centres. Rarely, a brown tourmaline is present in parallel intergrowth with the dark olive-green variety.

Xenoliths in the Boolaloo Granodiorite are a common feature and usually consist of well-rounded mafic bodies from one to 12 inches in diameter. Examples up to 8 feet in diameter are known but are very rare. The vast majority are even textured and fine-to medium-grained though rare examples have been noted with small white feldspars. Very rarely, near Mt. Hubert, there are xenoliths of banded quartz-cordierite rocks.

Nine miles north of Boolaloo Homestead, one example of the xenoliths in the granite of that region consists of fine-grained quartz and chlorite with accessory epidote, sphene and muscovite. The chlorite is bright green, shows anomalous purple interference colours and is closely associated with the epidote and sphene. Oval patches of sericite, probably after plagioclase, are present. The rock was probably originally a feldspathic greywacke.

Another example from the same general locality consists almost entirely of small flakes of medium-brown biotite and a smaller amount of blue-green hornblende with accessory quartz, calcite, sphene, epidote and sericitic patches probably after plagioclase. It may originally have been a dolomitic shale.

From the same locality another xenolith consists of plagioclase and hornblende with accessory biotite, opaques and traces of chlorite. The plagioclase is a calcic labradorite with somewhat more calcic cores. It shows well preserved ophitic texture. Oscillatory zoning is present in the few larger plagioclase phenocrysts present. The hornblende displays ragged crystal outlines, carries frequent enclosures of biotite and is sometimes sieved with quartz granules. The texture and composition indicate that the rock was originally basaltic.

Examples of reaction between xenoliths and enclosing granite are numerous. One basic xenolith with an assemblage of labradorite, hornblende, and pale-brown biotite shows a decrease in the hornblende content and a development of green biotite at the granite contact. In the granite itself, no hornblende is present and the biotite is a very dark-brown variety with abundant pleochroic haloes surrounding small zircons. In another xenolith of similar mineralogy, biotite increases both in amount and grain size at the contact, where it is sometimes seen in vermicular intergrowth with quartz. Small laths of labradorite similar to those in the xenolith are present in the contact region and extend a few millimeters into the granodiorite where they are surrounded by more sodic plagioclase. Mafic zones in the granite immediately surrounding xenoliths are not uncommon and testify to a certain amount of assimilation.

Kilba Granite

The Kilba Granite occupies a minimum area of 75 square miles in the Wyloo Sheet area. It probably extends to the west of Nanutarra and may also be continuous with the isolated granitic outcrops west of Parry Range. It intrudes metamorphosed Ashburton Formation rocks with strong discordance in the southwest where long thin apophyses of the rock penetrate the adjacent schists. Xenoliths of country rock are present in the mass but are not common; they are composed of mica schists identical to the nearby Ashburton Formation schists.

The Kilba body is a composite intrusion with two main facies: a medium-grained one, forming the bulk of the intrusion, and a porphyritic facies. Migmatites and gneissose granites are known along the western and southern contact regions; they possibly represent an early phase of instrusion. The distribution of these and the relation of the granite to the surrounding schists is shown in Plate 18.

In thin section the medium-grained facies, a muscovite-biotite granite, consists of subhedral laths of plagioclase with interstitial quartz, microcline, muscovite and biotite. The plagioclase, An_7, occasionally shows rims with more sodic composition. Rounded inclusions of quartz are present and very slight sericitisation has taken place. The mica flakes tend to be closely aggregated. Zircon inclusions are common in the biotite, but were not noted in the muscovite.

The porphyritic facies is similar, but carries euhedral microcline crystals up to three inches long usually exhibiting both cross-hatched albite-pericline and simple carlsbad twinning. A preferred long-axis orientation of the phenocrysts is a common feature. There is a general northerly trend modified near the contacts. Measurements were made in several places of the horizontal directional component and histograms constructed (Plate 19).

The relationship between the porphyritic and medium-grained facies is not fully understood. In the northeast of the porphyritic area, the abundance of phenocrysts decreases rapidly and one rock apparently grades into the other. In the extreme south the phenocrysts become smaller and poorly oriented, and the rock grades into the medium-grained facies, which forms the contact.

Quartz veins and pegmatites are rare in the granitic mass, but are more frequent in the marginal rocks. Most of the quartz is barren, but malachite and galena mineralisation was noted in a quartz reef developed at the contact of the granite and the country rock two and a half miles southeast of Mt. Alexander. Some 2½ miles south-southeast of Mt. Alexander abundant small crystals of beryl were found in a small pegmatite, with associated muscovite and dark brown triplite.

CONTACT EFFECTS

Contacts are not generally well exposed but, where seen, were found to show much variation.

On the western slopes of Mt. Alexander thin muscovite granite dykes intrude the metasediments. The contacts are sharp and show no reaction. Two and a half to three miles south-southeast of Mt. Alexander, the granite is probably responsible for the small amount of tourmalinisation which has affected nearby orthoquartzite. In the same general locality, a small roof pendant of tremolite marble shows a patchy development of very coarse grey-white tremolite blades along the contact and joint planes in the marble. This is a similar effect to that noted in a larger tremolite marble roof pendant 8 miles south-southeast of Mt. Alexander though here it is more pronounced. A small pebble of garnet-diopside rock was found in the immediate vicinity, but no skarns were found in situ. Abundant apophyses of the granite cut the marble and the granite carries many xenoliths of marble and amphibole schist, suggesting that stoping has to some extent been an active process in the emplacement of the Kilba Granite.

Apart from these occurrences, the Kilba Granite does not produce much contact alteration. Most of the contacts visited were sharp.

Exposures to within a few inches of the contact of the Boolaloo Granodiorite with the Ashburton Formation at Boolaloo Homestead consist of brown quartz-muscovite schists typical of the Ashburton Formation of this area. It is cut by quartz veins carrying occasional aggregates of pink andalusite crystals up to 1 inch across and 4 inches long. A vein of andalusite in micaceous schist has been recorded near the granite contact about 5 miles southwest of Mt. Black (Black Hill) (Talbot, 1926, p. 46).

On the eastern side of the Boolaloo Granite, 5 miles northeast of Boolaloo Homestead, and extending intermittently for some 14 miles southward is an area of cordierite and andalusite-rich rocks. These are generally well banded, hard and glassy in strong contrast to the more friable and well-cleaved Ashburton Formation elsewere. There is little doubt that these rocks are metamorphosed Ashburton Formation sediments which have been contact metamorphosed and metasomatised by the granite. Their more compact nature has preserved them from some of the effects of the

Ophthalmian Fold Period and they consequently exhibit a different air photo-pattern from the more normal Ashburton Formation. More work on these rocks is being undertaken.

Stoping has also been effective in the emplacement of the Boolaloo Granite. Evidence is readily available on the northeast of Mt. Hubert, where abundant granite veins cut the country rock of cordierite and andalusite-rich rocks. Fragments broken off have become rounded and in the neighbourhood of the contact are generally surrounded by a thin zone of mafic granite, suggesting gradual assimilation of the xenolithic material by the granite.

There is an unusual type of contact phenomenon some 10 miles north of Boolaloo Homestead. The Ashburton Formation here consists of strongly cleaved dark-brown quartz-mica schist with occasional very hard fine-grained bands of slightly micaceous feldspathic sandstone. The schist is cut by many quartz veins.

At the contact is developed a pale-blue medium-grained rock with abundant rounded or oval areas of bluish quartz up to half an inch in diameter. A similar rock is developed in the schists as apparently isolated pods and veins within 50 yards of the contact. In thin section, the rock is composed of a very fine-grained mylonitised groundmass of quartz and potash feldspar with small laths of biotite and some muscovite. Set in this matrix are oval aggregates of biotite, quartz mosaic and altered plagioclase. The biotite shows fragmentation at the edges and has frequently been drawn out into long trails. Generally the plagioclase shows a rounded sericitised core surrounded by a thin rim of relatively fresh (?) albite with, in contrast to the core, a tendency towards a euhedral outline. Oscillatory zoning is noted in the rim. The rock probably developed as a contact porphyry and was subsequently sheared. The shearing has not affected the nearby granite and probably ended before the complete solidification of the rock—hence the euhedral rim to some of the plagioclase grains. It is not impossible that the rock was injected as a crystal "mush".

ECONOMIC POSSIBILITIES

Galena was seen in a quartz vein at the contact of the Kilba Granite near Mt. Alexander. It has been worked some years ago on a very small scale. The workings include a pit 20 feet deep which was abandoned on account of the prevailing lead price. It appears that there is a genetic connection between the granite and the development of the galena. In the Wyloo Sheet area lead is known from several localities, among them the Silent Sisters deposit, some 48 miles southeast of Boolaloo. Here, galena occurs in veins in dolomite in the Wyloo Group. The galena has been dated at 1,700 m.y. $\pm$ 150 m.y. (Leggo and others, 1965); this age is close to that of the Boolaloo Granodiorite.

The association of Boolaloo Granodiorite with cordierite-rich rocks, probably partly metasomatic, resembles that described from Sweden by Geijer (1963). He stresses the close genetic connection between granite emplacement with sulphide mineralisation and accompanying magnesium metasomatism, this latter being responsible for the production of extensive bodies of cordierite-bearing mica schists. Some of the Swedish sulphide ores are thought to have developed "in front of the granite" (Geijer, 1963, p. 117). The cordierite-rich rocks near the Boolaloo Granodiorite show evidence of development before emplacement of the main mass. Grains of sulphide minerals have been found in the cordierite rocks, but no large masses located.

In view of the similarities to the Swedish examples, a prospecting programme for sulphides along the eastern margin of the Boolaloo Granodiorite is recommended. This region is poorly exposed, being largely covered with alluvium and river gravels associated with the Ashburton River.

There seems little possibility of beryl occurring in sufficiently large concentrations in the pegmatites to be of value.

CONCLUSIONS.

The granitic rocks of the Wyloo Sheet area are divisible into two groups: a mafic biotite granodiorite suite to the east and a leucocratic muscovite granite to the west. Both have been intruded during the waning phases of the Ophthalmian Fold Period. The biotite granodiorite suite is probably older, as it shows more effects of shearing than the muscovite granite.

Xenoliths are common in the biotite granodiorite but relatively rare in the muscovite granite. Those present in the latter closely resemble the adjacent country rock. This is not generally the case with the Boolaloo Granodiorite suggesting that incorporation of these xenoliths took place at a much greater depth than their present position. Evidence of stoping is present in both the Kilba Granite and the Boolaloo Granodiorite. The cordierite-rich rocks near Mt. Hubert are probably part of an early aureole which the granodiorite has later partially stoped and assimilated.

Intrusion has taken place in an area of general northerly trending structures where noticeable increase in the grade of metamorphism has occurred. It is also the area where migmatites are recorded.

REFERENCES

Geijer, P., 1963, The Precambrian of Sweden *in* The Precambrian, v. 1, ed. by K. Rankama: New York, Interscience.

Halligan, R., and Daniels, J. L., 1964, Precambrian geology of the Ashburton Valley region, North-West Division: West. Australia Geol. Survey Ann. Rept. 1963.

Leggo, P. J., Compston, W., and Trendall, A. F., 1965, Radiometric ages of some Precambrian rocks from the North West Division of Western Australia: Geol. Soc. Australia Jour., v. 12, pt. 1.

MacLeod, W. N., de la Hunty, L. E., Jones, W. R., and Halligan, R., 1163, A Preliminary Report on the Hamersley Iron Province, North West Division: West. Australia Geol. Survey Ann. Rept. 1962.

Maitland, A. G., 1909, Geological investigations in the Gascoyne, Ashburton and West Pilbara Goldfields: West. Australia Geol. Survey Bull. 33.

Spence, A. G., 1962, Carnarvon Basin airborne magnetic and radiometric survey W.A. 1961: Bur. Min. Resour. Aust. Rec. 1962/191 (unpublished).

Talbot, H. W. B., 1926, A geological reconnaissance of part of the Ashburton drainage basin with notes on the country southwards to Meekatharra: West. Australia Geol. Survey Bull. 85.

BRECCIAS ASSOCIATED WITH THE PROTEROZOIC BANGEMALL GROUP, NORTH WEST DIVISION

by J. L. Daniels

ABSTRACT

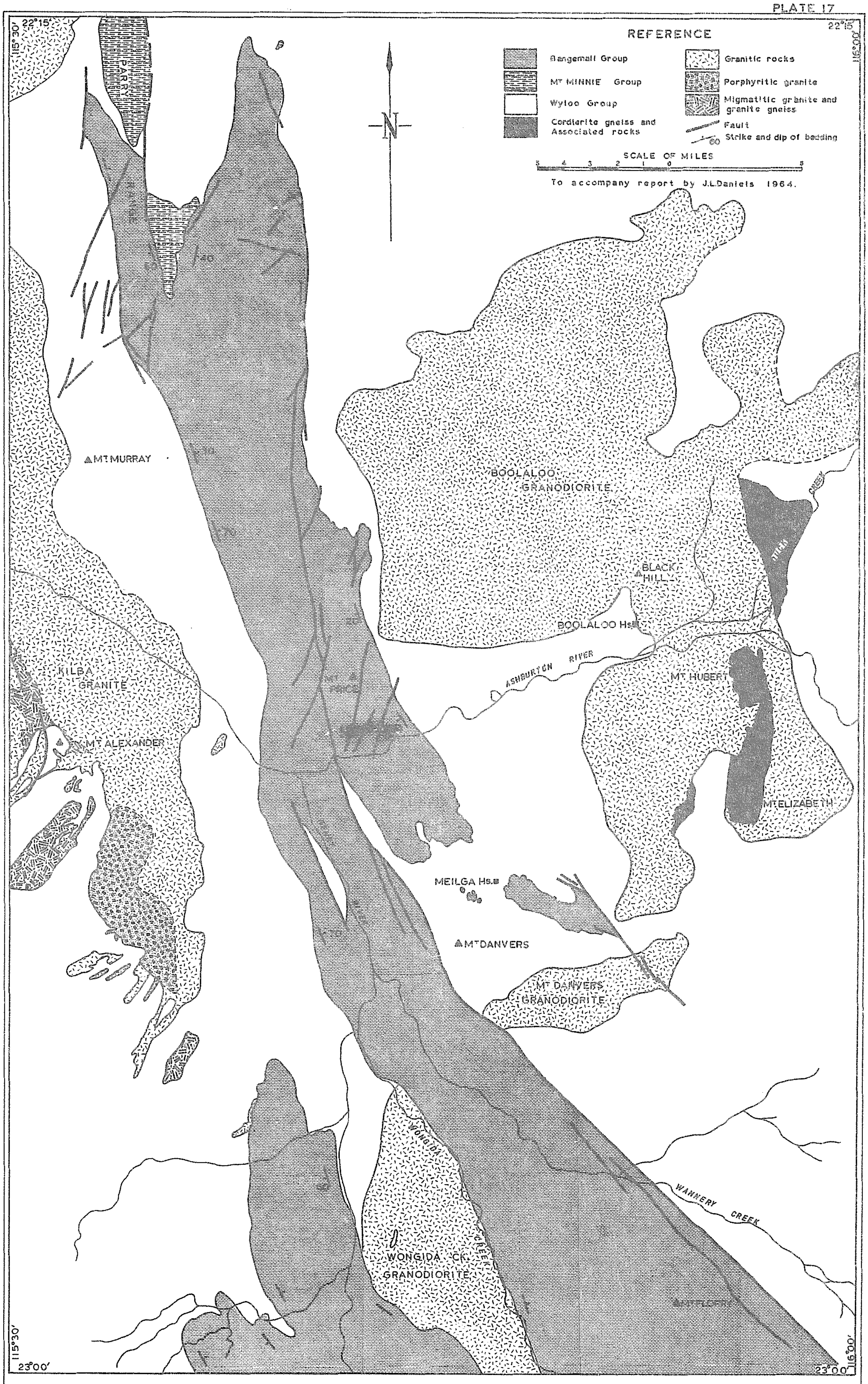
Breccias composed of fragmented sedimentary rocks are common in the Proterozoic Bangemall Group between the Parry Range and Mt. Florry. The fragments forming the breccias are almost entirely composed of Bangemall Group sediments. Three types of breccia are recognised and described: sedimentary, tectonic and diapiric.

They probably originated during a protracted series of land movements associated with the Edmundian Fold Period and are probably different results of the one process.

INTRODUCTION

During regional mapping of the western half of Wyloo and the northern part of Edmund Sheet areas (SF/50-10 and SF/50-14), comparatively abundant breccias were found closely associated with the youngest Proterozoic rocks of the area, the Bangemall Group. The breccias are coarse to extremely coarse, fragmented and poorly sorted sedimentary rocks usually forming a distinctive

PLATE 17



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL MAP SHOWING
DISTRIBUTION OF GRANITES
IN THE SOUTH WESTERN PART OF THE WYLOO 1:250,000 SHEET AREA

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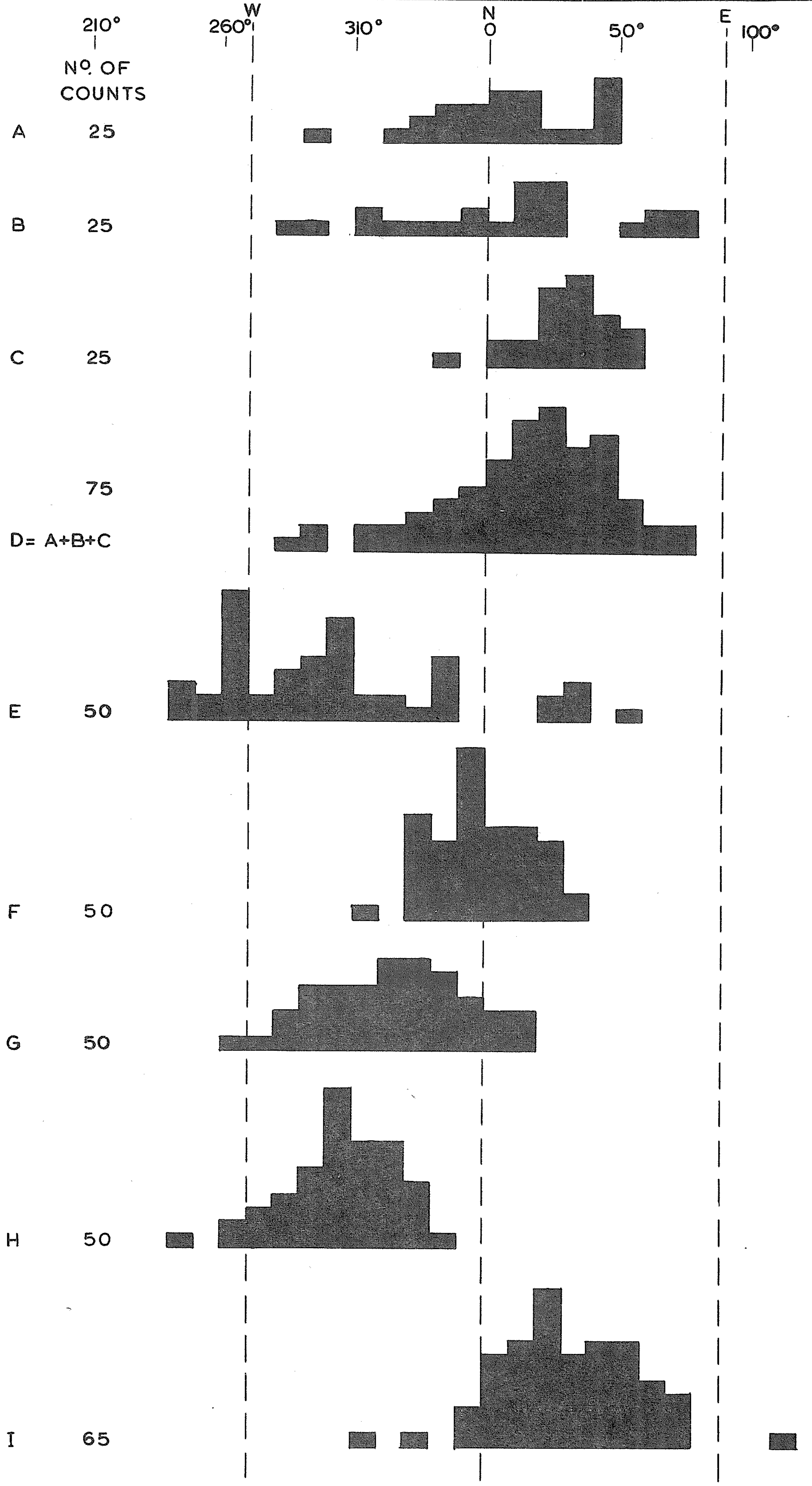
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SKETCH MAP OF THE SOUTHERN PORTION OF THE KILBA GRANITE

PLATE 18

8667



HISTOGRAMS SHOWING
ORIENTATION OF FELDSPAR LATHS, MEASURED IN THE HORIZONTAL PLANE, IN THE KILBA GRANITE

topography. Hills composed of the breccias are generally craggy with smooth lower slopes covered by secondary breccia debris. In consequence, field relations of the primary breccia to the rest of the Bangemall Group sequence are difficult to interpret. On many of the lower hills, considerable doubt exists as to whether one is dealing with a primary breccia or a recent talus deposit.

Three main types of breccia have been recognised and decribed according to their origin:

(a) sedimentary breccia

(b) tectonic breccia

(c) diapiric breccia.

It is probable that they are genetically connected even though a time difference exists between the sedimentary variety and the others. The former is of Bangemall Group age while the others are younger and probably contemporaneous with the post-Bangemall, Edmundian Fold Period and associated faulting. (Halligan and Daniels, 1964.)

On a regional basis this fold period has been most effective in deforming the Bangemall Group sediments between the Parry Range, the area a little to the east of Mt. Florry, and southwards into the Edmund Sheet area (see Plate 17). Further to the east, dips are generally shallower and strong folding is absent. It is in the strongly folded areas, especially between the Parry Range and Mt. Florry that the breccias are developed.

All the breccia probably originated during a protracted series of land movements associated with the Edmundian Fold Period. Movement is thought to have started during the deposition of the Top Camp Dolomite, the basal part of the Bangemall Group, and probably continued intermittently, culminating in the production of isoclinal and recumbent folds near Mt. Florry.

SEDIMENTARY BRECCIA

Sedimentary breccia is best developed at Mt. Price and the adjoining ridge, which runs northward for 2 to 3 miles, a haphazard arrangement of angular sedimentary fragments ranging in size from a fraction of an inch to large blocks several feet across. The breccia is approximately 200 feet thick.

The principal rock types involved are silicified algal dolomite and current-bedded sandstone. On the whole, little mixing of the two varieties is seen and large masses are composed dominantly of fragments of one variety, with only small amounts of one in the other.

The lower part of Mt. Price is composed dominantly of brecciated, silicified algal dolomite, while the crest is almost entirely made of current-bedded sandstone fragments.

The silicified algal dolomite is milky white and composed dominantly of silica. Iron staining and differential weathering accentuate the original structure of the rock which was primarily composed of either close-packed, cone-shaped algae with diameters up to 4 inches, or undulating sheets exhibiting a series of small flutes in vertical section. None of the supposed original dolomite remains.

The current-bedded sandstone is light grey, weathers to pale brown and frequently develops a porous texture.

In the breccia in one of the foothills of Mt. Price, extremely rare well-rounded orthoquartzite boulders up to 12 inches across have been found.

The breccia at Mt. Price occupies the axial region of a syncline. It overlies thin-bedded, current-bedded, sandstone in the south, but overlies dolomite further to the north. Isolated dolomite "stacks" surrounded by breccia occur on the south side of Mt. Price.

The stratigraphic sequence near Mt. Price consists of the following:

Top breccia
dolomite
sandstone
dolomite
Unconformity
Ashburton Formation

The lower dolomite is divisible into several units, one of which carries abundant silicified algal dolomite bands which are apparently identical with the dolomite fragments in the breccia. Similar algae are not present in the upper dolomite. Overlying the basal dolomite is a series of sandstones and quartzites, almost always showing well developed current-bedding. They vary from grey to light brown and weather to a porous, cindery texture in most places. These characters compare closely with those of the current-bedded sandstone fragments in the breccia.

These comparisons of lithology suggest that the breccia at Mt. Price has been derived from lower stratigraphic units of the Bangemall Group. In order for this to take place, two possible means may be considered: diapirism and sedimentation.

No evidence for diapirism was found near Mt. Price. Mapping shows that the breccia rests on different stratigraphic units at different places, but in all cases the observed contact was conformable for short distances (*i.e.,* the length of the outcrop) with the underlying bedding.

The presence of rare, water-worn boulders of quartzite suggests that, during transportation and deposition of the breccia, surface material was incorporated. It is difficult, if not impossible, to conceive how water-worn boulders could be incorporated in a diapiric mass when no evidence for the presence of similar boulders is forthcoming from the underlying rocks. A basal conglomerate is developed, mainly along the western margin of the Parry Range, but although it is absent in the eastern outcrop it is nevertheless a distinctive type, composed of much smaller vein-quartz pebbles up to two inches diameter that could not be the source for the boulders.

The paucity of rounded fragments and the low degree of mixing of the two main types suggests that erosion, transportation and deposition took place very rapidly.

I envisage two possible processes which may be capable of supplying the necessary conditions: (a) slumping, possibly initiated by faulting, and (b) rapid talus development along the line of a fault escarpment.

At present the evidence available is not sufficient to decide between these two possibilities. However it is almost certain that faulting played a major role.

TECTONIC BRECCIA

From a point just west of Mt. Danvers to the Mt. Florry region, for a distance of 20 miles, breccia is very common, forming long ragged ridges in a steeply dipping sequence of sandstone and shale. Close examination reveals that some of the sandstone bands have been brecciated intermittently along their outcrops. The breccia consists of angular fragments of sandstone up to 8 feet across in a very fine-grained quartzose groundmass. Sericite is present in small quantities. Iron staining with associated salt encrustations has been noted. Along strike the breccia passes into undisturbed sandstone.

The breccia has developed parallel to a major fault zone which, along most of its length, throws the upper part of the Bangemall Group against the Ashburton Formation. This fault is also parallel to the regional fold trends. At one point the fault zone cuts a Proterozoic granite which has developed a strong gneissose texture over a considerable width, proving that intense shearing accompanied the faulting.

There is no doubt that this breccia has remained, more or less, *in situ* and has developed as a direct consequence of the proximity of this major fault zone.

In the Kookabinah Valley about 12 miles southeast of Mt. Florry, strongly folded orthoquartzite is abundant. In the cores of the anticlines, and always parallel to the fold axes, a coarse brecciated zone or band is commonly developed. The breccia is composed of orthoquartzite fragments and confirms the relationship, in this area, of folding with brecciation.

DIAPIRIC BRECCIA

Approximately 2 miles northwest of Mt. Florry, breccia masses, varying from 50 to 200 yards across, are moderately abundant. They consist of small, angular sandstone fragments. In one locality, a horseshoe shaped "dyke" of breccia surrounds bedded dolomite, which elsewhere overlies sandstone. The sandstone closely resembles that found in the breccia and is regarded as the source rock. The contacts are vertical and the edge of the dolomite is partially brecciated. This appears to be the only good example of diapirism in the area.

It is possible that the intense folding which has affected the Mt. Florry region produced breccia in anticlinal axial regions and, where the forces were intense enough, injected this brecciated material into a higher stratigraphic unit.

REFERENCE

Halligan, R. and Daniels, J. L., 1964, Precambrian geology of the Ashburton Valley region; North-West Division: West. Australia Geol. Survey Ann. Rept. 1963.

NOTES ON A MOUND SPRING ON MARDIE STATION, NEAR CAPE PRESTON

by I. R. Williams

A hill on Mardie Station, midway between Onslow and Roebourne in the North-West Division, was discovered to be an active mound spring during geological mapping of the Yarraloola 1 : 250,000 Sheet (SF/50-6).

Known as Mt. Salt (Western Australian Lands Dept. Reference Point 11; lat. 21° 4′ 42″ S., long. 115° 58′ 22″ E.), the mound rises from the coastal marsh 8 miles north of Mardie Homestead. It lies approximately 1½ miles inland from the shore and ½ mile seawards from the edge of the coastal plain.

Approach by vehicle is by way of a mill track to Hilda Well, thence due north for 2½ miles to a point opposite the mound spring on the edge of the coastal plain. It is necessary to walk the remainder of the distance.

The mound spring deposit is roughly elliptical in plan outline, the long and short axes being 320 yards and 180 yards respectively. The long axis trends 295 degrees, in which direction are aligned two coalescing domes. The eastern dome rises approximately 25 feet above the tidal flats; the western dome is lower, reaching 18 feet. Both domes rise above the general level of the nearby coastal plain. At present, the active sections of the mound spring are mainly confined to the western dome. The water makes its appearance immediately below the summit in a series of small basin-like depressions. From these it flows down the side of the dome forming numerous small rimstone pools and depositing massive flowstone. There is also seepage from the base of the mound. Many of the basins contain a fine reddish flocculate thought to be iron oxide or hydroxide; iron-stained flowstone is also common. The twin domes are surrounded by a gently dipping platform stretching for several hundred yards down to the tidal mud flats which is built up by the spring water, and containing many shallow basins up to 5 feet in diameter.

The mound spring has been built up almost exclusively by calcareous tufa. Microscopically it consists mainly of calcite with patches and thin bands of iron hydroxide. Recrystallisation is apparent in the older tufa collected from the extinct easterly dome, and some of the larger crystals show relict accretionary cone-in-cone structures outlined by the iron hydroxides. This mode of growth indicates one of the possible methods by which the mound spring has been built up.

Four samples, two from the older weathered tufa and two from recently precipitated flowstone, were submitted to the Government Chemical Laboratories for total rock analysis. The results confirmed the microscopic observation of a high calcium carbonate content. The maximum percentage, 95.1, was obtained from fresh flowstone. The percentage of ferric oxide is related directly to the weathering of the rock, the water containing only a small amount of soluble iron. The remainder was made up of magnesium carbonate (generally low and roughly in the proportion of 1 : 30 calcium carbonate) with insoluble material, consisting of detrital quartz and clay material, and water-soluble salts, including sodium chloride. The sulphate content was negligible.

The water issuing from the springs is very salty to taste; a water sample was not collected. It is possible that the salt content is mainly derived from the nearby ocean and the possible leaching of marine sediments beneath the mound spring, thus contaminating the rising water, which is assumed to be rich in carbonate. At present, the evaporation rate is high, causing rapid deposition of the calcium carbonate. The greater solubility of the sodium chloride causes it to remain in solution until the final stages of evaporation are reached at the base of the mound.

Because Spence (1962) mentions Mt. Salt as being a fairly intense radioactive anomaly, a hand specimen of fresh flowstone was tested and found to be slightly radioactive. The source of the radioactivity is not known at present but it has been suggested by D. L. Rowston (pers. comm.) that it may be due to potassium-40 (contained in such minerals as sylvite), and which emits gamma rays. Senftle (1948) has recorded evaporites from elsewhere which have low radioactivity.

The formation of mound springs depends on two main points:

(a) The existence of a suitable aquifer containing sufficient quantity of water and the necessary hydrostatic pressure

(b) A path within the sediments to allow the artesian water to escape to the surface.

Geological mapping carried out in the surrounding region indicates the presence of a basin which rapidly deepens westwardly and lies beneath the mound spring. The basin is known to contain sediments ranging in age from Lower Cretaceous to Recent. The edge of the basin runs north—south, and the overlap on the Proterozoic basement is well exposed 20 miles southeast of the mound spring. It is suggested that the overlap of these sediments has led to the exposure of suitable intake beds which draw water from the westerly flowing drainage systems (for example the Fortescue River) which are known to contain carbonates derived from the Proterozoic sediments.

Apart from the strong east trend of the spring, no information has been obtained as to the nature of the spring outlet.

The age of the spring is not certain, although it appears to have existed before the eastward retreat, by recent erosion, of the coastal plain. The overall slope of the mound has since been modified by the continual addition of material.

The important point to arise from the study of the mound spring is that it supplies evidence of an artesian basin beneath the coastal plain with permeable beds capable of acting as aquifers; an important factor in the search for oil.

REFERENCES

Senftle, F. E., 1948, The effect of potassium in prospecting for radioactive ores: Canadian Mining Jour., v. 69, no. 11, p. 55-57.

Spence, A. G., 1962, Carnarvon Basin airborne magnetic and radiometric survey, W. A. 1961: Bur. Min. Resour. Aust. Rec. 1962/191 (unpublished).

REGIONAL METAMORPHISM IN THE LAMBOO COMPLEX, EAST KIMBERLEY AREA

By I. Gemuts

ABSTRACT

Regional metamorphism occurred in the East Kimberley area, Western Australia, during the Archaean. Greywackes, shales, dolomites, calcareous sediments and mafic igneous rocks were metamorphosed to assemblages ranging from the low greenschist to granulite facies. The metamorphism culminated with the intrusion of anatectic granites. Four metamorphic zones can

be recognised by changes in the absorption colours in the Z direction of calcic amphiboles present in metamorphosed mafic igneous rocks.

INTRODUCTION

These preliminary remarks on the regional metamorphism in the Lamboo Complex rise out of current investigations by the Geological Survey and the Commonwealth Bureau of Mineral Resources in the Kimberley District. The location of the area investigated is shown in Plate 20. Much of the information in the following pages has already been outlined in Bureau of Mineral Resources unpublished reports (Smith, 1963: Dow and Gemuts, 1964; Dunnet and Plumb, 1964; Dow and others, 1964). Dow and others (1964) discussed briefly the regional metamorphism of the East Kimberley area and subdivided the region into five metamorphic zones. I have slightly modified their original zonal subdivision.

M. V. Bofinger of the Bureau of Mineral Resources is studying the age of the rocks from the area. His initial results are used in this report.

I wish to acknowledge gratefully my reliance on the observations of other geologists in the field parties as it is largely on these observations that the present interpretation is based.

The name Lamboo Complex was used by Matheson and Guppy (1949) and defined by Guppy and others (1958) to include granite, granitic gneiss and metasediments. Traves (1955) used the name to include all the granitic rocks in the East Kimberley area, but excluded the metasediments. I prefer the original definition and have included in the Lamboo Complex all the high-grade metamorphics, as well as the associated basic and acid plutonic rocks. This approach is justified since there are areas where it is impossible to delineate a boundary between igneous and metamorphic rocks.

The Lamboo Complex forms a belt nearly 200 miles long and about 30 miles wide, between Mount Hawick in the south, (off Plate 20) and Pompeys Pillar to the north. Further north the complex is covered by younger sediments with the exception of inliers of granite near the Halls Creek Fault.

The metamorphic rocks of the Lamboo Complex are called the Tickalara Metamorphics (Dow and Gemuts, 1964) and make up about one third of the complex. Some irregular roof pendants of metasediments in granite in the southern part of the complex are also referred to the Tickalara Metamorphics. Anatectic gneissic granites intruding the metamorphics are thought to be derived by fusion and melting of the metamorphic rocks.

To study the regional metamorphism in the Lamboo Complex it is necessary to consider also the Halls Creek Group. This group has been subdivided into the following units: Ding Dong Downs Volcanics; Saunders Creek Formation; Biscay Formation; and Olympio Formation (Smith, 1963). The Tickalara Metamorphics are regarded as the metamorphosed equivalents of this group.

The relevant geology is sketched in Plate 20. In the sections that follow, the structural setting of the Lamboo Complex is described first, then the main varieties of metamorphic rocks in the Tickalara Metamorphics and their distribution; and after this there is a discussion in which four metamorphic zones are outlined and the facies of metamorphism are recognised. Also, metasomatism is considered and the discussion concludes with a brief geological history.

STRUCTURE

The major structural unit of the East Kimberley area is the Halls Creek Mobile Zone (Traves, 1955), a belt of intensely deformed crystalline rocks, which includes the Tickalara Metamorphics. This zone lies between two stable blocks (the Sturt and Kimberley Blocks). It is a zone of great lateral and vertical movement, whose magnitude and extent in time are not yet precisely known; all the folding in the Tickalara Metamorphics may be assumed to be connected with the movement.

FOLDING

South of the Ord River, folds in the Tickalara Metamorphics have steep northerly plunging axes. The anticlines have overturned eastern limbs; and the synclines are sheared out along faults branching from the Halls Creek Fault. The major fold axes and axial planes trend north-northeast. These folds are very similar to the axial-plane cleavage folds in the Halls Creek Group. The regional structure is disturbed to the west by intrusive granites and numerous shear zones.

North of the Ord River, the structure is very complex with both ptygmatic and isoclinal folds. Transposition of folded layers and plastic flow have been the dominant processes of deformation. Flowage phenomena are especially spectacular in marble bands, which have flowed plastically; whereas intercalated gneiss and amphibolite layers are shattered and disoriented.

In the least deformed areas, minor folds are generally paralleled by steeply plunging lineations caused by elongation of metamorphic minerals. The orientation of these lineations is constant over large areas. However in the Black Rock Anticline and in the metamorphics enveloping the basic sills at McIntosh Hills, there is a later strain-slip (crenulation) cleavage developed, cutting across and deforming the earlier folds and their accompanying lineations. In these areas there is a maximum development of knotted schist and pencil gneiss.

In the migmatites the plunges of dominant lineations (formed by alignment of acicular sillimanite and of biotite laths) are most variable. Detailed structural analysis would be needed to unravel the structural complexity.

FAULTING

The eastern boundary of the metamorphics is the Halls Creek Fault; it strikes north-northeast and extends over a distance of 250 miles. The fault has a large vertical component, with downthrow to the east. And it also has a large horizontal component; in the south it appears to have displaced the Halls Creek Group rocks horizontally at least 16 miles, west block south. With the exception of this fault and its smaller subsidiary faults there are no other large faults affecting the Tickalara Metamorphics.

TICKALARA METAMORPHICS

The Tickalara Metamorphics include a great variety of metamorphic rocks ranging in grade from low amphibolite facies in the south to granulite facies in the north. The following rock types have been recognised: schist, paragneiss, orthogneiss, calc-silicate, amphibolite and basic granulite. The boundaries between many of the types are gradational and generally impossible to map, but calc-silicate and amphibolite bands have been picked out and these are valuable markers throughout the metamorphics.

MICA SCHIST

Mica schist resulting from low-grade regional metamorphism is interbedded with calc-silicates and amphibolite, both on the eastern flank of the Black Rock Anticline and as a narrow belt northwards from Armanda River to Sally Malay Well along the Halls Creek Fault.

The dominant rock types are quartz-muscovite schist and quartz-biotite schist; garnet, andalusite, chloritoid and kyanite are locally present.

Crenulated schists, containing staurolite and a little sillimanite, occur in the core of the Black Rock Anticline; as a narrow band east of the anatectic granites between the Ord River and Turkey Creek Post Office, and west of McIntosh Hills. Pods of epidote-rich quartzite are present in these rocks.

PARAGNEISS

Paragneiss extends in a belt 20 miles wide and 100 miles long from the Armanda River in the south to Bow River in the north. To the east it is bounded by the Halls Creek Fault; and late granites intrude the gneiss to the west.

The mineral assemblages of the paragneiss change from quartz-feldspar-biotite to garnetiferous types in the south and ultimately in the north into rocks with sillimanite and cordierite.

Low-grade Paragneiss

Quartz-feldspar-biotite gneiss is the dominant rock type in the low grade paragneiss. It is intertongued with amphibolites, calc-silicates and ultrabasics. The gneiss is banded, with dark and light layers. The minerals in the dark bands are mainly biotite and hornblende, and in some cases biotite and garnet. Normally these mafic bands are not continuous but form schlieren which are strung out parallel to the foliation. The light layers have a granitic composition and a porphyroblastic texture that varies from medium to coarse grained.

High-grade Paragneiss

Close to the anatectic gneissic granites in the region between Turkey Creek Post Office and Violet Valley, the paragneiss is migmatitic and granulitic with good evidence of lit-par-lit injection of granitic fluids into metasediments. These high-grade metamorphic rocks are represented by assemblages rich in garnet, sillimanite and cordierite. The banding is not laminar or continuous and most bands are contorted and swirled in a complex fashion. The quartzo-feldspathic parts of the migmatite form discontinuous lenses and streaks as well as small rootless folds and boudins, all set in mafic bands. The bands are composed of sillimanite, biotite, garnet and cordierite in varying proportions. Interlayered with the migmatite are stringers of basic granulite.

CALC-SILICATE ROCKS

Marble and associated calc-silicate rocks crop out in a belt which extends for 100 miles from Halls Creek to Mount Pitt. In the south, near Armanda River, there are deformed roof pendants of calc-silicates (skarns) within granitic and basic rocks of the complex. To the north, calcareous rocks are interfoliated with amphibolite, knotted schist, and gneiss in the following areas: the Black Rock Anticline, on the margins of the McIntosh Hills, and along the Halls Creek Fault. Four continuous marble beds and a number of discontinuous beds have been mapped in the Black Rock Anticline. To the west of this area, where the structure is more complex and the metamorphism is of higher grade, the calc-silicate bands are truncated by granite and by amphibolite.

Skarns in the Armanda River Area

Near Armanda River, there are roof pendants of calc-silicates which are interlayered with other metasediments and intruded lit-par-lit by granite. The calc-silicates retain traces of bedding. The most common rock type consists of: coarsely granular green diopside or hedenbergitic pyroxene; pink garnet; light green epidote; and a little scapolite; all intergrown with fibrous white decussate wollastonite.

The calc-silicates in the Armanda River area have undergone migmatisation and it is difficult to say how much of the silica is original and how much is introduced.

Calc-silicate Rocks in the Black Rock Anticline

Numerous calcareous beds occur in the Black Rock Anticline and in the vicinity of Dougalls Bore. There are both calc-silicates and pure marbles. The marbles are generally white and coarse-grained, but some contain disseminated silicate minerals and others contain calc-silicate bands and blebs which parallel the regional foliation.

The calc-silicates are either massive, or interlayered with marble, amphibolite, gabbro and garnetiferous gneiss. In the massive calc-silicates, pink garnet is associated with green diopside and epidote in varying amounts. In the banded rocks, garnetiferous bands rich with epidote alternate with bands rich in scapolite and diopside.

Relationship with Amphibolites

The calcareous rocks along the Ord River and in the Dougalls Bore area are intimately intercalated with amphibolite. However, at all places where there appeared at first sight to be a graduation between calc-silicates and amphibolites, it was found that the changes were due to tight isoclinal folding. It is possible that some of the amphibolites associated with the calc-silicates have been derived from them.

AMPHIBOLITES

Amphibolites interlayered with metasediments crop out between Dougalls Bore and White Rock Creek Well, in the Black Rock Anticline, on the margins of the anatectic granites and in the McIntosh Hills.

In these areas, the amphibolites are well foliated and are intercalated with gneisses and calc-silicates. They range from foliated dark-green homogeneous, amphibole-rich types to banded amphibolites with bands of quartz and feldspar up to 1 inch thick. This banding is generally parallel to the regional cleavage, but in some areas appears transgressive.

Two suites were noted in the amphibolites. The first is present in a belt to the west of the Halls Creek Fault between Sally Malay Well and Alice Downs Homestead. It contains the following assemblages:

(i) Hornblende-plagioclase-quartz-epidote or clinozoisite-sphene;
(ii) Hornblende-plagioclase-quartz-sphene.

The second suite is present in the higher grade amphibolites close to the margins of the anatectic granites. In it are the following assemblages:

(i) Hornblende-plagioclase-quartz;
(ii) Hornblende-clinpyroxene-plagioclase-quartz.

Association with Pyroxene Granulites

In the Violet Valley region and north of Mabel Downs Station on the western side of the anatectic granites, the metamorphic grade of the amphibolites is higher and they grade into pyroxene granulites. The rocks are dark and massive in hand specimen. They have a grandular fabric and contain pyroxene, although some bands lack pyroxene. The following assemblages were noted:

(1) Hornblende-clinopyroxene-plagioclase-quartz;
(ii) Hornblende-clinopyroxene-orthopyroxene-plagioclase-quartz.

PYROXENE GRANULITES

Pyroxene granulites form dark lenses and bands in the high grade paragneiss between Tickalara Bore and Turkey Creek Post Office. The bands are from inches to miles in length and they pinch and swell along strike. North of Mabel Downs paragneiss wraps around stock shaped bodies. On closer inspection these have been found to be gabbros with margins of pyroxene granulites. Lenses inches in width occur within the migmatites close to the anatectic granites.

In hand specimen the pyroxene granulites are dark green to black. They have a grandular texture, and a rudimentary foliation but no lineation. The foliation is parallel to that of the enclosing paragneiss. The following mineral assemblages were recognised:

(i) Plagioclase - clinopyroxene - quartz - hornblende - garnet;
(ii) Plagioclase - clinopyroxene - orthopyroxene - quartz - hornblende;
(iii) Plagioclase - clinopyroxene - quartz - hornblende;
(iv) Plagioclase - clinopyroxene - cummingtonite - quartz;
(v) Plagioclase - clinopyroxene - orthopyroxene - biotite.

METAMORPHIC ZONES

The Halls Creek Group and the Tickalara Metamorphics can be divided into four broadly defined metamorphic zones based on the change in absorption colour in the Z direction of the calcic amphibole in basic rocks. This follows the principle enunciated by Engel and Engel (1962), that hornblendes undergo systematic changes in colour, composition and density during progressive metamorphism from almandine-amphibolite to hornblende-granulite facies. The change in absorption colour in the Z direction has proved to be consistent with mineralogical changes in other rock types from the area. Zones based on hornblende have been established in other parts of the world by Miyashiro (1958), Shido (1958), Layton (1963), and Binns (1963). The metamorphic zones are not shown on the map, but their distribution is outlined in the descriptions. The zones are considered to be valid although obviously in need of refinement. Further examination of schists and gneisses, paying special attention to biotite, garnet, staurolite and sillimanite appears warranted.

Changes in mineral assemblages with increasing grade of metamorphism in the Halls Creek Group and Tickalara Metamorphics are shown in Table 1.

Table 1

PRELIMINARY OBSERVATIONS OF MINERALOGICAL VARIATIONS WITH INCREASING GRADE OF METAMORPHISM, IN THE HALLS CREEK GROUP AND TICKALARA METAMORPHICS

Rocks	Mineral	Zone A	Zone B	Zone C	Zone D
MICA SCHISTS AND PARAGNEISSES	Quartz	———	———	———	———
	Chlorite	———	———		
	Muscovite	———	— — —	— — —	— — —
	Chloritoid		— — —		
	Biotite		———	———	———
	Garnet		— — —	———	———
	Staurolite			— — —	
	Kyanite		— — —		—·—·—·—
	Andalusite		— — —	———	— — —
	Sillimanite			— — —	———
	Cordierite			— — —	———
	Plagioclase	———	———	———	———
	Microcline			— — —	———
	Hornblende				—·—·—·—
SKARNS AND CALC-SILICATES	Dolomite	———			
	Tremolite	— — —	———		
	Hornblende			rare	throughout
	Cummingtonite				———
	Chlorite	— — —	———		
	Calcite	———	———	———	
	Diopside			———	———
	Epidote			———	
	Garnet			— — —	———
	Scapolite		— — —	— — —	— — —
	Wollastonite				—·—·—·—
	Plagioclase			— — —	———
	Quartz		very rare	throughout	
AMPHIBOLITES AND BASIC GRANULITES	Actinolite-Tremolite	Colourless to ———	Pale Green — — —		
	Hornblende		Dark Green ———	Green-Brown ———	Light Brown ———
	Cummingtonite				———
	Sphene		———		
	Chlorite	— — —	———		
	Epidote	— — —	———		
	Plagioclase	———	——— →	An content	increase ———
	Calcite	— — —			
	Orthopyroxene				———
	Clinopyroxene			———	———
	Biotite			— — —	— — —
	Quartz		— — —	— — —	— — —

Note : A full line indicates that a mineral is common and abundant ; a broken line indicates that it is common but not abundant; a dash-dot indicates that it is rare. (Arrangement after Miyashiro, 1958).

The four metamorphic zones in the East Kimberley area are:

ZONE A

In this zone amphibole is usually absent, but if present it is actinolite-tremolite forming discrete laths or replacing primary hornblende. Absorption colour in the Z direction varies from colourless to pale green. The rocks in this zone are slightly metamorphosed and include chlorite-muscovite rich greywacke and siltstone (chlorite 1 and 2 zones of Turner, 1938), dolomite, uralitised dolerites and ultrabasic rocks. This zone embraces the Olympio Formation.

ZONE B

This zone is defined by the appearance of common hornblende in subhedral acicular laths arranged either singly or in rosettes. The absorption colour in the Z direction varies from blue green to dark green. In some areas light green hornblende also occurs. Biotite, andalusite, garnet, kyanite and chloritoid schists are associated with calcareous rocks containing calcite and tremolite. The amphibolites contain epidote ahd sphene. This zone embraces parts of the Biscay Formation and the rocks on the margins of the Black Rock Anticline.

ZONE C

Zone C is characterised by acicular hornblende with a green-brown absorption colour in the Z direction. The disappearance of the bluish green tinge marks the transition from Zone B. Clinopyroxene is associated with hornblende in some rocks. There are areas however, where green hornblende persists and without more field information it is impossible to say whether these hornblendes are in Zone B or Zone C.

An indicator of grade in the mica schist and paragneiss is abundant garnet with staurolite and fibrolitic sillimanite. Knotted schist and pencil gneiss predominate in this zone. Calcareous rocks are rich in diopside, epidote and garnet. The amphibolites have no epidote or sphene. This zone occurs south of the largest anatectic granite body and it extends from McIntosh Hills to Tickalara Bore. The core of the Black Rock Anticline also contains rocks of Zone C.

ZONE D

In this zone granular hornblende occurs by itself or in association with an orthopyroxene. The absorption colour in the Z direction is brown or light brown. The paragneiss contains microcline, plagioclase, garnet, cordierite, sillimanite and subordinate kyanite. Marginal to the anatectic granites in the north there is a maximum development of cordierite, biotite and microcline. The calcareous rocks have assemblages containing either wollastonite, diopside and garnet or anorthite and cummingtonite associated with a clinopyroxene. The appearance of orthopyroxene in the amphibolites is a valuable indicator of Zone D. Rocks of this zone extend northwards from Tickalara Bore to Bow River.

METAMORPHIC FACIES

The slightly metamorphosed rocks of the Halls Creek Group belong to the greenschist facies, whereas the Tickalara Metamorphics range from high greenschist to granulite facies. The metamorphic zones can be placed in the following facies of Fyfe and others (1958):

ZONE A

Greenschist facies; quartz-albite-muscovite-chlorite subfacies.

ZONE B

Greenschist facies; quartz-albite-epidote-biotite to quartz-albite-epidote-almandine subfacies.

ZONE C

Almandine-amphibolite facies; staurolite-quartz subfacies.

ZONE D

Almandine-amphibolite to granulite facies; sillimanite-almandine subfacies transitional to hornblende-granulite subfacies.

METASOMATISM

Metasomatism has been an important process in the high-grade metamorphic rocks, and it is usually associated with the late intrusive porphyritic granites or the anatectic granites. Irregular masses of skarn form roof pendants in coarse-grained granite in the southern part of the Lamboo Complex. Garnet, hedenbergitic pyroxene and scapolite in the skarns seem to be pyrometasomatic. Similarly the presence of scapolite and apatite in Zone C can be taken to indicate a metasomatic introduction of silicates and halogens, although these constituents may quite possibly be connate. It appears that water has been one of the main agents in altering some of the calcareous silicate lenses and sheared gabbros to tremolite-talc-serpentine rocks in Zone B.

Close to the anatectic granites, paragneiss has been soaked by granitic fluids forming migmatites. Without doubt this has been accompanied by an introduction of magnesium, potassium and silica into the country rocks. It is evident that without supporting chemical data, the exact nature of the metasomatism involved cannot be indicated.

Metasomatic action, other than that involving water, is not so obvious in the lower grades of metamorphism. Tourmaline is present in the pelites of Zones A and B. In Zone A it is detrital, but in Zone B most probably allochemical. A metasomatic origin is favoured in this zone because euhedral tourmaline forms veins and is usually associated with apatite. This hypothesis is supported by the suggestion of Binns (1963), that tourmaline in knotted schists from the Broken Hill region of New South Wales is metasomatic. And Read (1939) states that: ubiquitous tourmaline in regionally metamorphosed rocks is an indicator of the action of "emanation" throughout all grades.

GENESIS OF THE LAMBOO COMPLEX

The history of the Lamboo Complex is considered to be as follows:

1. Geosynclinal sedimentary and volcanic rocks were formed and intruded by ultrabasic and basic sills, and dolerite dykes. All these rocks are part of the Halls Creek Group and considered to be Archaean in age.

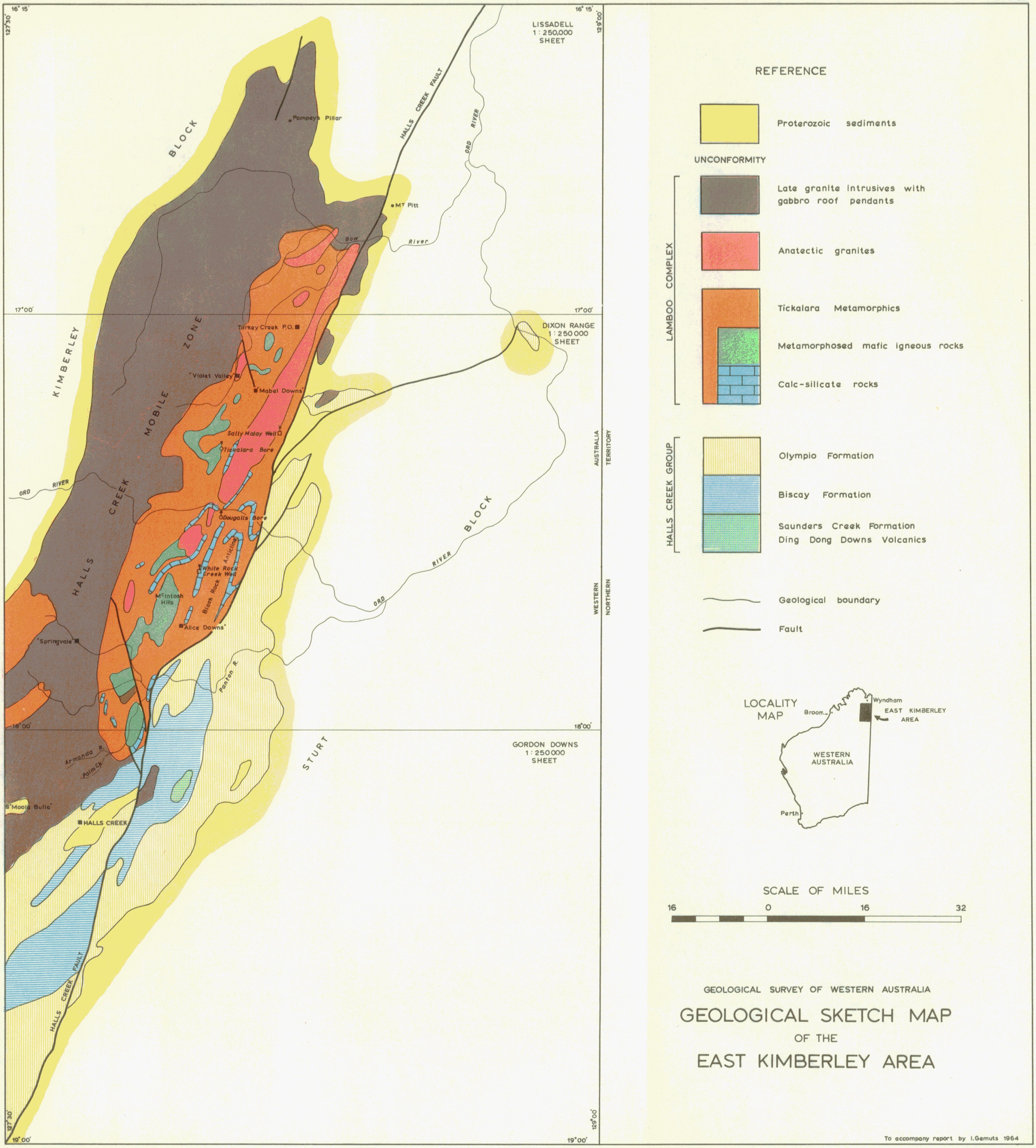
2. The geosynclinal pile was then deformed and metamorphosed. The grade of metamorphism of the rocks increased from moderate greenschist facies in the south to granulite facies in the north. The high-grade metamorphic rocks to the north, and west of the Halls Creek Fault, are the Tickalara Metamorphics. In the south the low-grade metamorphic rocks with features such as bedding, ripple marks, load casts and graded bedding are sediments of the Halls Creek Group. All the basic rocks of this group are uralitised. The metamorphism is probably Archaean in age.

Greywackes and shales of the Olympio Formation and acid volcanics of the Biscay Formation were changed to schists and gneisses of the Tickalara Metamorphics. The calc-silicates are the metamorphic equivalents of dolomites in the Biscay Formation. The amphibolites are thought to have been formed by the reconstitution of basic lava flows, basic dykes, and dolomite of the Biscay Formation. The close association of the pyroxene granulites with amphibolites indicates that many of them are higher grade equivalents of the amphibolites. Others are derived more directly from calcareous rocks and basic igneous rocks.

3. Anatectic gneissic granite was intruded during the waning stages of metamorphism, forming migmatites around the margins. Here also there was local retrogressive metamorphism. These events are probably Archean or Early Proterozoic in age.

4. Granite was intruded as a batholith along the western margin of the complex, incorporating pendants of Tickalara Metamorphics and the Halls Creek Group. The granite was intruded in Early Proterozoic time.

PLATE 20



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REFERENCES

Binns, R. A., 1963, Some observations on metamorphism at Broken Hill, N.S.W.: Australasian Inst. Mining Metall. Proc., no. 207, p. 239.

Dow, D. B. and Gemuts, I., 1964, Explanatory notes to accompany the Dixon Range 1:250,000 Sheet SE/52-6 Western Australia: Bur. Min. Resour. Aust. Rec. 1964/56 (unpublished).

Dow, D. B., Gemuts, I., Plumb, K. A. and Dunnet, D., 1964, The geology of the Ord River Region, Western Australia. Bur. Min. Resour. Aust. Rec. 1964/104 (unpublished).

Dunnet, D. and Plumb, K. A., 1964, Explanatory notes to accompany the Lissadell 1 : 250,000 Sheet SE/52-2 Western Australia: Bur. Min. Resour. Aust. Rec. 1964/70 (unpublished).

Engel, A. E. J. and Engel, G. G., 1962, Progressive metamorphism of ampibolite, N. W. Adirondack Mountains, New York: Geol. Soc. America Petrologic Studies (A volume to honour A. F. Buddington), p. 37.

Fyfe, W. S., Turner, F. J. and Verhoogen, J., 1958, Metamorphic reactions and metamorphic facies: Geol. Soc. America Mem., v. 73.

Guppy, D. J., Lindner, A. W., Rattigan, J. H., and Casey, J. N., 1958, The geology of the Fitzroy Basin, Western Australia: Bur. Min. Resour. Aust. Bull. 36.

Layton, W., 1963, Amphibole paragenesis in the Birriman Series of the Winneba District of Ghana: Geol. Soc. Australia Jour., v. 10, pt. 2, p. 261-272.

Matheson, R. S. and Guppy, D. J., 1949, Geological reconnaissance in the Mount Ramsay area, Kimberley Division, Western Australia: Bur. Min. Resour. Aust. Rec. 1949/48 (unpublished).

Myashiro, A., 1958, Regional metamorphism of the Gosaisyo-Takanuki District in the Central Abukuma Plateau: Tokyo Univ. Fac. Sci. Jour., v. 11, p. 219.

Read, H. H., 1939, Metamorphism and igneous action: Nature, v. 144, p. 729.

Shido, F., 1958, Plutonic and metamorphic rocks of the Nakaso and Tritono Districts in the Central Abukuma Plateau: Tokyo Univ. Fac. Sci. Jour., v. 11, p. 131.

Smith, J. W., 1963, Explanatory notes to accompany Gordon Downs 1 : 250,000 Sheet SE/52-10 Western Australia: Bur. Min. Resour. Aust. Bull. 27.

Traves, D. M., 1955, The geology of the Ord-Victoria region, Northern Australia: Bur. Min. Resour. Aust. Bull. 27.

Turner, F. J., 1938, Progressive regional metamorphism in southern New Zealand: Geol. Mag., v. 75, p. 160.

VERMICULITE DEPOSITS AT YOUNG RIVER, EUCLA DIVISION

by W. N. MacLeod

The vermiculite deposits at Young River, Eucla Division were discovered in 1939 by prospector G. Halbert of Ravensthorpe, and were worked by him in 1940 and 1941 for the production of 186 tons from M.C.'s. 204H and 205H. The deposits were taken over by the Perth Modelling Works Ltd. in 1941 and worked until 1953 with the production of 1,499.8 tons from M.C. 187H. In all 1,685.85 tons have been produced valued at £10,890; an average value of £6 9s. per ton. There has been no further development or exploration since 1953.

The deposits were first examined geologically by H. A. Ellis in 1940 and again in December, 1943. The deposits and underground workings were re-examined and mapped by W. Johnson and J. Gleeson in January, 1949. The results of these surveys are described in Annual Reports of the Geological Survey for 1943 and 1949 respectively.

The deposits were visited by the writer in April, 1964, to ascertain the state of the old workings and to review the prospecting and development programmes outlined by previous workers. Additional shafts and prospecting pits had been sunk in the period 1949-1953. (The additional information gained from these openings has been plotted on Plate 21). After a lapse of over 10 years many of the old workings had collapsed or were in such a dangerous condition as to be inaccessible. Development has been confined mostly to zones of decomposed rock of poor standing quality.

GEOLOGY OF THE DEPOSITS

Both the regional geology and geological environment of the vermiculite deposits have been described by Ellis (1943), and Johnson and Gleeson (1951).

The vermiculite occurs in irregular seams and veins in shear zones in a large ultrabasic intrusion which has been metamorphosed to an actinolite-anthophyllite-hornblende complex. This complex intrudes biotite gneiss and is in turn intruded by sills or dykes of hornblende granulite; the metamorphic derivative of a basic rock. The entire suite has been intruded by a later discordant acid granite surrounded by an aureole of minor pegmatite and quartz reefs. The vermiculite is considered to be a product of metasomatism of actinolite by fluids introduced by the late granite and the uniform relationships of these two minerals supports this view. Horses of friable green actinolite are intimately intergrown with the vermiculite along the shear zones and there is no indication that the vermiculite is due to the alteration of pre-existing micas.

The metamorphosed ultrabasic host rock of the vermiculite is very poorly exposed. The upper soil layers are heavily impregnated with magnesite. In places there has been siliceous induration of the rock with silica possibly derived from the late intrusive granite. The intrusive hornblende granulite is better exposed and its presence usually marked by lines of granulite boulders.

The ultrabasic rock has been strongly sheared with the shear directions concentrated around 320°, due north and 040°. These directions correspond in a general way to the alignment of the hornblende granulite bodies and it has been suggested that these more competent "ribs" have exerted some measure of control on the shear pattern. In underground workings individual shear zones are said to have been followed for as much as 100 feet but most of them die out both laterally and vertically over smaller distances than this.

RECOMMENDATIONS FOR PROSPECTING.

General.

Vermiculite was first discovered in this area from the acute observation of the prospector G. Halbert who noticed flakes of the mineral in the extremely large ant heaps which are typical of the area. In the absence of outcrop this is the sole indication of underlying veins of the mineral. In most openings that have been made there is seen to be a heavy development of magnesite in the upper soil profile which serves to obscure the vermiculite even directly above a wide vein. The magnesite layer is generally less than 3 feet thick but it is necessary to cut below this to gain any idea of the width or character of a vermiculite vein.

It has been suggested that the elongated bodies of hornblende granulite have exerted some measure of control on the intensity and orientation of the shear zones with which the vermiculite is commonly associated. This may be the case but it is felt that there is insufficient evidence to apply this as a general rule to the whole field as a prospecting guide for vermiculite. There is certainly a strong development of vermiculite in the northern end of the field near the boundaries of horneblende granulite but there are numerous localities, particularly in the southern end of the field, where there are occurrences of excellent vermiculite well away from such bodies. It is a possibility that more intensive shearing near the horneblende granulite has aided deeper weathering of the ultrabasic rock. As practically all development and exploration of the deposits has been deliberately confined to such easily worked zones of decomposition it is felt that this relationship could be more apparent than real and does not reflect the true character of vermiculite distribution. The prospecting of these deposits has been confined to ground that could be moved with pick and shovel and it is believed that a much more comprehensive investigation would have to be made before the relationship of the vermiculite to the hornblende granulite could be established.

Throughout the field vermiculite veins are exposed in scores of prospecting pits and shallow shafts and from the frequency of its occurrence there is the inclination to infer a very widespread distribution of the mineral. It would seem that the most efficient prospecting tool in this area would be a bulldozer capable of making a series of shallow cuts below the magnesite layer across selected areas. Only by obtaining continuous exposure of the rock below the magnesite mantle could any reliable inferences as to the persistence and correlation of the veins be made. As a prospecting tool it is not considered that the diamond drill would be of much advantage. The vermiculite veins pinch and swell and die out abruptly and pockets of workable grade could be missed entirely. Furthermore, from the character of the vermiculite flakes it is doubtful whether anything approaching satisfactory core recovery would be achieved in the zones where it would be most required. The drill would certainly be of use over short intervals in planning development ahead from existing workings, but it is not considered that it would be of much value in an overall initial assessment of the field or of selected areas of the field.

Individual Areas

In view of the collapsed state of most of the old workings any future development would have to be prefaced by a systematic exploration programme aimed at the delimitation of the richest zones of vermiculite concentration, together with an appreciation of the variations in the quality of the material. Up to the present all workings and prospecting appear to have been haphazardly based on zones of easy mining and thick veins. A continuation of such methods could lead to the rapid despoliation of a potentially valuable mineral asset.

In the present investigation an attempt has been made to select areas for systematic prospecting on the basis of evidence presented by existing openings and the information gained in past geological examinations. Four such areas have been selected, termed A, B, C and D (see Plate 21). These are dealt with as follows:

Area A is situated in the northwestern sector of the field surrounding the underground workings on No. 3 Lode. This has been the most productive zone of the field with underground workings to a depth of 60 feet. Sections of the workings are illustrated in the report by Johnson and Gleeson (1951). Since their inspection several new pits near the shaft have been sunk and some of the existing pits have been deepened. Further pits have also been opened in the area close to the granite contact, about 300 feet southwest of the shaft.

There is a large tonnage of vermiculite in the shaft dumps and it is seen in veins in all openings in the area immediately north of the shaft. The already mined material should be beneficiable, and as an immediate mining project, the area north of the shaft between the hornblende granulite and the pegmatite could be open cut.

The zone between the shaft and the pits about 300 feet southwest of the shaft would merit prospecting by a series of northeast trending cuts between the access track and the hornblende granulite intrusion. The vermiculite in the low pits near the base of the spur is of excellent quality with flakes up to 2 inches in diameter and this zone calls for closer examination.

Area B is situated southwest and south of the workings on No. 4 Lode. This lode was developed by means of a shaft and open cut. The shaft, originally 70 feet deep, has collapsed completely, as have the walls of the open cut. As at Lode 3, there is a substantial quantity of vermiculite in the dumps. South of the old workings there are numerous vermiculite veins exposed in prospecting pits and the entire area seems to hold considerable promise. Johnson and Gleeson recommended the sinking of a prospecting shaft near the northern tip of the westernmost hornblende granulite body and laid out a diamond drill programme from the base of this shaft. As most of the exposed veins have a general north strike it is suggested that a series of cuts of east trend between the road and the western granulite be made over an area measuring approximately 800 by 300 feet as outlined on the accompanying plan. The abundant quartz float and pegmatite in this zone points to a concentration of hydrothermal activity from the granite and this could favour increased concentration of vermiculite.

Area C is in the central portion of the field south of the old camp site. There are few openings in this area. A shaft 14 feet deep, has been sunk on a vermiculite seam 6 feet wide at a point about 400 feet south of the camp, and another pit has exposed a seam 4 feet wide close to the road about 350 feet southeast of the camp. The area between the track and the hornblende granulite would appear to merit prospecting as vermiculite flakes are common in the soil in many zones. If surface trenching revealed any promising concentrations in this area they could be developed by an adit from the steep cliff face along the Young River. The gully to the south of this area has been the site of shaft workings on Lode 1A and in an open cut which reached a depth of 26 feet.

Area D is in the southern section of the field and was apparently developed after Johnson and Gleeson's examination. The main openings consist of a shaft 19 feet deep and an adjacent pit 10 feet deep which have been sunk on a seam 7 feet wide of general northeast trend. Actually there are two seams exposed, separated by a narrow horse of actinolite rock. Vermiculite also appears in some nearby costeans and pits. Another pit, now partly collapsed, has been opened on a vermiculite seam about 300 feet southwest of this shaft. This opening follows the northwesterly dip of the vein which is at least 6 feet wide and strikes northeast. Vermiculite is common in the soil between the two worked areas. To the northwest there is abundant quartz and pegmatite but no exposures of the ultrabasic rock. It is recommended that this area be prospected by a series of northwest trending cuts.

CONCLUSIONS

From the data available and the mode of occurrence it is impossible to make any reliable assessment of the reserves of vermiculite available in the Young River deposits. From its widespread occurrence in thick, if impersistent seams, it is considered that the reserves could be very substantial. In view of the general decomposition of the host rock, prospecting by bulldozer cuts would appear to be the most economical and rapid means of gaining a better appreciation of the mineral distribution.

There is a very substantial tonnage of lower grade material at present lying in dumps near the old workings. Any further development of the deposits should include consideration of the beneficiation of this material. In past working the vermiculite has been mined selectively to produce a usable product and in consequence a great quantity of contaminated material has been rejected into dumps. There is probably more vermiculite lying in these dumps than has been taken away.

REFERENCES

Ellis, H. A., 1943, The Young River vermiculite deposits, Young River, Eucla Division, W.A.: West. Australia Geol. Survey Ann. Rept. 1943, p. 60.

Johnson, W., and Gleeson, J., 1951, Report on the vermiculite deposits on M.C. 187H, Young River, Oldfield District, Eucla Land Division of W.A.: West. Australia Geol. Survey Ann. Rept. 1949, p. 42.

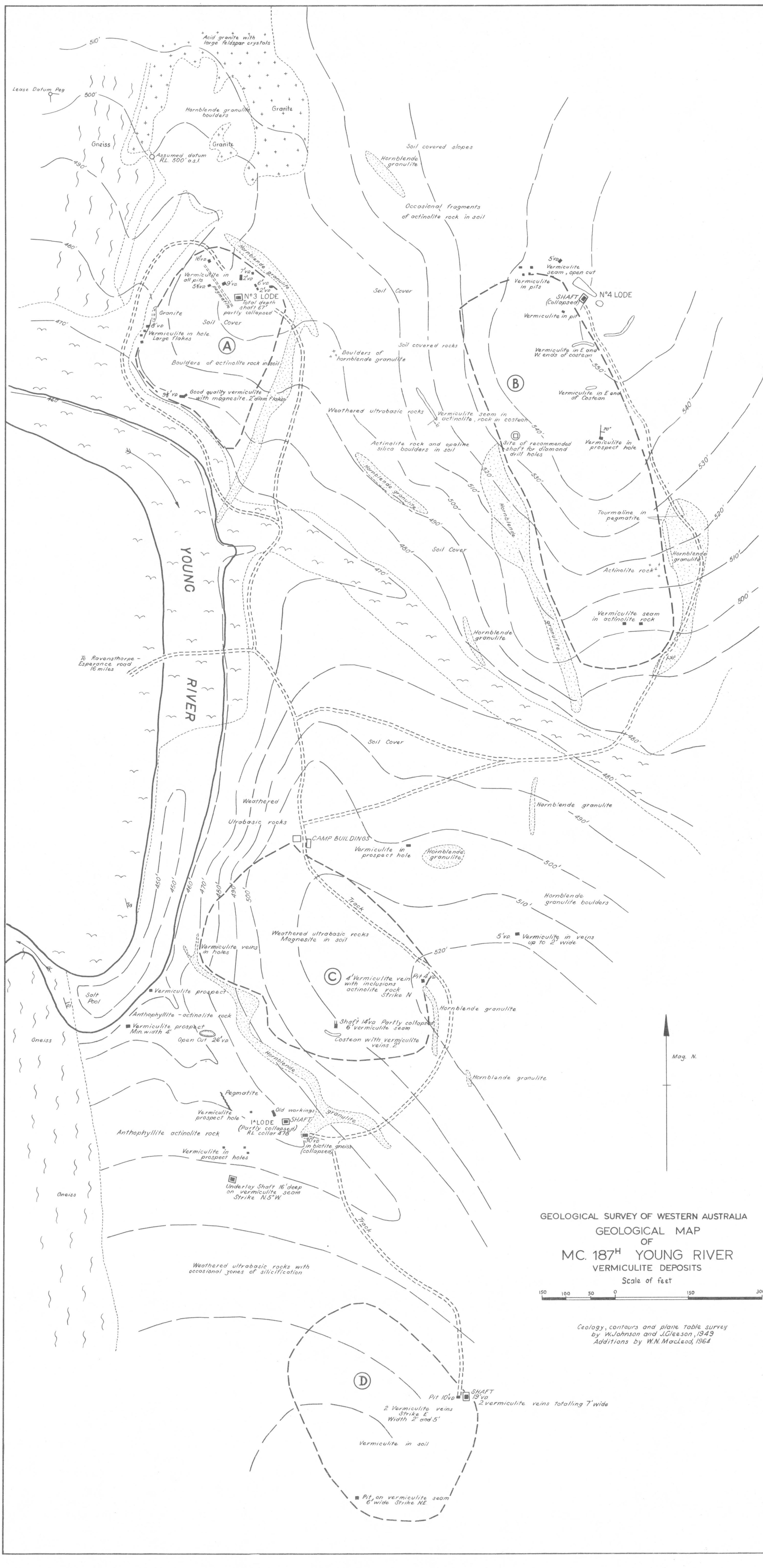

PLATE 21

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THE NARLARLA LEAD - ZINC DEPOSITS, BARKER RIVER AREA, WEST KIMBERLEY GOLDFIELD

by R. Halligan

ABSTRACT

The Narlarla lead-zinc deposits are near Napier Downs Station, about 85 miles by road east of Derby, West Kimberley Goldfield. They consist of two deposits, known as No. 1 and No. 2; No. 1 has been mined out and No. 2 is being worked at present by Devonian Pty. Ltd. The deposits have been known since 1906, and have been worked intermittently since then. To date, about 9,000 tons of ore have been won, averaging over 40% total lead plus zinc. At present the body is worked in a small open cut and the ore is shipped from Derby to Europe for smelting.

The ore bodies have been largely controlled by faulting. They lie within the Napier Limestone, a Devonian fore-reef facies deposit which unconformably overlies granite, gneiss and schist of the Precambrian Lamboo Complex.

The No. 2 ore body is a massive, finely crystalline lead-zinc sulphide deposit which is rather irregular in form, overlain by a mass of secondary oxide and carbonate ore. Silver is also present. The secondary minerals form a cap to the main sulphide body, but they are also present in fault zones as "shoots" or apophyses which are separated by "ridges" of unaltered limestone.

Total indicated reserves of high grade ore are 11,500 tons, of which about 7,750 tons has already been mined.

The galena is abnormally rich in radiogenic lead, which suggests that the genesis of the ore is due to remobilisation of older lead-zinc from a vein in the Lamboo Complex, with subsequent re-deposition in a faulted area of Napier Limestone. Alternatively, the abnormal lead isotope ratios could be due to contamination of the mineralising fluids by radiogenic lead contained in the basement rocks themselves.

No other deposits of this nature are known in the State and this is the youngest dated ore body in Western Australia. Exploratory drilling, geochemistry, and geophysics are suggested as possible means of discovering further ore.

INTRODUCTION

The Narlarla deposits are located in the Napier Range on the south side of the Barker River Gorge, about 2 miles by road from Napier Downs Homestead and 85 miles east by good road from Derby (see Plate 22). The location is marked on the map of Finucane and Jones (1939) and on the Lennard River 4-mile geological map produced by the Bureau of Mineral Resources, Canberra (1956), where it is shown as "Devonian Lead Mine".

The deposits were originally pegged by R. B. Pettigrew and F. Wilson in 1901, but were later abandoned. In 1906 they were taken up by Mr. G. J. Poulton, a former owner of Mondooma Station, West Kimberleys, and investigated by a Mr. J. H. Grant. According to a newspaper report of June 8th, 1906, Grant estimated the ore in outcrops at "over 5,000 tons" and a shaft and crosscut were put in. A company was floated to mine these ores, and apparently there was considerable speculation in the shares at that time. As a result, the find was investigated by Mr. W. Windred, a Tasmanian prospector who thought the place "over-estimated", and also by H. P. Woodward, the then Assistant Government Geologist. Woodward (1906) described the two ore bodies, but suggested that it was probably not an economic proposition because of the high cost of cartage. He advised intending prospectors to wait till further work had beeen done on the deposits, whereupon the venture seems to have collapsed. A short report with some assays, presumably of samples collected by Woodward, was later made by Simpson (1951).

Finucane and Jones (1939) re-examined the deposits during the Aerial, Geological and Geophysical Survey of Northern Australia, and Prider (1941) has reported on the mineralogy.

The deposits have been worked intermittently from 1948 onwards. The ore bodies have little surface expression at the present time, but prominent outcrops of secondary ore, which have since been mined, led to their original discovery. Early work was almost entirely in the secondary ore, though sulphides were known from the crosscut (Woodward, 1906; Finucane and Jones, 1939). Since 1947, Mr. E. Russell and his partners in Devonian Pty. Ltd., have held the mine. In 1952, the deposits were drilled under option by Zinc Corporation, but no development work was undertaken. In 1964 Devonian Pty. Ltd. opened up the present workings, to take advantage of the Imperial Smelting Process for mixed lead-zinc ores which, together with the present high prices for lead-zinc, makes these workings a commercial proposition.

GEOLOGY

Host Rock

The ore bodies lie within fore-reef facies limestone (calcarenite and calcirudite) of the Upper Devonian Napier Limestone. Interbedded thin green siltstone is also seen in some exposures. The rocks dip generally at 20° to 30° to the west and southwest, forming a gentle anticline which plunges west-southwest at a low angle. The Napier Limestone overlies Precambrian gneiss, schist, and granite of the Lamboo Complex.

The Ore Bodies

There are two deposits, No. 1 and No. 2.

No. 1 ore body has been almost completely worked out. It consisted of a low hill of cerussite and hydrozincite, with some galena, blende, limonite, and minor malachite and chessylite (azurite). Some loose fragments at the surface contained up to 40% hydrozincite (Prider, 1941). Workings consist of an east-west trench 60 feet long and 15 feet wide, with a shallow pit at the western end. Slickensides, together with a sharp change in strike in a green silty shale exposed in the floor of the trench suggest that a fault may have provided a focus for the ore. The limestone dips at about 20° to the west.

No. 2 ore body lies 1,600 feet southwest of No. 1, on the southeastern limb of the anticline, and is exposed in an open pit about 60 feet square and up to 40 feet deep, with an inclined entryway on the southeastern side. It consists of a massive sulphide body overlain by an irregular mass of secondary ore. The distribution of ore is largely controlled by faults (see Plate 22).

The sulphide body consists of fine-grained crystalline galena (crystals generally less than ⅛-inch face) with some interstitial powdery black sulphide. Pyrite and chalcopyrite are sometimes present, though generally in minor amounts, and from the presence of zinc in analyses, zinc blende must also be present. At the time of inspection, about 10 feet of sulphide ore was exposed on two sides of the open cut, and exploratory drilling has proved this ore to depths of from 4 to at least 16 feet below the floor of the cut. Immediately overlying the sulphides is a narrow zone of a bright red powdery or clayey rock, averaging 2 feet thick, often associated with a green clay. This zone coincides with the water level reached in the old workings. The red zone contains from 39% to 44% zinc, and probably consists largely of zincite; some lead and silver minerals are also present. Other secondary minerals, mainly cerussite, with some malachite, azurite, hydrozincite, calcite, and limonite occur above the red zone. Galena is also present in minor amounts. The secondary ore is soft, porous, and mottled pale brown and white in colour, with a definite "sparkle" in some outcrops; some vuggy material occurs in this zone, along the line of one of the faults; calcite, cerussite, and limonite are commonly developed within the vugs as crystals, stalactitic growths, and encrustations.

Secondary minerals have developed in fault zones appreciably higher than in the areas between such zones. Thus it was found that working the secondary zone was complicated by "ridges" of limestone within the secondary ore body. It seems that the ore worked in the early days was located on a fault or faults on the northeastern margin of the present workings. The throw of such faults as can be measured is less than 5 feet, but in most cases no estimate can be made. Slickensides are developed on the fault planes in the limestone and in several cases a black or grey sulphide-rich pug is developed at the fault plane. This pug probably represents fault gouge material, and indicates some fault movement after the deposition of the ore. It is interesting to note that the supergene ore is generally high in zinc and low in lead, while lead is relatively more abundant in the sulphide body.

The sulphide body, as shown by drilling, gives a roughly rhomboidal outline when projected at the surface and has abrupt margins. The southwestern face of the cutting, which is parallel to the strike of the Napier Limestone, shows some exposures of the contact with country rock which suggest a conformable upper limit to the body, but this is probably due to coincidence of the water table with the trace of the bedding in the face. Other exposures, e.g. on the northeastern and northwestern faces, show that faulting defines the lateral extent of the mineralisation. The base of the ore body has not been exposed to any extent, but three exploratory holes drilled from the flat floor of the open cut show that it is likely to be influenced by faulting, and therefore irregular. The bottom sulphide-limestone contact was met at depths of 4 feet and 7 feet, in two holes, but the third hole was still in ore at 16 feet; the contact at 4 feet was on strike with a limestone "ridge" previously encountered during mining of the secondary zone. As previously explained, such ridges represent unaltered limestone between mineralised fault zones. The small ore sections encountered in drillholes 1, 9 and 12, away from the main ore body, probably represent mineralisation on other faults.

Ore Genesis

Several modes of origin of the Narlarla lead have been considered. Finucane and Jones (1939) state that "In their general mode of occurrence and mineral constituents they are similar to the lead ores of Missouri, except that they contain a little more silver. There is no evidence of post-Devonian igneous activity in the area and it is probable that the ores were formed by deposition from waters of meteoric origin." Thus they envisage a syngenetic origin for the lead and zinc. However, post-Devonian igneous rocks, occurring as small volcanic necks and plugs, are known from Mt. North, Mt. Percy, and further to the south in the northern part of the Canning Basin.

Prider (1941) has suggested that there might be a connection between this igneous activity and the sulphide mineralisation. Mt. North lies 17½ miles to the south-southeast of Narlarla. No trace of igneous rocks has yet been seen in or near the mine.

A third hypothesis now proposed suggests that the ore was derived directly from lead mineralisation in the underlying Lamboo Complex. The cause of the remobilisation is not known, but in the absence of nearby igneous activity, it probably was due to migrating ground water. Lead veins are known to occur in these rocks in other parts of the Kimberleys, e.g. Mt. Amherst, Argyle Downs, Alice Downs, Pandanus Creek, Old Leopold Downs; in addition, lead minerals, probably associated with gold, have been reported from several places in the East Kimberley District and from Barker River and Richenda River in the West Kimberley. The Old Leopold Downs locality is about 90 miles southeast of Narlarla.

A. F. Trendall (pers. comm.) drew attention to the fact that a lead isotope determination had been made on lead from Narlarla (Farquhar and Cumming, quoted in Russel and Allen, 1957), and suggested that an age determination might help fix the date of formation or concentration of the ore. R. M. Farquhar, who made the Narlarla determination, was asked to comment on his results; he states in a letter that the Narlarla sample "contains more radiogenic Pb^{206}, Pb^{207}, Pb^{208}, than average Tertiary or Recent leads, and I think this pretty certainly means that the sample has been enriched by lead extracted from granitic basement rocks". Farquhar also drew attention to recent lead isotope work done on lead ores by Slawson and Austin (1962), who describe lead mineralisation in limestones in New Mexico. They postulate that mineralising fluids formed deposits in two zones. The first, above a zone of crustal weakness, yields "modern" lead isotope ratios. The second, away from the zone of weakness, yields anomalously high lead isotope ratios, and this they attribute to contamination of the mineralising fluids as they passed through basement rocks containing radiogenic lead. In one case however, they suspect contamination from an older mineral deposit. On the other hand, Eckelmann and Kulp (1959), and Eckelmann and others (in press), describe anomalous lead ratios from deposits *close to the ore channels.* Thus they envisage an anomalous lead isotope ratio present in the original mineralising fluids, and while they suggest that this is produced by "inhomogeneous extraction of lead from granitic rocks in the basement" it could, presumably, be due to extraction from a pre-existing ancient lead deposit.

Applying these hypotheses to the Narlarla bodies, it seems that they are most likely due to remobilisation of pre-existing mineralisation in the Lamboo Complex; ore search for similar bodies should thus be aimed at finding suitable structures in the Napier Limestone close to or overlying lead veins in the Lamboo Complex (see Eckelmann and Kulp, 1959). On the other hand, there is the possibility that the deposits could be due to mineralising fluids derived elsewhere, possibly at some distance from the host rocks (see Slawson and Austin, 1962; Prider, 1941). This would greatly widen the target area for ore search.

ORE RESERVES

The true shape of the No. 2 ore body is not known, so ore reserve estimates are necessarily approximate.

From available data, it is calculated that the mean cross section area of oxidised ore is 825 square feet, which at 10 cubic feet per ton over 60 feet mean length amounts to 4,950, say 5,000 tons. Similarly, there is indicated 907.5 square feet of sulphide ore, over a mean length of 50 feet. Using a factor of 7 cubic feet per ton, sulphide ore reserves are 6,482, say 6,500 tons. Total indicated reserves of high grade ore are thus 11,500 tons, of which about 7,750 tons has already been mined and shipped to the smelter, leaving 3,750 tons as indicated reserves.

In addition, a quantity of concentrates from earlier workings are available at grass. No new ore reserves have been discovered within the lease during the current production period.

GRADE

Drill logs and assays and channel sample assays by Zinc Corporation are given in Halligan (1964). The sulphide ore is of good grade, containing between 27% and 68% lead plus zinc over ore sections which range between 7 and 37 feet in thickness. The silver content varies between 0 and 6.2 fine oz. per ton. The secondary ore shows values ranging from 2.8% to 32.4% lead, 3.8% to 32% zinc, and 0 to 8.6 fine oz. per ton silver. No systematic sampling of ore has been done during mining, but grab samples from mined ore are taken from time to time.

PRODUCTION

Mines Department statistics show that from July 1948 to June 1964 ore mined was 1,844.14 tons, yielding concentrates containing:

	Value £
Lead 731 tons (f.o.b. Fremantle)	42,289.
Zinc 342.31 tons (f.o.b. Fremantle)	1,376.27
Silver 13,630.87 fine oz.	3,069.23
Total	46,733.60

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

PLAN AND SECTIONS OF THE NARLARLA LEAD-ZINC MINE No2 ORE BODY WEST KIMBERLEY G.F.

R. Halligan 1964

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Mr. E. Russell states that about 600 tons of ore was won from the No. 1 body. Since then, in August 1964, 3,750 tons of ore was shipped overseas from Derby, and a further 4,000 tons was shipped in October 1964. Assay figures and values are not yet available for these shipments.

METHOD OF WORKING

Open cut mining is used. Overburden and ore are worked by blasting, then removing the rill with a mechanical shovel and tip truck. A tractor-mounted Holman drill is used to drill shotholes, and also for exploratory drilling. The ore is sent by road to Derby, and shipped from there to Europe for smelting. Water in the workings is not a problem so far, and a small portable pump is used to dry out the floor of the cut each day.

RECOMMENDATIONS

1. Because of the irregular nature of the body, all mining should be preceded by test holes drilled from the working face in the proposed direction of mining.

2. Test holes should be drilled west of the present workings to seek any possible extension controlled by the fold and fault directions detected in the area.

3. Test holes should be put down on the north-east side of the present workings. No holes have been drilled here as yet, but it is known that galena was struck when the foundations were dug for the old mill building. It is also possible that ore could be repeated on this side by faulting.

4. An inclined test hole should be drilled from south of No. 1 body in a northerly direction, to search for possible sulphide mineralisation beneath the secondary ore.

5. Geochemical and geophysical prospecting of the Napier Limestone and of other Devonian limestones might be carried out to locate further bodies. Geochemical stream sampling would be the quickest prospecting method, as the limestones are very difficult to traverse, due to their karst-type weathering. Geophysics would be necessary to locate any bodies as yet uncovered; electromagnetic and induced polarisation would probably be the most reliable methods here. Faulted areas of limestone would seem to be the most likely areas of mineralisation.

ACKNOWLEDGMENTS

I would like to thank Mr. E. Russell and his partners of Devonian Pty. Ltd., for their help and hospitality when working at the mine, and Dr. J. F. B. Jeppe of the University of Western Australia, for much helpful discussion and for the use of his maps and other information.

REFERENCES

Austin, C. F., and Slawson, W. F., 1961, Isotopic analysis of single galena crystals; a clue to the history of deposition: Am. Mineralogist, v. 46, p. 1132-40.

Eckelmann, F. D. and Kulp, J. L., 1959, Lead isotopes and ore deposition in the south-east Missouri lead district: Geol. Soc. America Bull., v. 70, p. 1595 (abstract).

Eckelmann, F. D., Kulp, J. L., Ault, W. U., and Miller, D. S., in press, Lead and sulfur isotopes and the history of mineralisation in southeast Missouri: Geol. Soc. America Bull. (Quoted in Austin & Slawson, 1961).

Finucane, K. J. and Jones, F. H., 1939, The Barker River area, West Kimberley District: North Australia Aer. Geol. Geophys. Survey, West. Australia Rept. 43.

Halligan, R., 1964, The Narlarla lead-zinc deposits, Barker River area, West Kimberley District: West. Australia Geol. Survey Rec. 1964/34 (unpublished).

Prider, R. T., 1941, Hydrozincite from Narlarla, West Kimberleys, Western Australia: Mineralog. Mag., v. 26, no. 173, p. 60-65.

Russell, R. D. and Allan, D. W., 1957, The age of the earth from lead isotope abundance: Geophysical supplements to the Monthly Notices of the Royal Astronomical Society, v. 7, nos. 1-6 p. 85.

Simpson, E. S., 1951, Galena at Narlarla: Minerals of Western Australia, v. 2, p. 303-304.

Simpson, E. S. and Gibson, C. G., 1907, The distribution and occurrence of the baser metals in Western Australia: West. Australia Geol. Survey Bull. 30, p. 79.

Slawson, W. F. and Austin, C. F., 1962, A lead isotope study defines a geological structure: Econ. Geology, v. 57, p. 21-29.

Woodward, H. P., 1906, Mineral discoveries at Narlarla in the West Kimberley District: West. Australia Mines Dept. Ann. Rept. 1906, p. 147.

INVESTIGATION OF MANGANESE DEPOSITS IN THE MT. SYDNEY—WOODIE WOODIE AREA, PILBARA GOLDFIELD

by L. E. de la Hunty

ABSTRACT

Diamond drilling of manganese deposits at Mt. Sydney and Woodie Woodie was undertaken in 1964, as a joint venture by the Department of National Development and the Western Australian Mines Department, to provide additional information on the mode of occurrence of the deposits. Gravity surveys were also carried out and a geological survey was made of a restricted area. Information was also gained from recent mining activity.

The area is the main source of high-grade metallurgical manganese ore in Australia with an average annual production of about 30,000 tons for the past 5 years. Most of the production has been from Mineral Claim 269 at Woodie Woodie; other deposits are worked intermittently.

The manganese deposits are supergene cavity fillings in the Carawine Dolomite (Lower Proterozoic), probably emplaced during the Upper Proterozoic Era. The deposits are associated with the Pinjian Chert Breccia and are probably of comparable age. They are older than the Waltha Woora Beds, which are Upper Proterozoic, and have been acted upon by Permian glaciation and Cainozoic weathering processes.

Three holes were drilled, one at Mt. Sydney and two at M.C. 268, Woodie Woodie. The drill-hole at Mt. Sydney indicated little depth extension beyond the quarry floor of the ore body on M.C. 532. However, an intersection of high-grade ore was made in D.D.H. No. 1, on M.C. 268, at a vertical depth of 75 feet; and the attitude grade and extent of that ore body was indicated. A concealed ore body was also intersected and this is considered worthy of further testing by vertical wagon drilling.

Drilling, gravity testing and mining development during 1964 have increased the indicated reserves of manganese ore in this area.

INTRODUCTION

Early in 1964 the Commonwealth Department of National Development financed a programme of diamond drilling designed to provide additional information on the mode of occurrence and origin of manganese deposits in the Mt. Sydney and Woodie Woodie areas of the Pilbara Goldfield. The drilling was carried out by a Mines Department crew, and the programme was planned and supervised by the writer.

D. L. Rowston of the Geological Survey, carried out gravity surveys on selected ore bodies in the area in May and June, 1964, and the writer remapped the area.

Additional information was gained from the new openings made by the mining companies during 1964, on M.C.s 269 and 487.

GENERAL INFORMATION

LOCATION

Both the Mt. Sydney and Woodie Woodie areas lie within Warrawagine Cattle Station in the East Pilbara District. Mt. Sydney is 186 air miles east-southeast of Port Hedland and the distance by graded road is about 230 miles. The Woodie Woodie area extends from about 10 to 30 miles south of Mt. Sydney.

PRODUCTION

Manganese ore was first shipped from this area in 1954 and production has been continuous since then. Total production to the end of September, 1964 was about 231,000 tons. The grade of most of the ore produced was greater than 50% Mn.

MANGANESE PRODUCTION*

Year	M.C. 532	M.C. 268	M.C. 269	Other Claims
	Tons	Tons	Tons	Tons
1954	....	....	6,000	6,000
1955	....	12,200	....	....
1956	....	....	....	....
1957	....	13,500	....	....
1958	10,000	4,000	2,800	800
1959	....	....	19,300	....
1960	....	....	29,400	....
1961	....	....	32,400	....
1962	....	....	38,400	....
1963	....	....	22,500	....
1964†	....	....	29,800	3,900
Total	10,000	29,700	181,500	10,700

* All tonnages are approximate.

† Figures quoted for 1964 are to the end of September only.

GEOLOGY

The manganese deposits in this area are all associated with Proterozoic rocks; more specifically with the Carawine Dolomite and younger rocks. In other localities (e.g. Ripon Hills, Skull Springs, Mt. Cooke) the manganese deposits have been formed by supergene enrichment of manganiferous sediments (de la Hunty, 1963), and mining has revealed that they have little depth extension. However, the deposits at Mt. Sydney and Woodie Woodie form cavity fillings and replacement deposits in dolomite, and are known to extend to more than 100 feet depth (M.C.269), although still supergene at that depth. The ore was deposited from solution in circulating waters.

The deposits are generally associated with outcrops of the Waltha Woora Beds, but have not been derived from them. The Waltha Woora Beds are demonstrably younger. Locally, the Waltha Woora Beds appear to be conformable with the Carawine Dolomite, but there is actually a large time interval between the deposition of the two units.

Manganese is known to be mobile under present weathering conditions but the main period of manganese emplacement was obviously subsequent to the exposure of the Carawine Dolomite and prior to the deposition of the Waltha Woora Beds.

STRATIGRAPHY

The oldest rocks exposed in the area mapped are of Lower Proterozoic age. These are unconformably overlain by rocks of the Upper Proterozoic, Permian glacials and Cainozoic sediments (Plate 23).

Lower Proterozoic

The *Little De Grey Lava* is the oldest rock mapped. It is an amygdaloidal basalt with abundant interbedded coarse pyroclastics; it contains the Tumbiana Pisolite Member, which was mapped near the Ragged Hills Lead Mine and also in the southeastern part of the area. This basalt has been correlated with the Mt. Jope Volcanics (MacLeod and de la Hunty, in press). It is folded and sheared and has been intruded by mineralised quartz reefs containing galena, sphalerite and pyrite. To the east of the area mapped, the basalt is intruded by Proterozoic granite (Noldart and Wyatt, 1962). No mineralisation was seen in the basalt in the western part of the area.

The Lewin Shale was first reported by de la Hunty (1963) and was subsequently correlated (MacLeod and de la Hunty, in press) with the Jeerinah Formation and the Marra Mamba Iron Formation. It lies conformably between the Little De Grey Lava and the Carawine Dolomite and consists of shale, chert, jaspilite and thin-bedded dolomite. The average thickness is 400 feet.

The *Carawine Dolomite* has been correlated with the Wittenoom Dolomite (MacLeod and de la Hunty, in press) and is therefore assigned to the Lower Proterozoic. The Wittenoom Dolomite is known to be older than 2,100 million years from radiometric dating of younger rocks. The Carawine Dolomite is the host rock for the manganese deposits on the eastern limb of the Oakover Syncline. It is a blocky, grey and pink, crystalline, dolomitic limestone with chert bands, and contains *Collenia* in its lower part. In many localities, the upper part of this formation is thin-bedded and contains many bands of chert. This is the source of the material for the Pinjian Chert Breccia. The dolomite is also partly silicified but this has probably resulted from weathering. The thickness of the Carawine Dolomite is about 500 feet in this area.

Upper Proterozoic

The Upper Proterozoic *Pinjian Chert Breccia* is about 100 feet thick. It was formed by the cementing, with silica, of angular fragments of chert which have been derived from the Carawine Dolomite. These fragments are characteristically angular but some are partly rounded. Some of the breccia was formed by faulting but most of the chert fragments were caused by the collapse of chert bands when the intervening dolomite had been dissolved out during weathering. The fragments were then cemented together in situ or transported and then cemented. The Pinjian Chert Breccia is not confined to any level. It is generally present on accordant hilltops but is also exposed at plain level 2½ miles northeast of Carawine Gorge. There does not seem to be a local base level of weathering relative to the plateau level. The relative depth of weathering varies by as much as 200 feet over a distance of half a mile, as in the dolomite southwest of Mt. Sydney.

The Pinjian Chert Breccia contains a grooved, striated, glacial pavement at plain level near Carawine Gorge, another at Woodie Woodie, and one in the Ripon Hills (west of the area); so in these localities the unit is older than Permian. However, chert breccia of Tertiary age is also known south of the area (de la Hunty, 1963), so it is probable that not all of the chert breccia in this area is pre-Permian.

The *Waltha Woora Beds* were named by Noldart and Wyatt (1962). They are thin-bedded, pink, calcareous siltstones, fossiliferous, pink, siliceous dolomite, thin-bedded grey dolomite, shale and sandstone. The thickness of the beds exceeds 500 feet. Within the area investigated, these rocks are restricted to the eastern part of the Oakover Syncline. Some superficial manganese staining was observed on sandstone near M.C. 274, but the Waltha Woora Beds are characteristically barren of manganese oxides.

In many places the basal bed is a pebbly sandstone that locally is more than 150 feet thick. It is best developed in the Woodie Woodie locality and is correlated with the long outcrop of pebble conglomerate on the fringe of the desert about 10 miles east. This is called the Googhenama Conglomerate and is younger than the Upper Proterozoic manganiferous sediments to the south (de la Hunty, 1963).

H. S. Edgell, of the Geological Survey, identified *Collenia undosa* in a specimen of the pink siliceous dolomite which was deposited in "littoral to intertidal conditions." The rock has a cuspate surface and the cusps are constant (about 1 cm across) throughout the rock, which is about 20 feet thick.

Permian

The *Braeside Tillite* has been described previously. It is demonstrably younger than the Waltha Woora Beds, since it contains erratics of pink siltstone, and it has been correlated with Permian glacial deposits elsewhere in Western Australia. It also contains boulders of manganese ore and overlies manganese deposits. Steep to overturned dips in thin-bedded glacial beds were exposed by bulldozing along the eastern edge of the ore body on M.C. 487.

Cainozoic

The western side of the Oakover Syncline, in the vicinity of Carawine Gorge, is the type area for the *Oakover Formation.* It consists of white limestone and river gravel with an opaline cap, with a layer of soil with iron pebbles at the base. In many places the limestone surrounds glacial boulders, so that the boundary between the Oakover Formation and the Braeside Tillite is indistinct. The Oakover Formation probably covered all of the glacials in the Oakover Syncline but much of the cover has since been stripped—leaving plateaux and mesas about 100 feet high.

Other Cainozoic sediments in the area are colluvium and alluvium.

Intrusives

The only intrusive rock in the mapped area is dolerite which intrudes the Carawine Dolomite near Mt. Sydney and Carawine Pool. There are two dykes at Mt. Sydney, and it appears from photo-interpretation that the more northerly of these intrudes the Waltha Woora Beds; but this has not been established.

STRUCTURE

The Oakover Syncline is the dominant structural feature of the area. It trends generally 330° but is nearly north in the southern part of the area. It has a low northerly plunge and is more than 20 miles across. The folding took place subsequent to the deposition of the Upper Proterozoic rocks but before the Permian glaciation.

In the vicinity of the deposits, minor folds are generally parallel with the axis of the main syncline, and the en echelon nature of the folding is evident from the outcrop distribution of the Waltha Woora Beds. Two exceptions are the fold trending 285° at Mt. Sydney, and that trending 300° 3 miles east of M.C. 268.

Although the folding is generally simple and of low amplitude, the beds are overturned 4 miles northwest of Mt. Sydney, and isoclinally folded a further 2 miles to the northwest.

Faulting is in the direction 285° at Mt. Sydney and in the southeastern part of the area; also at 320° just south of Ragged Hills Mine, east of M.C. 268, and in the southwestern part of the area. Another fault direction at 015° was observed at Mt. Sydney.

GEOPHYSICAL WORK

Rowston (1965) carried out gravity surveys over several manganese deposits in the area, to test the efficiency of the gravimeter in determining the presence of concealed manganese ore. He concluded that the method was "a rapid and relatively inexpensive way of examining a prospect" and that it could be useful in testing for a concealed deposit.

He estimated a tonnage of just less than 700,000 tons for the ore body on M.C. 487, and subsequent mining of this deposit is tending to confirm his estimate. Satisfactory results were also achieved in gravity work over the western ore body on M.C. 269.

DIAMOND DRILLING

The diamond drilling programme was designed to give information on the attitude and composition in depth of the ore bodies in this area. The total footage drilled was 576 feet—250 feet on M.C. 532 at Mt. Sydney, and 326 feet on M.C. 268 at Woodie Woodie. The programme was modified considerably during its progress: modifications were occasioned by the high cost of drilling relative to the amount of money available for the work, and by the knowledge gained from holes drilled.

Inclined holes were favoured since, as can be seen at M.C. 268, they offer the greatest chance of making an intersection when the attitude of the orebody is unknown. Once the attitude of the orebody is established, a wagon drilling programme, using vertical holes, is desirable.

The surface rock on M.C. 268 is chert breccia and thin-bedded chert; both varieties of chert are hard and highly jointed. Several diamond bits were wrecked in this material and drilling costs were high. However, it was thought inadvisable to resort to wagon drilling in this broken ground because of the danger of jamming the bit. Small pieces of chert could fall into the hole behind the bit, causing the loss of the bit and the hole.

Core recovery was good in the ore bodies but low in country rock.

M.C. 523—MT. SYDNEY

Two holes were planned to test the ore body at Mt. Sydney, but drilling was terminated after only one hole, for financial reasons.

There was a small intersection of high-grade ore at 128 feet in D.D.H. No. 1—probably a "root" from the main ore body—but there was little indication of an economic ore body in depth. The targets for this hole were the vertical, or near-vertical, depth extension of the ore body and possible extensions along the contact between the blocky, thick-bedded Carawine Dolomite and the underlying thin-bedded, shaly dolomite (Lewin Shale).

D.D.H. No. 1

D.D.H. No. 1 was drilled to 250 feet—90 feet past the last small intersection of manganese ore (Plate 24). The main features of the hole were:

1. the presence of dolomite throughout the hole.
2. the absence of an ore body.
3. the low core recovery.

1. The hole was in finely-brecciated, pink, crystalline dolomite throughout. The only variations throughout the core were a few small seams of manganese oxide and earthy calcite. The core following the 7-foot cavity at 225 feet was probably Lewin Shale but it differed little from the previous core.

2. Small deposits of manganese oxide were intersected at 96 feet (5 ins.), 128 feet (29 ins.), about 147 feet (4 ins.), and about 159 feet (9 ins.). The largest two are probably depth extensions of the main ore body, in a cavernous zone, but are too small to be economic. The ore at 128 feet assayed 56.6% Mn, 1.80% Fe, and 4.92% SiO_2.

3. Although the core recovery in the manganese oxide was 100%, the overall core recovery for this hole was only 25%. This is due, no doubt, to the highly cavernous nature of the dolomite in this locality.

M.C. 268—WOODIE WOODIE

Two holes were drilled on M.C. 268—each with azimuth 279° and angle of depression of 45° (Plate 25). The first hole was designed to intersect the ore at less than 200 feet in the drillhole—assuming a steep easterly dip for the orebody. The intersections made with the hanging wall and footwall revealed the dip of each wall, and indicated a lensing and flattening of the ore body, down-dip to the east. D.D.H. No. 1 intersected the main ore body at 112-142 feet in the hole, but the ore intersected at 43 feet and 54 feet in the second hole is not part of the main orebody, nor does it crop out. The small intersection of manganese ore at 134 feet in D.D.H. No. 2 is probably the eastern extention of the main ore body.

(4)—95166

D.D.H. No. 1

D.D.H. No. 1 was drilled to 171 feet—29 feet past the footwall of the ore body. Core recovery was 78 per cent. in the ore and 65 per cent. overall. The main features of the hole were:

1. a hard silicified hanging-wall rock.
2. a high grade ore body, 30 feet thick.
3. a soft dolomite footwall rock.
4. cavities at both hanging-wall and footwall.
5. the presence of the mineral chalcophanite.
6. the distribution of hematite.

1. The hanging-wall rock was jointed chert breccia and thin-bedded chert, with joint fillings of manganese dioxide, chalcophanite and hematite. It contains minor amounts of jasper and several narrow, non-coring zones. The rock has resulted from the jointing, brecciation, oxidation, and almost complete silicification of a rock consisting of alternating thin layers of chert and dolomite. The rock is part of the Carawine Dolomite.

2. The high-grade ore intersected in the drill-hole is the depth extension of the body mined in the open-cut. Assays of samples taken over 5-foot lengths (see Table 1) indicate that the intersected ore contains more than 50% Mn, less than 2% Fe, and less than 13% SiO_2. Mineral determinations made at 4-foot intervals on this ore (see Table 2) indicate that replacement by cryptomelane has taken place at the hanging wall of an ore body, which was originally emplaced as braunite, chalcophanite, pyrolusite and quartz. Replacement is almost complete at 113 feet but has not penetrated far beyond 121 feet. Dolomite was the only other mineral determined in these samples, although barite was seen at about 120 feet in the core.

3. The footwall rock is pink crystalline dolomite, with minor manganese staining and some thin bands of hematite. The dolomite is thick-bedded and easily drilled. It underlies the ore body at the open-cut.

4. The presence of cavities at the hanging-wall (4 feet) and footwall (3 feet) supports the idea of emplacement of the manganese deposit by deposition from solution in a cavity in dolomite. The ore is porous and the pores are probably cavities from which calcite (?) has been dissolved.

5. The mineral chalcophanite has not been identified from any other ore body in this area, and the determination is somewhat suspect in this instance as the mineral contains little more than a trace of zinc. However, it has the optical and X-ray properties of chalcophanite. It is finely disseminated throughout the ore, except at the hanging wall. There are also some small black crystals in places in the hanging wall rock which have a bronze sheen and may be chalcophanite.

6. There are several seams of earthy hematite in both the hanging-wall and footwall rocks of the ore body, but there are no hematite seams in the ore. Nor is there much hematite in the ore, the maximum Fe content being 3.07%. The low hematite content is a feature common to most of the deposits in dolomite in this area. Many of these deposits have a hematite "shell" which indicates the outer limits of the ore body. This shell is usually only a few inches thick but is often very high grade, fibrous, platy hematite.

Table 1

SAMPLING DETAILS—WOODIE WOODIE

Sample No.	Locality of Sample	Assay Results		
		Mn	Fe	SiO_2
2993	D.D.H. No. 1 : 112′ 0″ to 117′ 0″....	50·5	1·83	11·7
2994	,, ,, 117′ 0″ to 122′ 0″....	53·2	1·40	8·05
2995	,, ,, 122′ 0″ to 127′ 0″....	52·7	1·28	13·8
2996	,, ,, 127′ 0″ to 132′ 0″....	48·4	3·07	16·2
2997	,, ,, 132′ 0″ to 137′ 0″....	50·7	1·24	18·9
2998	,, ,, 137′ 0″ to 141′ 9″....	53·8	2·03	7·22
10344	D.D.H. No. 2 : 42′ 9″ to 48′ 0″....	51·9	1·38	15·7
10345	,, ,, 54′ 1″ to 58′ 0″....	47·1	1·37	26·2
10346	,, ,, 58′ 0″ to 61′ 7″....	54·3	1·19	15·3

Note.—All samples are of split core.

Table 2

MINERAL DETERMINATIONS—WOODIE WOODIE

Sample No.	Locality of Sample	Determination
2985	D.D.H. No. 1, 113 feet	Cryptomelane, a little braunite and quartz.
2986	,, ,, 117 feet	Braunite, chalcophanite, cryptomelane and quartz.
2987	,, ,, 121 feet	Braunite, dolomite, chalcophanite, cryptomelane and quartz.
2988	,, ,, 125 feet	Braunite, chalcophanite, pyrolusite and quartz.
2989	,, ,, 129 feet	Braunite, chalcophanite, pyrolusite and quartz.
2990	,, ,, 133 feet	Braunite, chalcophanite, pyrolusite and quartz.
2991	,, ,, 137 feet	Braunite, chalcophanite, pyrolusite and quartz.
10347	D.D.H. No. 2, 44 feet	Braunite, pyrolusite, a little cryptomelane and quartz.
10348	,, ,, 47 feet	Braunite, with a little pyrolusite, cryptomelane and quartz.
10349	,, ,, 56 feet	Braunite and quartz, with a little pyrolusite and cryptomelane.
10350	,, ,, 60 feet	Braunite, with a little pyrolusite, cryptomelane and quartz.

D.D.H. No. 2

D.D.H. No. 2 was drilled to 155 feet—20 feet past a small intersection of manganese ore, which is believed to represent the eastern extension of the main ore body. Core recovery was 100 per cent. in the ore and 56 per cent. overall. The main features of the hole were:

1. The discovery of unsuspected ore.
2. The lensing of the main ore body.
3. The presence of chert in the footwall.
4. The abandonment of the hole.

1. The hanging-wall rock intersected in this hole was fine-banded chert and chert breccia. Manganese oxides have replaced the rock in many places and the ore intersection at 43-48 feet and 54-61 feet are in this chert hanging-wall. These ore bodies are replacement deposits in the chert, either as dykes or lenses. The grade of the uppermost body where sampled was 51.9% Mn, 1.38% Fe, and 15.7% SiO_2; and it consisted of braunite, pyrolusite, cryptomelane and quartz, with an increase in the ratio of braunite to pyrolusite from top to bottom.

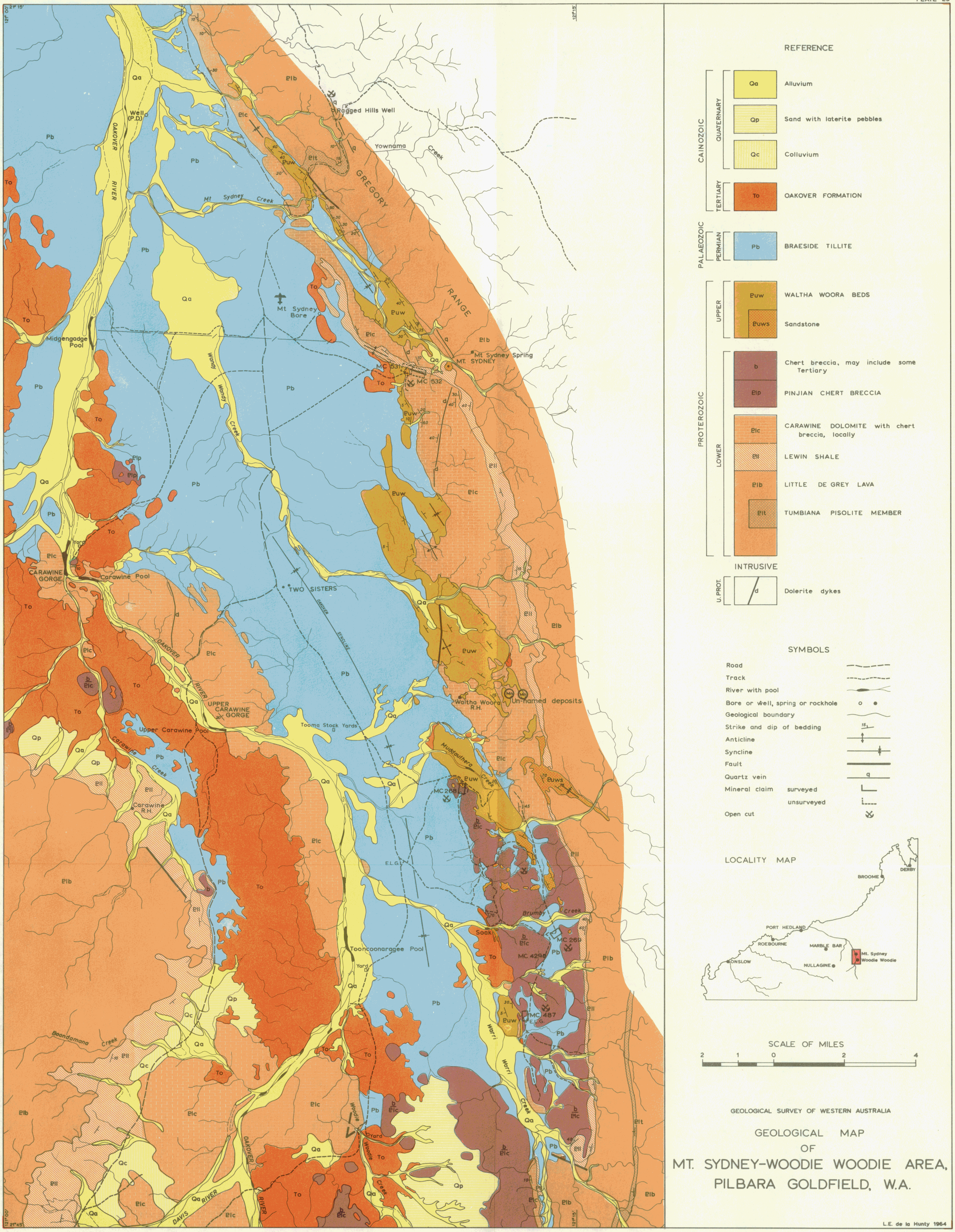
The ore in the second intersection (54-61 feet) has a high silica content, especially in the upper section. There is very little iron in the ore (1.28%) and the average Mn content is about 50%, but the average silica content is 20%. The ore was composed of braunite, minor amounts of pyrolusite and cryptomelane, and variable amounts of quartz.

Further exploration of this ore by wagon drilling is recommended. The ore probably strikes north and it may have any attitude from vertical to horizontal. It does not crop out.

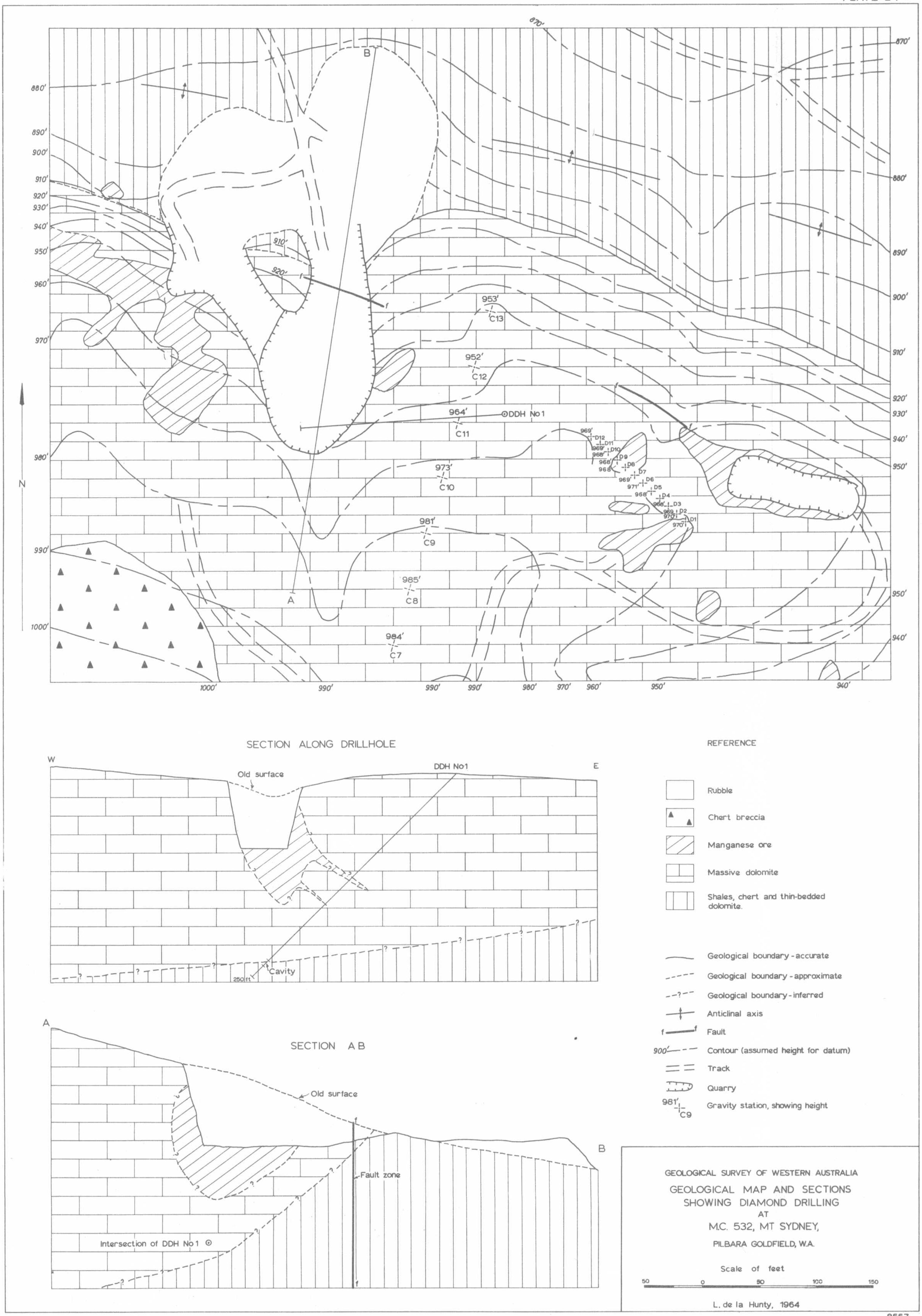
2. Although there are other possible interpretations of the attitude and shape of the main ore body, that shown in the section seems to be the best fit with the intersections in D.D.H. No. 1. The extension of the ore body to the intersection at 134 feet in D.D.H. No. 2 is reasonable since the Carawine Dolomite has variable and low easterly dips in this locality, and it seems that the cavity in which the main ore body was deposited was controlled by bedding. There are also 4-feet gaps (cavities?) in the core, immediately above and below the 134-foot intersection in this hole, as for the main ore body in D.D.H. No. 1.

3. There is far more chert in the footwall in this hole than in D.D.H. No. 2, but there is some dolomite. The quantity of chert is known to be variable in the Carawine Dolomite.

4. At 155 feet the core barrel became inextricably jammed and the hole and barrel were abandoned. A minimum depth of 200 feet had been planned for this hole but as the eastern extension of the ore body had been established in its anticipated correct structural position, redrilling to gain confirmatory evidence over the last 45 feet was not considered necessary.

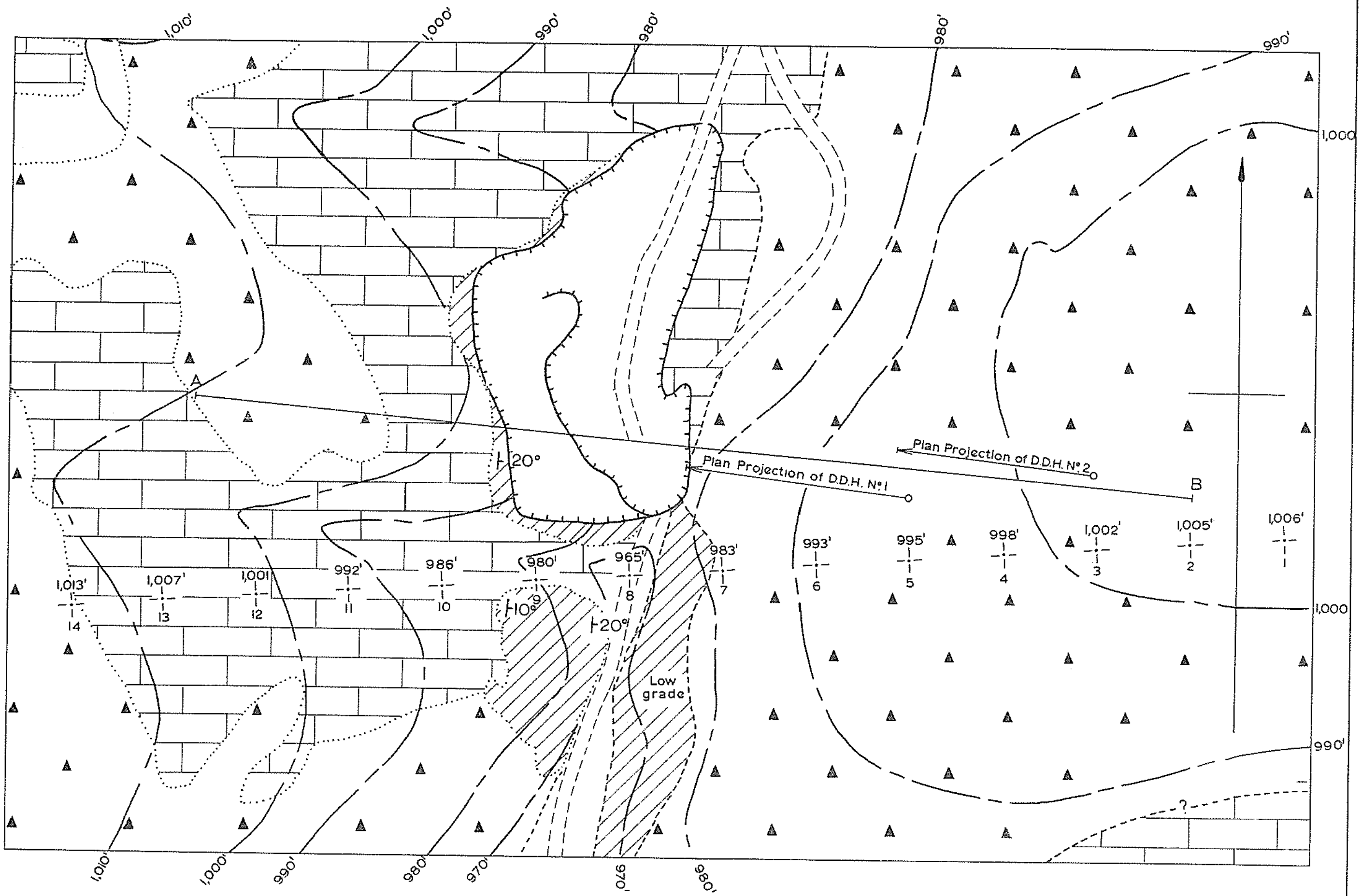

REFERENCE
CAINOZOIC
QUATERNARY
Qa Alluvium
Qp Sand with laterite pebbles
Qc Colluvium
TERTIARY
To OAKOVER FORMATION
PALAEOZOIC
PERMIAN
Pb BRAESIDE TILLITE
PROTEROZOIC
UPPER
Ꞓuw WALTHA WOORA BEDS
Ꞓuws Sandstone
b Chert breccia, may include some Tertiary
Ꞓlp PINJIAN CHERT BRECCIA
LOWER
Ꞓlc CARAWINE DOLOMITE with chert breccia, locally
Ꞓll LEWIN SHALE
Ꞓlb LITTLE DE GREY LAVA
Ꞓlt TUMBIANA PISOLITE MEMBER
INTRUSIVE
U. PROT.
d Dolerite dykes
SYMBOLS
Road
Track
River with pool
Bore or well, spring or rockhole
Geological boundary
Strike and dip of bedding
Anticline
Syncline
Fault
Quartz vein
Mineral claim surveyed
unsurveyed
Open cut
LOCALITY MAP
DERBY
BROOME
PORT HEDLAND
ROEBOURNE
MARBLE BAR
ONSLOW
NULLAGINE
Mt. Sydney
Woodie Woodie
SCALE OF MILES
2 1 0 2 4
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL MAP OF
MT. SYDNEY-WOODIE WOODIE AREA,
PILBARA GOLDFIELD, W.A.
L.E. de la Hunty 1964

8570

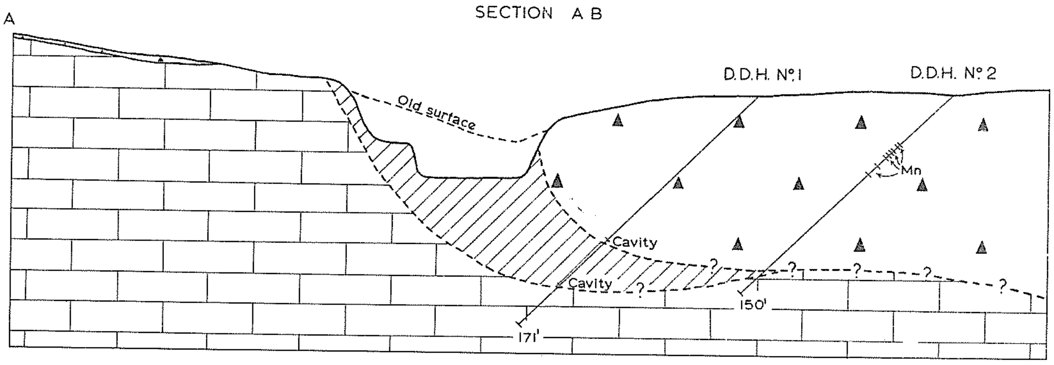

SECTION ALONG DRILLHOLE
W
E
DDH No1
Old surface
Cavity
250 ft
SECTION AB
A
B
Old surface
Fault zone
Intersection of DDH No1
REFERENCE
Rubble
Chert breccia
Manganese ore
Massive dolomite
Shales, chert and thin-bedded dolomite
Geological boundary - accurate
Geological boundary - approximate
Geological boundary - inferred
Anticlinal axis
Fault
Contour (assumed height for datum)
Track
Quarry
Gravity station, showing height
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GEOLOGICAL MAP AND SECTIONS
SHOWING DIAMOND DRILLING
AT
M.C. 532, MT SYDNEY,
PILBARA GOLDFIELD, W.A.
Scale of feet
50 0 50 100 150
L. de la Hunty, 1964
N
DDH No1

8557

PLATE 25



SECTION A B



REFERENCE

- Alluvium and rubble
- Chert and chert brecia
- Manganese ore
- Dolomite
- Geological boundary-accurate
- Geological boundary-approximate
- Geological boundary-inferred
- 1,000' Contour (assumed height for datum)
- Track
- Quarry
- 998' 4 Gravity station, showing height

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GEOLOGICAL MAP AND SECTION SHOWING DIAMOND DRILLING AT M.C. 268, WOODIE WOODIE

PILBARA GOLDFIELD, W.A.

Scale of feet

0 25 50 75 100 200

L. de la Hunty, 1964

8556

CONCLUSIONS

1. The manganese deposits in this area were emplaced after the Lower Proterozoic and probably during the Upper Proterozoic Era. They are older than the Waltha Woora Beds.

2. The deposits have been subjected to Permian glaciation and to Cainozoic weathering processes.

3. The deposits occur as cavity fillings in the Carawine Dolomite, and are not the result of supergene enrichment of manganiferous sediments.

4. Some of the ore bodies persist in depth to beyond 100 feet.

5. The drilling on M.C. 532, Mt. Sydney, did not increase the ore reserves and indicated reserves are less than 6,000 tons of high-grade ore.

6. The drilling on M.C. 268, Woodie Doodie, revealed the attitude and grade of the depth extension of the ore body, and increased the indicated reserves to 130,000 tons of ore greater than 50% Mn. A concealed ore body was also intersected.

7. Mining on M.C. 269 did not deplete the indicated reserves during 1964, as new ore was exposed by the operations. Gravity surveys also tended to confirm indicated ore reserves.

8. Gravity testing and mining development on M.C. 487 indicated an increase in ore reserves to several hundred thousand tons of high-grade ore.

ACKNOWLEDGMENTS

The co-operation of the mining companies in the communication of technical information and their assistance in the form of roadmaking, transport of fuel and stores is gratefully acknowledged.

REFERENCES

Casey, J. N. and Wells, A. T., 1956, Manganese deposits, Gregory Range—Pilbara Goldfield, W.A.: Bur. Min. Resour. Aust. Rec. 1956/8 (unpublished).

de la Hunty, L. E., 1955, Report on some manganese deposits in the North-West Division, Western Australia: West. Australia Geol. Survey Ann. Rept. 1952, p. 34-40.

— 1963, The geology of the manganese deposits of Western Australia: West. Australia Geol. Survey Bull. 116.

— 1964, Balfour Downs, W.A.: West Australia Geol. Survey 1:250,000 Geol. Series Explan. Notes.

— in press, Mt. Bruce, W.A.: West. Australia Geol. Survey 1:250,000 Geol. Series Explan. Notes.

MacLeod, W. N. and de la Hunty, L. E., in press, Roy Hill, W.A.: West. Australia Geol. Survey 1:250,000 Geol. Series Explan. Notes.

Noldart, A. J. and Wyatt, J. D., 1962, The geology of portion of the Pilbara Goldfield covering the Marble Bar and Nullagine 4 mile Map Sheets: West. Australia Geol. Survey Bull. 115.

Owen, H. B., 1953, Manganese deposits near Ragged Hills, Gregory Range, North-West Division, Western Australia: Bur. Min. Resour. Aust. Rec. 1953/62 (unpublished).

Rowston, D. L., 1965, Gravity survey of manganese deposits in the Mt. Sydney-Woodie Woodie area, Pilbara Goldfield: West. Australian Geol. Survey Ann. Rept. 1964.

GRAVITY SURVEY OF MANGANESE DEPOSITS IN THE MT. SYDNEY—WOODIE WOODIE AREA, PILBARA GOLDFIELD

by D. L. Rowston

ABSTRACT

A test geophysical survey over some Pilbara manganese deposits has demonstrated that the gravimeter can detect potential ore bodies. The method is advocated for preliminary assessments of partially concealed deposits prior to drilling and for prospecting other suspected occurrences.

INTRODUCTION

During June 1964 a brief geophysical survey was made over several manganese deposits in the Pilbara Manganese Province to test the effectiveness of the gravity method for detecting and delineating potential ore bodies. The survey was initiated by the Commonwealth/State interest in manganese reserves at the time; the field work was carried out by officers of the Geological Survey of Western Australia with the Worden Gravimeter W.61 on loan from the Bureau of Mineral Resources.

The deposits examined are situated in the Woodie Woodie and Mt. Sydney areas of the Pilbara Goldfield in the North West Division of Western Australia (Plate 23). Manganese is currently mined by open cut methods at Woodie Woodie and transported 230 miles by road to the port of Port Hedland. The geology of most of the deposits, and the area generally, has been described by de la Hunty (1963).

Earlier laboratory investigations indicated a high density contrast (about 1.25) between the manganese ore and country rocks and that the gravity method should therefore be capable of detecting deposits of commercial interest. The method could be particularly useful in assessing whether or not bodies largely concealed by alluvium and detritus warrant test drilling.

FIELD PROCEDURE AND REDUCTIONS

Field work usually consisted of one or more gravity traverses across each deposit; a more comprehensive grid was surveyed at Mineral Claim 269 in the Woodie Woodie area. Gravity station intervals along the traverses varied from 25 to 100 feet depending on the proximity of the body and each station was levelled to an accuracy of 0.01 feet. Base stations were established at the individual localities and reoccupied frequently to determine the drift rate for the meter. These bases were not tied together on a regional scale because of levelling difficulties.

Laboratory determinations of samples of the three principal rock types in the area gave the following average densities: dolomite, 2.84 gm/cc.: chert breccia, 2.64 gm/cc.; manganese 4.12 gm/cc. Whilst the dolomite and breccia gave densities over a narrow range the manganese ore varied widely depending on the grade and amount of siliceous impurity in the sample. Four samples from Mt. Sydney ranged from 3.87 to 4.22 gm/cc. and because similar local variations probably occur elsewhere, an arbitrary density of 4.0 gm/cc. was adopted for the calculations.

A combined free-air and Bouguer correction factor of 0.0600 corresponding to a density of 2.69 gm/cc. was used in the reductions. This value was substantiated by applying Nettleton's technique of least correlation between the topography and corrected gravity results obtained over a ridge of breccia with minor dolomite at Mt. Sydney (Traverse B., Plate 30). This factor also agrees well with the density of the breccia and its application has been justified by the obvious elimination of topographic effects in other localities.

Regional, latitude and terrain corrections are also normally applied to the observed gravity data. However, because of the restricted coverage of the deposits, it was not practicable to compensate for these effects by the standard methods. As most of the traverses were long enough to discriminate between anomalies due to the manganese body and those from deep-seated gravity variations, regional gradients were determined by inspection and the results corrected accordingly. The latitude correction for the area only amounts to a north-south component of about 0.016 milligal/100 ft. and, as most traverses were oriented approximately in an easterly direction, has been neglected. It was not possible to make the detailed topographic surveys necessary for terrain corrections and the lines were disposed to minimise these effects.

INTERPRETATION OF RESULTS

The interpretation of a gravity anomaly consists essentially of assuming some simple geometrical and geologically plausible form for the body and calculating a theoretical anomaly for this body. The theoretical anomaly, usually a sectional profile, is then compared with the observed gravity and discrepancies removed by successive modification of the original model until a "best fit" between observed and theoretical curves is obtained. Under normal conditions there is no unique solution to a particular gravity problem but the inherent ambiguity in interpretation can be reduced by geological control. The major unknowns are the depth, density contrast, shape and size of the body. All the deposits investigated during the survey occur at or near the surface and the uncertainty of the depth factor has been thus practically eliminated. A density contrast of 1.25 has been employed for the calculations and is considered to be a realistic approximation in the absence of more comprehensive density data. The objectives of the survey were to determine the shape and size of the body.

The calculations of gravity profiles for the simple two dimensional forms were made with the standard dot chart; it is assumed that the bodies extend to infinity in the third dimension and end effects have been ignored. In the case of the finite vertical cylindrical form at M.C. 487 the theoretical anomaly was calculated by the method of solid angles detailed by Nettleton (1942). It is emphasised that the solutions given are only approximations compatible with the preliminary nature of the work.

Two estimates of the probable tonnages of manganiferous material available from the deposits at M.C. 269 and M.C. 487 were made by the method of total anomalous mass described by Parasnis (1962.) It was necessary to interpolate residual gravity values to complete grids about the two deposits and at M.C. 487, to assume circular symmetry to use the method.

DISCUSSION OF RESULTS

The localities of the various mining tenements investigated during the survey are shown on Plate 23. They are M.C. 269, M.Cs. 531, 532, M.C. 268, M.C. 487, M.C. 429 and an unnamed prospect.

Plates 26 to 31 show the corrected gravity results in the form of Bouguer and residual contours and/or profiles. Where interpretation has been practicable, the profiles include the theoretical gravity curve for comparison and the assumed geological section from which the theoretical gravity was obtained.

M.C. 269

This tenement is just south of the Woodie Woodie ore body currently being worked by Mt. Sydney Manganese Pty. Ltd. The deposit has been tested by wagon and diamond drilling and the overburden partially removed. Gravity datum for the investigations was the northwestern lease peg from which the grid centreline was surveyed on a magnetic bearing of 104.5 degrees; six traverses spaced about 100 feet apart and up to 600 feet in length were pegged at right angles to the centreline.

The Bouguer and residual gravity contours of the gridded area (Plates 26, 27) contain a well defined lenticular anomaly which conforms in part with the postulated geological outline of the manganese deposit and attains a maximum of 0.85 milligal. The 0.4 milligal contour which approximately delineates the boundary of the manganese body extends over a distance of 400 feet from Line B to Line F with no definite sign of closure at the eastern end. Mullock dumps and the open cut precluded additional work to find the eastern extremity of the deposit.

Drilling has indicated that much of the manganese is ore grade although the quality is variable, ranging from about 31 to 50 per cent. manganese with the poorer grades towards the margins of the body. As far as is known the ore body is surrounded by glacial deposits and is partly associated with the Carawine Dolomite, an environment similar to that of the adjacent ore body.

According to the gravity data, both contours and profiles, the most massive part of the body lies between Lines F and D. From Line D it either plunges beneath the surface at the western end or becomes a sheetlike deposit; it is most likely that the body terminates somewhere between Lines C and B and that the minor anomaly on Line B is due to end effects. This purely geophysical interpretation is at variance with the drilling information which shows that ore was encountered from the surface to a depth of 35 feet in two holes near stations C/00 and B/00. Despite this evidence it is difficult to reconcile the observed gravity of Line C with a surface sheet to produce a better fit than that given for the assumed section on Plate 29. Selection of the other theoretical body for Line E was guided by drillhole intersections with the ore body; two holes put down to the north and south of station E/00 encountered 82 and 34 feet of manganese. Excellent agreement between the observed and calculated gravity was obtained using a density contrast of 1.25.

Calculation of the probable tonnage of manganiferous material contained in the area of the gravity survey, derived by Parasnis's method of total anomalous mass for a 100 foot grid, gave a figure of 400,000 tons. An ore body of this size could have dimensions of 100 by 80 by 450 feet which is not unrealistic. However, this figure is only an approximation because of the meagre density data of the manganese body and host rock. Much of the manganese would not be classed as ore grade.

M.Cs. 531, 532

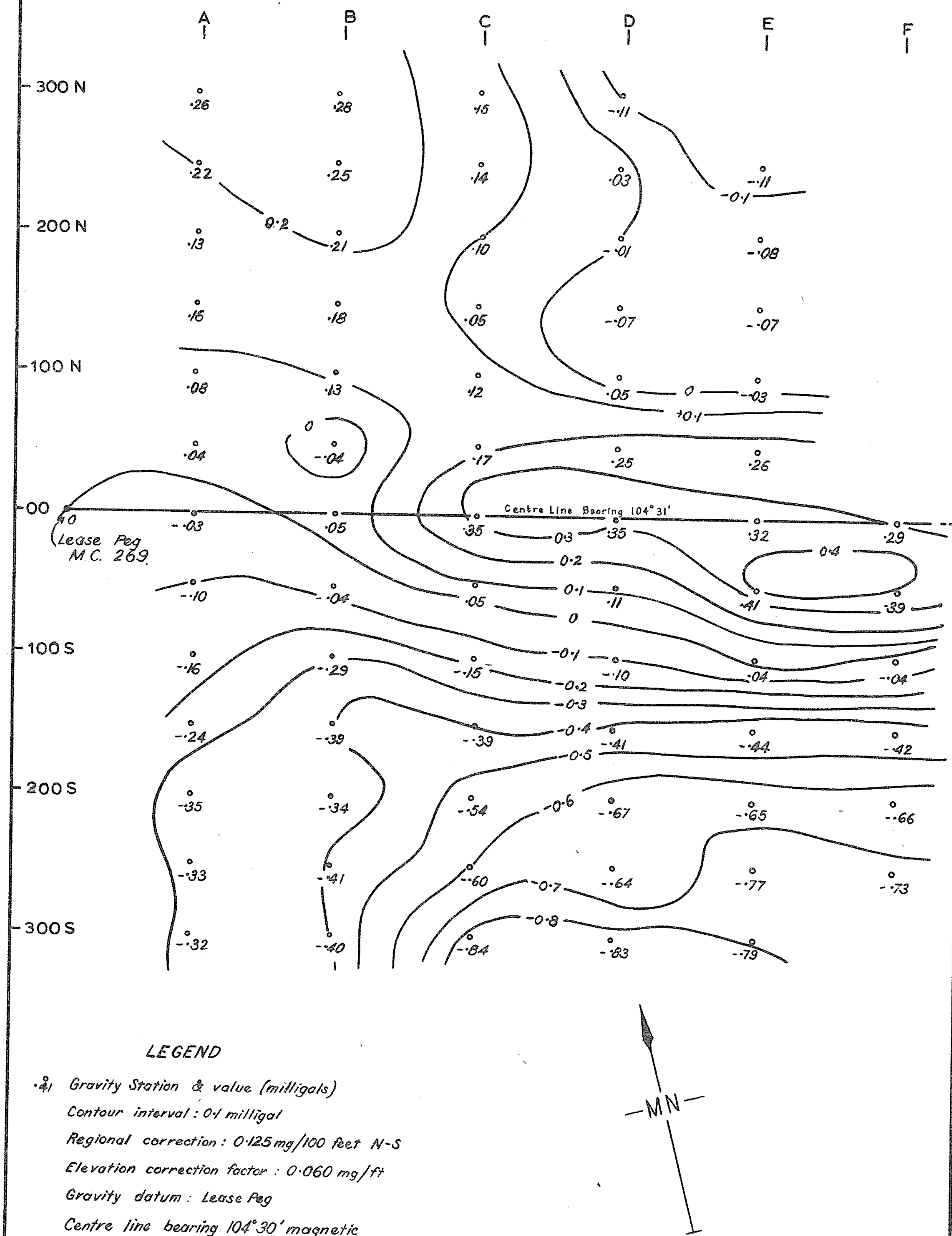
At Mt. Sydney where the main ore body occurs as a cave or fissure filling in the Carawine Dolomite the gravity results were inconclusive. The rugged topography precluded an adequate investigation of the deposit, and terrain effects may contribute largely towards the 0.3 milligal anomaly obtained on traverse C (Plate 30). Neglecting terrain effects and assuming a density contrast of 1.25, this broad anomaly could arise from a horizintal cylindrical body of manganese with a radius of 35 feet and depth to centre of 70 feet. However, detailed gravity and topographic surveying beyond the scope of the test survey are required before any definitive interpretation can be made. Traverses A and B were occupied to obtain an elevation correction factor for the area and are not associated with the manganese deposit.

M.C. 268

M.C. 268 has been mapped geologically (de la Hunty, 1963) and partially mined. Two diamond drillholes were proposed to investigate the possible easterly continuation of the ore body beneath a chert breccia ridge and the gravity traverse was oriented to take advantage of this future information. The observed gravity profile (Plate 30) contains an anomaly of about 0.1 milligal, which under normal circumstances, would be considered insignificant and bordering on the magnitude of reading and corrections error. However, the the subsequent drilling revealed about 30 feet of managanese at the breccia-dolomite contact and, considering the uniformity of the remainder of the gravity profile, the minor anomaly is ascribed to the ore. With the interpolation of station 00 accepted, the anomaly could be due to a theoretical horizontal cylinder with a radius of 20 feet and depth to centre of 60 feet.

M.C. 487

The circular mesa of manganese outcropping at this tenement and rising some 30 feet above the surrounding scree covered country had not been exploited or tested geologically. Two parallel traverses A and B were surveyed to investigate the deposit. Traverse A, directly across the centre of the outcrop, resulted in a residual gravity anomaly of about 1.0 milligal attributable to the manganese (Plate 31). Traverse B was occupied to determine whether or not the manganese continued beneath the scree cover to link with



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

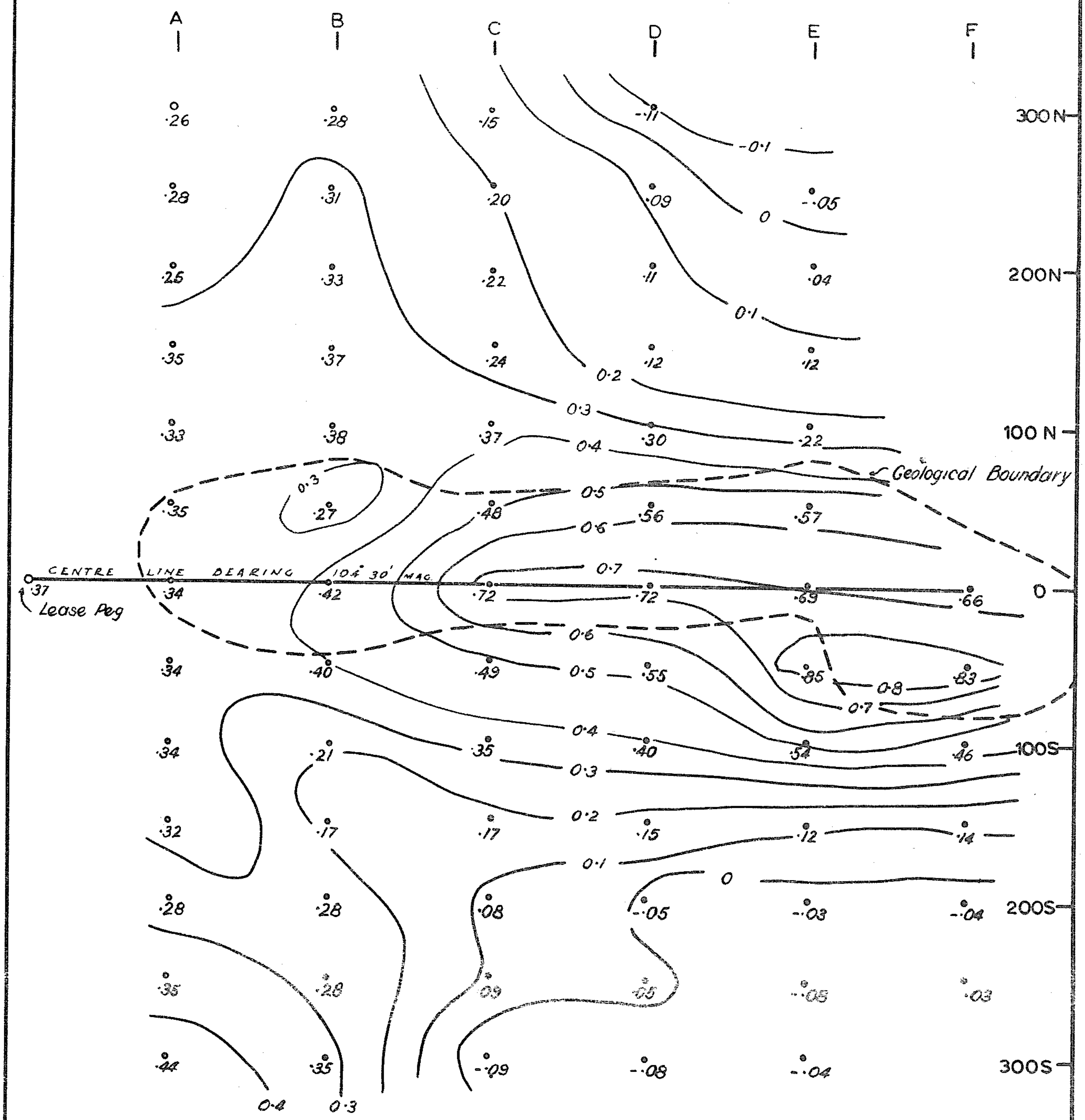
GRAVITY SURVEY WOODIE WOODIE AREA - M C 269

GRAVITY CONTOURS — BOUGUER ANOMALY

Scale in feet

100 50 0 100 200

To accompany report by D.L.Rowston, 1964



N

LEGEND

·41 *Gravity Station & value (milligals)*

Contour interval: 0·1 milligal

Regional correction: 0·125 mg/100 feet N-S

Elevation correction factor: 0·060 mg/ft.

Gravity datum: Lease Peg

Centre line bearing 104°30′ magnetic

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

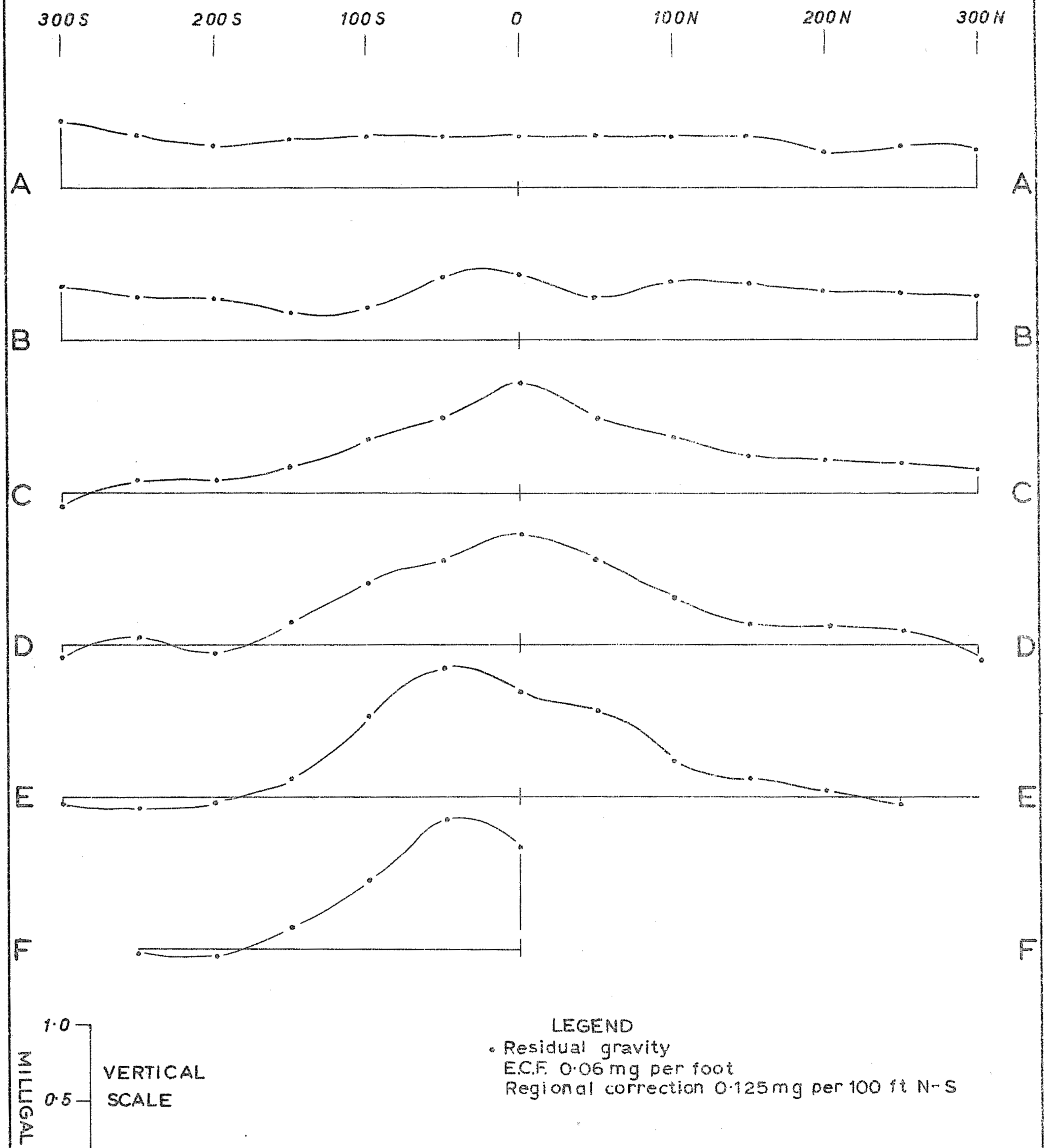
GRAVITY SURVEY WOODIE WOODIE AREA - M C 269

GRAVITY CONTOURS — RESIDUAL ANOMALY

Scale of feet

100 50 0 100 200

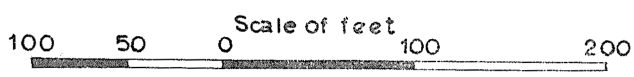
To accompany report by D.L.Rowston, 1964



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

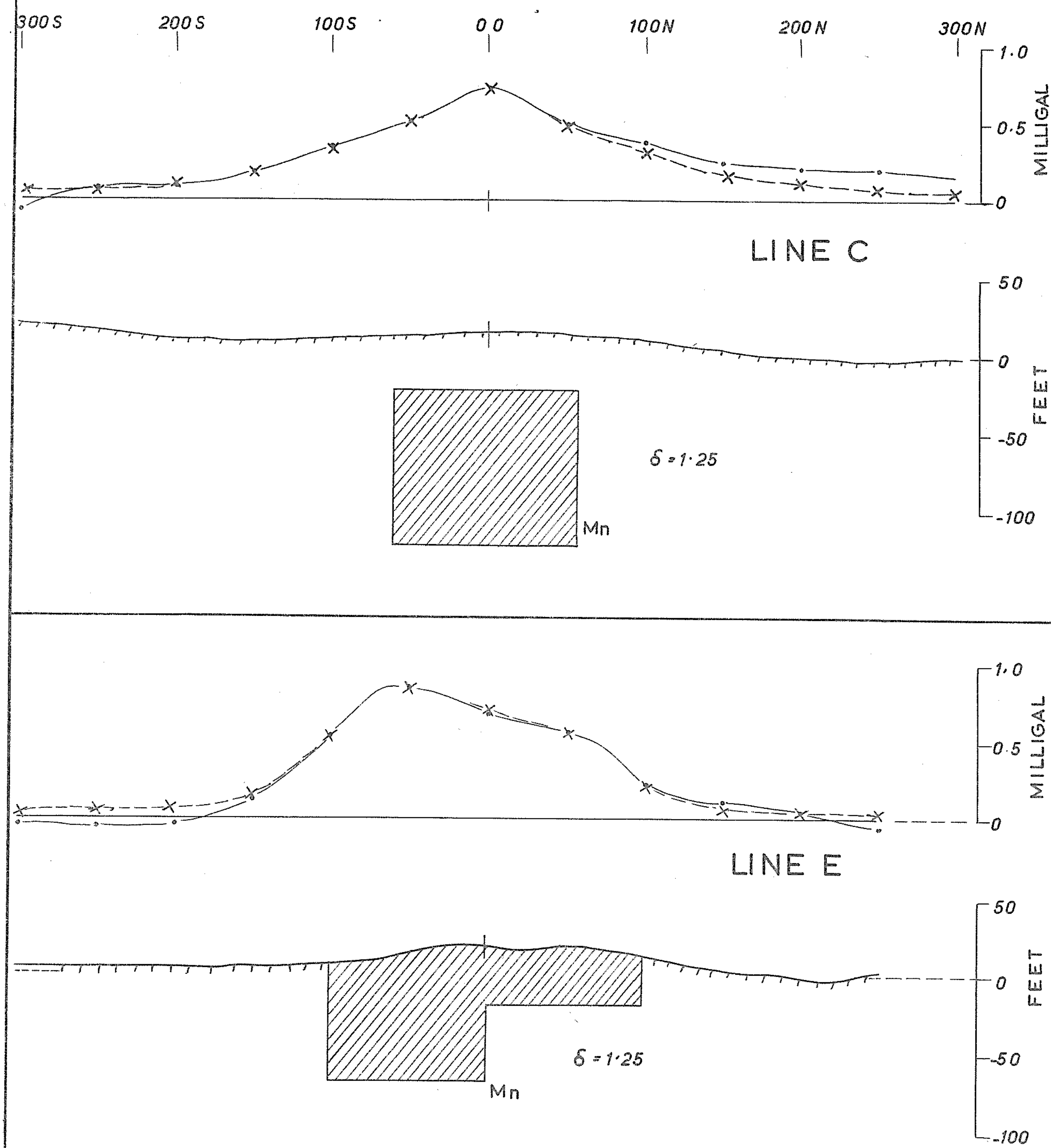
GRAVITY SURVEY, WOODIE WOODIE AREA MC 269

RESIDUAL GRAVITY PROFILE



To accompany report by D.L.Rowston, 1964

8631



LEGEND

· Residual gravity
× Computed gravity
Theoretical two dimensional body
E.C.F. 0·06 mg per foot
Regional correction 0·125 mg per 100 ft. N-S

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

GRAVITY SURVEY, WOODIE WOODIE AREA - M C 269
RESIDUAL AND THEORETICAL GRAVITY PROFILES

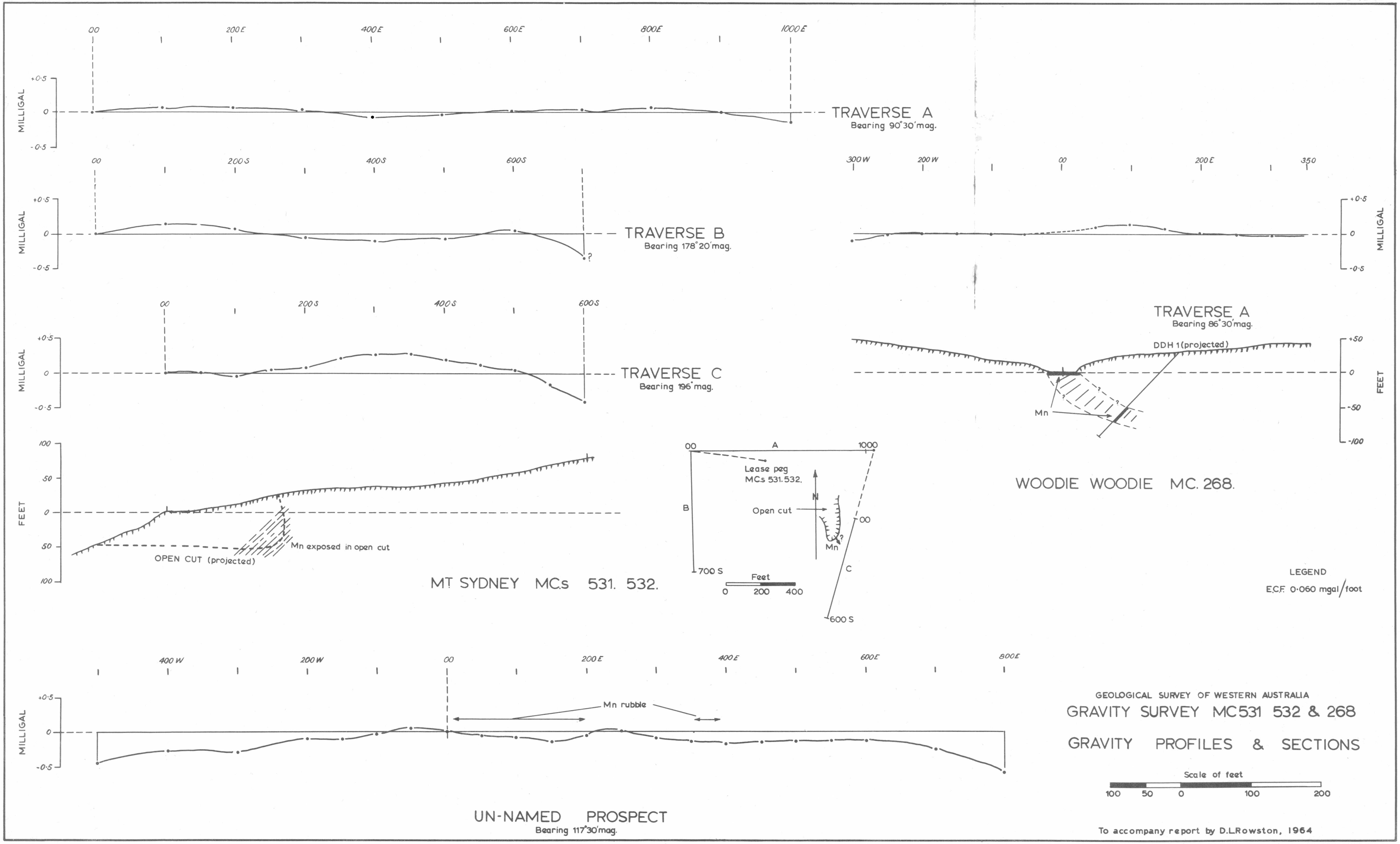
Scale of feet

100 50 0 100 200

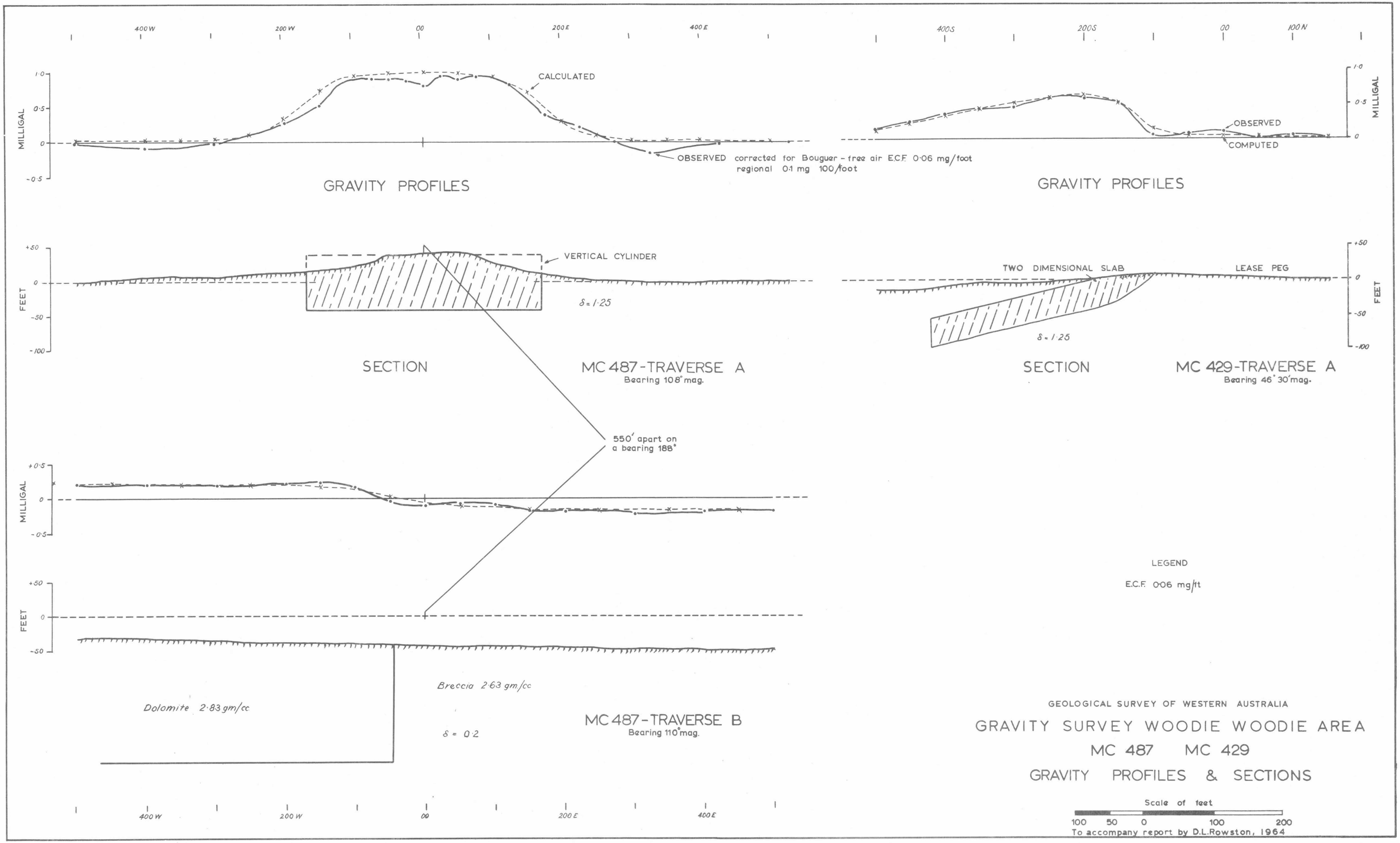
To accompany report by D.L.Rowston, 1964

8632

PLATE 30



8376


400 W
200 W
00
200 E
400 E
400 S
200 S
00
100 N
MILLIGAL
1·0
0·5
0
-0·5
CALCULATED
OBSERVED corrected for Bouguer - free air E.C.F. 0·06 mg/foot
regional 0·1 mg 100/foot
GRAVITY PROFILES
OBSERVED
COMPUTED
GRAVITY PROFILES
+50
0
-50
-100
FEET
VERTICAL CYLINDER
δ = 1·25
SECTION
MC 487 - TRAVERSE A
Bearing 108° mag.
TWO DIMENSIONAL SLAB
LEASE PEG
δ = 1·25
SECTION
MC 429 - TRAVERSE A
Bearing 46° 30′ mag.
550′ apart on
a bearing 188°
+0·5
-0·5
LEGEND
E.C.F. 0·06 mg/ft
Breccia 2·63 gm/cc
Dolomite 2·83 gm/cc
δ = 0·2
MC 487 - TRAVERSE B
Bearing 110° mag.
GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
GRAVITY SURVEY WOODIE WOODIE AREA
MC 487 MC 429
GRAVITY PROFILES & SECTIONS
Scale of feet
100 50 0 100 200
To accompany report by D.L. Rowston, 1964

6377

another prominent outcrop to the south; the minor anomaly on this traverse indicates a probable geological contact or fault at about the point of inflection of the anomaly but contains no evidence of manganese.

The theoretical solution of traverse A was calculated for a finite vertical cylinder of radius 170 feet and thickness of 80 feet assuming a density contrast of 1.25. At three tons of manganese to the cubic yard and with due allowance for the annulus removed by weathering the body contains about 660,000 tons of manganiferous material. Another estimation of the possible available tonnage was made from the total anomalous mass on the assumption of circular symmetry of the gravity data. The figure of 690,000 tons obtained agrees substantially with the previous estimate. It is emphasised however, that these tonnages are only approximations because of the paucity of gravity data and density control.

M.C. 429

This one acre claim pegged about a small outcrop of manganese was investigated by one gravity traverse 650 feet long on a magnetic bearing of 46.5°. The Bouguer anomaly profile shown on Plate 31 indicates either a fault contact or a dipping two dimensional slab. In the absence of surface geology, interpretation has been based on the latter and the theoretical body to give a best fit solution is depicted in the section. Although this solution is regarded as conjectural, the deposit warrants further examination either by drilling or gravimeter, because of its proximity to the current mining operations at Woodie Woodie.

UNNAMED DEPOSIT

Two small outcrops situated in undulating country some 2.7 miles north-northeast of M.C. 268 were tested by a traverse 1,300 feet long on a magnetic bearing of 117.5°. Although two small gravity maxima were detected the profile (Plate 30) does not appear to indicate a deposit of commercial interest.

CONCLUSIONS AND RECOMMENDATIONS

The test geophysical survey has demonstrated that the gravity method can be usefully applied to investigate manganese deposits in the Pilbara area and elsewhere.

The method is rapid and, compared to the usual alternative of drilling, relatively inexpensive. Whilst drilling is an essential in any final assessment of a manganese deposit as an economic proposition, preliminary gravity work can indicate whether or not drilling is warranted and can be used to select drilling tragets. This applies particularly to those deposits where surface alluvium and detritus prevents a geological appraisal.

The somewhat tentative interpretations of the gravity anomalies obtained during the test survey could be refined considerably and more accurate estimates of probable tonnages made, if time had been available to extend the gravity coverage and collect more manganese samples for density determinations.

Future preliminary investigations of a manganese prospect should include at least three gravity traverses; two across the strike of the outcrop and another longitudinally. Any residual anomaly exceeding about 0.3 milligal should then be systematically gridded at about 50 or 100 foot intervals to enable a thorough interpretation of the results. Comprehensive sampling of the manganiferous and country rocks will give better density control and also provide a possible correlation between density and grade.

The gravity results indicate that, excluding the deposit at M.C. 269 which is to be exploited, the manganese bodies at M.C.s 487 and 429 warrant further examination as possible sources of manganese.

A more detailed description of the gravity survey and its results is given by Rowston (1964).

REFERENCES

de la Hunty, L. E., 1963, The geology of the manganese deposits of Western Australia: West. Australia Geol. Survey Bull. 116.

Nettleton, L. L., 1942, Gravity and magnetic calculations: Geophysics, July, 1942.

Parasnis, D. S., 1962, Principles of applied geophysics: Methuen Monograph Series.

Rowston, D. L., 1964, Pilbara manganese deposits, W.A.—gravity survey, 1964: West. Australia Geol. Survey Rec. 1964/25 (unpublished).

PISOLITIC TUFFS IN WESTERN AUSTRALIA

by A. F. Trendall

ABSTRACT

Tuffs containing discrete pea-like aggregations of fine-grained tuff (pisoliths) in a tuff matrix occur in the Precambrian Fortescue Group of the Pilbara area, at two main stratigraphic levels with a lateral extent of over 300 miles. At these levels, beds of pisolitic tuff are distributed irregularly within a greater thickness of similar but non-pisolitic rocks. The average diameter of pisoliths varies between 1 and 13 mm and they have a small range of size in any one bed. Commonly they are close-packed in thin homogeneous beds without internal stratification, but other varieties show effects of current sorting. Diagenetic replacement of the matrix by calcite shows that most originally spherical pisoliths have been deformed by late compaction to oblate ellipsoids with elongation ratios between 1.40 and 1.75. Accretion of moist ash in eruptive clouds with consequent fall of mud-pellet rains has been suggested for closely similar rocks in the United States. An origin by colloidal flocculation of the finest material in subaqueous, originally non-pisolitic, tuff close to the sediment-water interface is favoured by the evidence from Western Australia, but more work is required for reasonable certainty.

INTRODUCTION

Pisolitic tuffs are tuffs which contain discrete pea-like aggregations of fine-grained material known variously as accretionary lapilli, chalazoidites, fossil raindrops, mud balls, mud pellets, volcanic hailstones and volcanic pisolites; here they are called volcanic pisoliths or simply pisoliths. The purposes of this report are: (1) to record the occurrence of these rocks in Western Australia, (2) to review past and current references to them by geologists of the Survey, (3) to list specimens of pisolitic tuff in the registered rock collection of the Survey, (4) to describe briefly these specimens, (5) to note published references to similar rocks, and (6) to comment briefly on their origin and significance.

OCCURRENCE

Except for a single example, noted below, all the known pisolitic tuffs of Western Australia occur within the Fortescue Group (MacLeod and others, 1963). This is the lowest stratigraphic division of a thick sequence of comparatively undisturbed Precambrian sediments and volcanics which in the Pilbara area (here considered as approximately lats. 21°-23°S, longs. 116°-121°E) unconformably overlies the Pilbara System, an older Precambrian complex of folded sediments, volcanics and intrusive granites. The Pilbara System appears to be about 2,900 m.y. old in part, while acid volcanics 20,000 feet above the basal unconformity of the Fortescue Group have an age of 2,100 m.y. (Leggo and others, 1965).

The Fortescue Group (Kriewaldt, 1964) has an average thickness of 3,000 feet of alternating tuffs, basic lavas and shales. Although correlation within the group is still tentative, pisolitic tuffs are known to occur within two main stratigraphic units, and other minor developments are reported. The upper unit, which in the east is split by a lava about 200 feet thick, is separated by 600-700 feet of lava from the lower. The upper is continuous from east to west for over 300 miles, and the lower for some 130 miles.

The pisolitic tuffs occur within stratigraphic units up to 2,000 feet thick which include shales, sandstones, conglomerates, jaspilites, minor lavas, dolomites and pyroclastics varying from silt grade to agglomerate. Rough estimates of the proportions of pisolitic tuffs in these formations suggest about a tenth of their thickness, and the total of such beds in the Fortescue Group is probably between 100 and 200 feet.

Even at those levels within these formations at which pisoliths are common they are distributed sporadically in beds up to 2 feet thick, but generally less, separated by non-pisolitic tuffs. The shape of individual pisolitic beds is not known, but beds inches thick certainly extend laterally for hundreds of feet.

An exceptional specimen (R709) comes from the underlying Pilbara System, ¼ mile north of Warambie Homestead, at approximately lat. 20° 57′ S, long 117° 22′ E. Although pisolitic tuff in this System is known only from this single locality, the occurrence is significant in showing that, whatever were the conditions under which these rocks were formed, they existed some 2,900 m.y. ago.

PAST AND CURRENT WORK

Amygdaloidal lavas recorded by Maitland (1908, p. 125) from Wild Dog Camp are pisolitic tuffs of the Fortescue Group. Talbot (1920, p. 132) later described a 40 foot-thick limestone between lavas which Farquharson (in Talbot, 1920) noted was oolitic. The specimen referred to (13976) is a laminated non-pisolitic tuff; there has probably been a later confusion of numbering. Noldart and Wyatt (1962, p. 66, 67, 80) later formally named the formation from which Maitland's and Talbot's specimens came as the Tumbiana Pisolite (misspelt "Tumbinna" Pisolite throughout their publication), and de la Hunty (1964) mapped the same formation in an adjacent area. All this work was done near the eastern end of the Fortescue Group outcrop.

Later mapping has extended the known outcrop of pisolitic rocks some 300 miles westwards; they occur in the Mt. Herbert Tuff (which is correlated, at least in part, with the Tumbiana Pisolite) and in the Cliff Springs Formation, a second pyroclastic unit lying at the base of the Fortescue Group (de la Hunty, Kriewaldt, Ryan, Williams; pers. comm.). Realisation of the tuffaceous nature of these pisolitic rocks came during this mapping through their constant volcanic association and by petrological examination. Further references to these rocks will appear in the Explanatory Notes of the Roy Hill, Pyramid, Mount Bruce, and Yarraloola 1:250,000 Geological Sheets.

MATERIAL AVAILABLE

The registered rock collection of the Geological Survey of Western Australia contains 37 specimens of pisolitic tuff collected over 60 years; all but one (R709) of these come from the Fortescue Group. The numbers of these specimens are:

5808	2/4698	2/4699	2/4700	2/4701	2/4702
2/4073	2/4705	2/4707	R35	R36	R68
R371	R709	R712	R964	R965	R966
R972	R985	R1006	R1021	R1053	R1087
R1101	R1102	R1106	R1110	R1203	R1204
R1205	R1206	R1207	R1208	R1209	R1210
R1211					

DESCRIPTION OF THE PISOLITIC TUFFS

The various textural and compositional characters of the Western Australian tuffs, as expressed in the specimens listed above, are described below:

Composition of the Rocks

As emphasized below, matrix and pisoliths in any one rock have the same composition, and this description applies to both. The distribution of coarse and fine material is described under "Internal Structure of the Pisoliths".

The rocks are fine-grained tuffs in which the coarsest fragments (R1006) reach 2mm; but generally, in even the coarser-looking rocks (R1101, R1102), the largest grains are no greater than 0.5 mm across. Fragments as large as this never constitute a large proportion of the rock, and there is a continuous downward gradation to irresolvable material. In many specimens (e.g. R1087) no fragments larger than 0.1 mm occur. The recognisable fragments consist of subangular and sharply angular broken grains of quartz, microcline, albite, cloudy alkali feldspar, elongate prisms of green amphibole, subrounded to subangular rock (chert, quartzite, ?rhyolite) fragments, and typically curved and pointed shards of volcanic glass devitrified to an isotropic mosaic of colourless chlorite. The fragments in one rock may be almost entirely quartz and feldspar (R1006), mainly shards (R1110) or a mixture of the two. Small ilmenites, often embayed by later alteration, are sometimes present (R371; R965).

All the finer parts of these rocks are now represented by a dense aphanitic aggregate of quartz, chlorite, sphene, ?sericite and ?amphibole in which individual grains are difficult to distinguish although the original structures of the rock are defined by lighter and darker patches. More detailed descriptions are given (R35, R68) in unpublished Petrologist's Reports Nos. 6 and 9 of the Geological Survey of Western Australia.

It is noteworthy that pisoliths only occur in the acid tuffs intercalated between basic lavas.

Size and Shape of Pisoliths

The mean apparent greatest diameters of 20 pisoliths each from five specimens (R964, 2/4699, R371, R1204, R1102) are 1.38, 3.81, 4.84, 8.23 and 9.62 mm repectively, measured on a face perpendicular to the bedding. A subjective assessment of these five rocks is that the true mean greatest diameters would be about a third greater than these figures, giving a size range in this group of less than 2 to about 13 mm. R1102 has the largest pisoliths of the whole collection but others not measured (R1205, R1208) have pisoliths of average diameter about 1 mm.

Almost all complete pisoliths in the collection, including those of the five measured specimens above, are oblate spheroids with their shortest axes within about 20° of a normal to the bedding plane; exceptions are the current-modified 2/4700 and 2/4701 (see below) and R35, in which the longest axes of the elongate pisoliths lie at about 25° to the bedding owing to deformation during folding. In the five measured specimens listed above the mean elongation ratios for 20 pisoliths are 1.08, 1.08, 1.40, 1.75 and 1.42 respectively; the significance of these figures is discussed below.

Sorting of Pisoliths

In most specimens there is little range in pisolith diameter; few depart more than ± 10% from the mean. In 2/4706 a plane of stratification is defined clearly by a sharp change in average pisolith diameter from about 1.5 to 3.0 mm. R35, R371 and R1204 show this limitation of size range particularly well. In R1208 a single pisolitic bed 3.5 mm thick shows a steady gradation from a basal average diameter of nearly 2 mm to an uppermost diameter of about 1 mm.

Volume and Distribution of Pisoliths

In the bulk of the specimens (particularly good examples are: 5808, 2/4699, 2/4700, 2/4706, R35, R371, R964, R1021, R1102, R1203, R1208) the pisoliths are more or less tightly packed, and therefore of necessity evenly distributed in a rock with little internal evidence of stratification. Point counts (using a 2 mm grid over at least 30 cm^2) of five of these gave percentage volume estimates as follows:

Specimen	Matrix	Pisoliths
R 371	18	82
R 1021	37	63
R 1102	50	50
R 1203	30	70
R 1204	26	74

The figures for R1204 fall close to the theoretical 25.9 and 74.1 for close-packed spheres, while those for R1021 and R1203 indicate little separation of pisoliths. The 82% pisolith volume of R371 is probably due to mutual plastic yielding of pisoliths in contact. R1102 shows a larger departure from close-packing which is confirmed by inspection of the specimen.

In three rocks (R712, R1206, R1210) pisoliths are scattered irregularly in a fine-grained tuff, although in one of these (R1206) they tend to be concentrated in bands parallel to the bedding. In four specimens (2/4700, 2/4701, R1203, R1207) there is evidence of current action; in three of these current-modified rocks (all except R1207) the pisoliths are closely associated with finely laminated siltstone. Pisoliths are truncated (2/4700), squashed into unusual irregular shapes (2/4700, 2/4701) or broken (all four specimens). In R1203 pisoliths appear to have been trapped in the troughs of current ripple marks.

Composition and Internal Structure of Pisoliths

The composition of the pisoliths is always exactly the same, except for a greater proportion of fine material, as that of the matrix. Thus if shards are the main fragment type in the matrix (R1110) this is also true for the pisoliths; if ilmenite grains are present in the matrix (R965) they are present in the pisoliths also. In no slide has it been possible to find any detail in which matrix and pisolith differ.

In the structurally simplest pisolith there is a sharply defined edge of fine material which grades evenly inwards to a core of structureless tuff of similar grain-size to that of the matrix. The main variants are:

1. There may be at the core a single coarse grain giving the effect of a nucleus. A sequence of close parallel cuts across R1102 showed that in this rock such nuclei were present in about half of the pisoliths only.

2. There may be little or no inward increase of grain-size, so that the pisoliths are almost homogeneous spheroids of structureless fine tuff. This type occurs in rocks of both coarse matrix (R985) and relatively fine matrix (R1204).

3. Alternatively the grading may take place over a small fraction of the radius, so that a thin outer shell of very fine material encloses homogeneous tuff like that of the matrix (2/4701, R1053).

4. There may be a repetition of the grading sequence to give alternations of fine and coarse tuff (up to 7 observed—R1101). Where there are several rings the finest tuff is always peripheral.

In all pisoliths any elongate fragments present have their long axes arranged tangentially to give a concentric pattern.

Broken and Modified Pisoliths

In several specimens (2/4700, 2/4701, R36, R709, R1006, R1053, R1087, R1101, R1102) broken pisoliths appear in association with whole pisoliths. The breaking appears to be divisible into three types:

1. In 2/4700 and 2/4701 the pisolitic tuffs are current-modified types in which the pisoliths are defined by thin peripheral shells. A few of these are broken and it is clear from the arangement of the pieces that the pisoliths have been crushed in place during current sorting.

2. In others (e.g. R36, R709, R1053) there is a fairly equal and homogeneous mixture of whole and broken pisoliths closely packed in either a fine-grained tuff or a calcite matrix. In both R709 and R1053 it is clear that some of the fracturing took place in situ, possibly during mass preconsolidation movement of the rock unconnected with current action. In R36 the fracture seems to have taken place right across internally competent pisoliths, while in R1053 the shapes give the impression that a competent skin surrounded a plastic core, since although the outer shell is cracked there is no sign of fracture in the interior.

3. In R1102, the specimen with the largest pisoliths, evenly distributed through the rock and occupying half of the volume, the pisoliths show variable states of modification. Some have segments cleanly removed, with truncation of interior rings. In others, outer layers of the pisoliths are partly stripped. In others, outer layers are indented and deformed, while inner rings are perfectly circular. Few have escaped minor injuries of some kind.

Incipient Pisoliths

In a few specimens (e.g. R966, R1106, R1110, R1206) which have well developed pisoliths, a transition can be followed through successively less well defined pisoliths into vague spheroidal structures which, in a rock lacking pisoliths, would pass unnoticed.

Calcite Diagenesis

Quite commonly the matrix of the pisoliths is represented by coarsely crystalline calcite (5808, 2/4699, R35, R36, R964, R1208, R1211). Sometimes ghost outlines of replaced crystal fragments are recognisable in this (R964), but more frequently the calcite shows no sign of tuff structure. In R35 there are irregular patches of fine-grained tuff within the calcite.

Elongation ratios of 20 pisoliths each from two rocks with calcite matrixes (2/4699, R964) both gave averages of 1.08 (see above). Twenty pisoliths each from three rocks with tuff matrixes (R371, R1102, R1204) gave average elongation ratios of 1.40, 1.42, and 1.75. All pisoliths were measured on a vertical face perpendicular to the bedding. Although only five rocks were measured the measurements reflect what would be concluded from a subjective assessment of all the pisoliths: tuff with a calcite matrix have nearly round pisoliths, while tuffs with a tuff matrix have flattened pisoliths. Thus the calcite diagenesis which protected the enclosed pisoliths from deformation, took place at a very early stage in the compaction of the rocks.

"Pisoliths" in Agglomerate

The specimen R972, although listed above, was collected (by L. E. de la Hunty) from the Fortescue Group as conglomerate. It is an aggregate of subangular fragments of aphanitic tuff and altered lava mostly 10-15 mm across with much calcite replacement. A cut and smoothed face reveals that about 5 per cent. of the fragments are structureless whole spheroidal "balls" of fine-grained tuff. Although superficially resembling the pisoliths just described, they lack grading and concentric structure of any kind, and appear to represent reworked pieces of lithified tuff in a later agglomerate.

PUBLISHED ACCOUNTS OF PISOLITIC TUFF, AND COMPARISON WITH WESTERN AUSTRALIAN EXAMPLES

Moore and Peck (1962) have described tuffs with accretionary lapilli (= pisolitic tuffs) of various ages in the western continental United States and have very thoroughly reviewed all previous relevant literature. The rocks described by Moore and Peck are so closely similar to the Western Australian tuffs as to leave no doubt that the two groups of rocks have the same origin. They list (p. 189) and give authorities for the three observed mechanisms of formation of volcanic pisoliths as follows: (1) accretion on the ground of fresh ash around a nucleus blown by the wind or rolling down a slope; (2) absorption by fresh ash of the water of a fallen raindrop during a light rain; and (3) accretion of moist ash in an eruptive cloud to form mud-pellet rains. They also note a fourth possible mechanism akin to that favoured by Hansen and others (1963) for pisolitic tuffs of the Oak Springs Formation in southern Nevada: (4) that the lapilli formed in water by the gentle agitation of a nucleus in contact with unconsolidated volcanic ash.

In spite of their close resemblance the pisolitic tuffs appear to differ from those described by Moore and Peck (1962) as well as those noted later by Sundelius (1963) in the following ways:

1. In the United States examples, the pisoliths occur in poorly stratified, probably terrestrial rocks (Moore and Peck, 1962, p. 184, 190, 191). Commonly the Fortescue Group tuffs are subaqueous rocks; this is clear from the nature of the stratification, the presence of dolomites with *Collenia* (Edgell, 1964) and the presence of ripple marks (Kriewaldt and Ryan, in press) and small-scale cross-bedding.

2. The United States pisoliths are not sorted (p. 190). Pisoliths of Fortescue Group specimens typically have a narrow size range.

3. Moore and Peck (p. 190) note the presence of broken pisoliths in all specimens. In the Fortescue Group rocks most specimens lack broken pisoliths.

PROBLEMS OF ORIGIN

Apart from the textural disqualifications listed by Moore and Peck (1962) of the first two genetic hypotheses, no origin involving rainfall on dry ash is easily acceptable for a pisolitic tuff stratigraphically consistent for more than 300 miles. Moore and Peck favour the third hypothesis. Although they cite two observed falls of tuff posilites it is a pity that there is no published evidence that the resultant tuffs resembled typical pisolitic tuffs in all minor textural details. There are a number of cogent objections to this hypothesis for the Fortescue Group pisolites:

1. The Fortescue Group tuffs are subaqueous rocks. It is difficult to believe that falling pisoliths would not only survive impact against water but also retain enough strength under immersion to keep their spherical shape as they fell and accumulated on the bottom.

2. The similarity between the tuff of pisolith and matrix is extremely close. It would be expected that aggregation of particles in a cloud would, at least sometimes, act as a mechanism for sorting airborne material, to give some observable difference in composition.

3. Typically, pisolitic tuff has closely packed pisoliths of even size in a tuff matrix in a homogeneous bed. It seems an extraordinary coincidence, if pisoliths and tuff fell together, that the supply of each was always just enough for the interstices of the pisoliths to be evenly filled by ash as they accumulated.

The following hypothesis, similar to Moore and Peck's fourth alternative, would not be faced with these objections. In certain subaqueous tuffs of critical limits of composition and grain-size distribution, there is soon after deposition a tendency for aggregation of the finer material towards evenly distributed centres whose average separation is controlled by the grain-size of the rock. Although no detailed explanation of the process is attempted here it is likened to the flocculation of colloids, which is simply an aggregation of fine particles. A coarse nucleus is not thought essential for the process, but represents a centre of attraction which happened to be occupied by coarse material. The process takes place within a few feet, or possibly a few inches, of the surface, since pisoliths may be exposed and broken or sorted by current winnowing. The finest outer shell acquires competence quickly and the gradual expulsion of water and compaction of each pisolith is associated with an inward extension of the hardening, and an increase in permeability of the matrix.

The hypothesis seems to fit certain features of the collection described which on other hypotheses are irrelevant or coincidental. In three of the current-modified rocks (2/4700, 2/4701, R1203) the pisoliths are of the type with fragile peripheral shells. These I suppose to be early-formed types, which are most likely to be uncovered and sorted. From the manner of their breaking it is clear that this type has a soft plastic core. The extreme similarity between pisolith and matrix is explained, as is the lack of size range and the close, even distribution. On this hypothesis I interpret the graded bed of R1208 as an originally non-pisolitic graded tuff in which pisolith size was controlled by grain-size. It is easy too, to see the common development of interstitial calcite as a natural result of the increase of permeability in, and withdrawal of fine material from, the matrix.

The differences noted above between the pisolite tuffs described here and those described by Moore and Peck suggest that the common rock of the Fortescue Group, with even-sized, spheroidal, close-packed, whole pisoliths, is the first result of internal development, by flocculation, of pisoliths; and that the variants with broken, scattered and sorted pisoliths, which have been described from the United States and which occur less abundantly in the Fortescue Group, are later modifications of such rocks. This process of flocculation is not, of necessity, an observable phenomenon, but, until it is shown that mud-pellets of the type which have been seen to fall to form rocks resembling the pisolitic tuffs described here in all textural details, the flocculation hypothesis seems to have more advantages than disadvantages as a genetic hypothesis.

CONCLUSIONS

Pisolitic tuffs, though never abundant, are widespread in space and time. No hypothesis for their origin either satisfactorily explains all the observed characters of the rocks or has sufficient supporting evidence to prove its truth beyond reasonable doubt. Fortunately it is easy to see what further evidence should be sought. Some priorities are:

1. What is the detailed geometry of individual pisolitic tuff beds? The greater their lateral persistence the weaker the case for falling mud pellets.

2. Do the pisoliths which have been observed to fall from dust charged clouds near volcanic eruptions correspond in detail, or result in deposits which correspond in detail, to pisolitic tuffs of the commonest type?

3. How do grain-size distribution analyses of pisolitic and non-pisolitic tuffs compare? They should be very close if pisolith formation is simply a colloidal flocculation. They may be close on a falling mud pellet hypothesis but should sometimes differ.

REFERENCES

de la Hunty, L. E., 1964, Balfour Downs, W. A.: West. Australia Geol. Survey 1 : 250,000 Geol. Series Explan. Notes.

Edgell, H. S. 1964, Precambrian fossils from the Hamersley Range, Western Australia, and their use in stratigraphic correlation: Geol. Soc. Australia Jour., v. 11, pt. 2.

Hansen, W. R., Lemke, R. W., Cattermole, J. M., and Gibbons, A. B., 1963, Stratigraphy and structure of the Rainier and U. S. G. S. tunnel areas, Nevada test site: U. S. Geol. Survey Prof. Paper 382-A.

Kriewaldt, M., 1964, The Fortescue Group of the Roebourne region, North-West Division: West. Australia Geol. Survey, Ann. Rept. 1963.

Kriewaldt, M. and Ryan, G. R., in press, Pyramid, W. A.: West. Australia Geol. Survey 1 : 250,000 Geol. Series Explan. Notes.

Leggo, P. J., Compston, W., and Trendall, A. F., 1965, Age measurements on some Precambrian rocks from the North-West Division of Western Australia: Geol. Soc. Australia Jour., v. 12, pt. 1.

MacLeod, W. N., de la Hunty, L. E., Jones, W. R., and Halligan, R., 1963, A preliminary report on the Hamersley Iron Province, North-West Division: West. Australia Geol. Survey Ann. Rept. 1963.

Maitland, A. G., 1908, The geological features and mineral resources of the Pilbara Goldfield: West. Australia Geol. Survey Bull. 40.

Moore, J. G. and Peck, D. L., 1962, Accretionary lapilli in volcanic rocks of the western continental United States: Jour. Geology, v. 70, no. 2, p. 182-193.

Noldart, A. J., and Wyatt, J. D., 1962, The geology of portion of the Pilbara Goldfield covering the Marble Bar and Nullagine 4 mile Map Sheets: West. Australia Geol. Survey Bull. 115.

Sundelius, H. W., 1963, Accretion lapilli in rocks of the Carolina Slate Belt, Stanly County, North Carolina: U. S. Geol. Survey Prof. Paper 475-B, Article 12, p. B42-44.

Talbot, H. W. B., 1920, The geology and mineral resources of the North-West, Central and Eastern Divisions: West. Australia Geol. Survey Bull. 83.

PROGRESS REPORT ON THE BROCKMAN IRON FORMATION IN THE WITTENOOM—YAMPIRE AREA

By A. F. Trendall

ABSTRACT

The Precambrian Brockman Iron Formation, of the North-West Division of Western Australia, is 2,200 feet thick in the central part of its outcrop, which is 300 miles long and 100 miles across. Drilling through the lowermost 600 feet of the unmetamorphosed, unoxidised and undisturbed formation in the Wittenoom-Yampire area has yielded 6,250 feet of core from 27 holes separated over a maximum distance of 15 miles. These samples reveal that between 100 and 460 feet above the base there is a regular alternation of "shale" (mainly shale but with some chert and carbonate) bands 1-20 feet thick and bands of banded iron formation (b.i.f.) 8-28 feet thick, with the b.i.f./"shale" ratio over the whole thickness close to 2.0. These major bands are called *macrobands*; thinner alternations of chert, magnetite, etc., within the b.i.f. are called *mesobands*, while fine even laminations of quartz and carbonate within chert mesobands are called *microbands*. Lateral correlation between all holes is effectively perfect at mesoband and larger scales. Thickness variations are small and have no simple regional pattern. Near the top and bottom of the specific 360-foot thickness already referred to, abundant massive blue (mass-fibre) riebeckite mesobands over thicknesses of about 40 feet define upper and lower *riebeckite zones*. Two main *seams* of blue asbestos (crocidolite; cross-fibre), in which a few mesobands of fibrous riebeckite may be mined together, are associated with the lower riebeckite zone. In this zone there is no correlation between total riebeckite content and either stratigraphic thickness or fibre thickness, and the riebeckite has no simple regional distribution. Massive riebeckite mesobands result from metasomatic replacement of particular ("riebeckite-prone") cherts at a restricted number of levels in an erratic manner. The specific gravity of the b.i.f. varies between 3.36 and 3.39 and the bulk mineral composition by weight is approximately:

	Per Cent.
Quartz	45
Magnetite	30
Carbonate	15
Stilpnomelane	8
Others	2

"Others" include riebeckite and other amphiboles, hematite, pyrite, apatite, other phyllosilicates, and feldspar. Three main mesoband types, chert, quartz-iron oxide (QIO), and magnetite, constitute about 90% of the total b.i.f. From the evidence of microbanding there is a gradation from "primitive chert" with coarse microbanding either into "flat-modified" chert with fine microbanding or into chert pods within QIO; this is thought to reflect two types of diagenetic modification of an original microbanded material whose exact nature is not known. If microbanding results from annual changes in geochemistry of depositional environment an acceptable depositional rate of one foot of compacted b.i.f. every 2,000 years is arrived at.

INTRODUCTION

Objectives

Diamond drill cores recovered by the Australian Blue Asbestos Co. (A.B.A.) during an exploratory drilling programme in this area, started in 1961, represent samples of unoxidised unmetamorphosed and undistorted Precambrian iron formation unique in the degree to which all three qualities are developed together. The main objective of this report is to begin an assessment of the geological significance of this drilling, particularly insofar as it contributes to the solution of the three problems:

(1) What is the origin of banded iron formations?

(2) What is the origin of riebeckite within these?

(3) What is the origin of the fibrous riebeckite (crocidolite) in riebeckite-bearing iron formations?

The Brockman Iron Formation, from which these cores were derived, is of great economic interest both for iron and asbestos, and this report represents an early stage in a continuing study of the formation.

Regional Geological Environment

The Brockman Iron Formation (MacLeod and others, 1963) crops out over an area of the North-West Division about 300 miles long in an east-southeast direction and 100 miles across in a north-northeast direction. It is a formation of the Hamersley Group, from which acid volcanics have been dated at 2,100 m.y. (Leggo and others, 1965), and is 2,200 feet thick in the central part of its outcrop. It is underlain conformably by nearly 20,000 feet of iron formation, dolomite, shale, sandstone and mixed volcanics of the Hamersley and Fortescue Groups and is overlain conformably by 15,000 feet of similar rocks, but with a higher proportion of clastic sediments, of the Hamersley and Wyloo Groups. In the northern part of its outcrop, along the Hamersley Range, dips are generally less than 5°, although local puckers cause abrupt but confined steepening. Unfortunately, much of the upper part of the formation has been removed. Between about 80 and 150 feet above the top of the underlying Mt. McRae Shale, bands of riebeckite asbestos are mined by the Australian Blue Asbestos Co. at Colonial Mine, Wittenoom Gorge. Mining was formerly carried on at about the same stratigraphic level at Yampire Gorge, 13 miles to the east. It is in both these areas, in the effectively undisturbed lower part of the formation, that the drilling programme was, and is being, conducted.

The Drilling Programme

Between 1961 and September 1964, forty-four holes were drilled. Until 1963 drilling techniques were variable and a number of technical difficulties which led to erratic core recovery had to be overcome. Specially designed bits were later used and a system developed whereby a down-the-hole hammer was used until it became easier to core. Coring was then carried out until the lowest mined asbestos had been passed. Thus cores start at a variety of stratigraphic levels (see Plate 32) but all finish at about the same horizon. Recovery is virtually 100% in the later holes.

Most of the holes were drilled just to the north, west and south of the existing mine, and would be included in a circle of radius 1 mile centred on the western part of the mine area. Exceptions are: Hole 47, about 4½ miles west-southwest of the mine; Hole 46, about 3 miles west of the mine; Holes 67-81, extending about 2 miles southwest along Wittenoom Gorge; and Holes Y1 and Y3 at Yampire Gorge, 13 miles to the east.

These localities are only given roughly since, as noted below, they are not significant for this report.

Material Available

In September, 1964 about 6,250 feet of core from 27 holes was available for study, individual holes varying from 630 feet (63) to 52 feet (59) in length of core. The core from most of the earlier holes is too disordered to be of correlative use, and even in the later holes gaps exist (largely due to removal of this highly decorative core) which, as noted below, may affect some of the results recorded. A.B.A. has kindly supplied graphic logs of 24 holes, asbestos assay values of 33 holes, and grid localities of all sites. The complete core of Hole 51 (314 feet) has been transferred to the Geological Survey for permanent record and reference.

Plan and Progress of Work

I visited Wittenoom briefly in August, 1963 and was impressed by the unique opportunities presented by the A.B.A. core for obtaining precise information on the lateral persistence of "bands" in "banded iron formation" at a range of scales, apart from its obvious value as a stratigraphically continuous unweathered sample of part of the Brockman Iron Formation. I collected approximately 6 feet of stratigraphically equivalent core (Plate 32) from Holes 28, 33 and 46, and three feet equivalent to the lower part of this from Hole 40. By July, 1964 over a hundred thin sections had been cut and the small-scale lateral continuity had been studied. Petrologist's Report No. 66 (unpublished) summarised petrographic results of this work.

In cooperation with A.B.A. the Geological Survey of Western Australia initiated a special study of the asbestos in 1964, with G. R. Ryan in charge, and in September, 1964 I spent a further 14 days at Wittenoom concentrating on riebeckite and crocidolite.

With well over a mile of core, the first problem becomes one of deciding what information to select. Since large-scale graphic logs existed I logged at Wittenoom:

1. A specific stratigraphic level about 45 feet thick at a smaller scale (the "lower riebeckite zone"—see below).

2. A level within this about 3 feet thick at a smaller scale (1:1).

3. The upper mined asbestos seam, also within the 45 feet of "1" above.

Apart from the common sense of studying a successively smaller sample in increasing detail the particular sections logged were chosen to bear largely on the origins of riebeckite and crocidolite. About 12 feet of core was taken for laboratory study.

NOMENCLATURE OF THE MAIN ROCK-TYPES

"Shale" and Banded Iron Formation

The Brockman Iron Formation contains these two rock-types in alternating bands; brief descriptions of each follow:

The *banded iron formation* (abbreviated to *b.i.f.* in much of this report) has a specific gravity varying between 3.36 and 3.39, and although a programme of properly sampled chemical analysis is not yet completed the following estimate of mineral content (by weight) is probably not much in error:

Quartz 45%
Magnetite 30%
Carbonate 15%
Stilpnomelane 8%
Others 2%.

The "others", in probable order of abundance, are riebeckite (all textural varieties), hematite, pyrite, apatite, other amphiboles and phyllosilicates, and feldspar. The carbonates include siderite, ankerite, ferroandolomite and calcite. The rock is hard, compact and has a conspicuous and even banding on a range of scales caused by the concentration of the principal minerals into layers in which one or other is dominant.

The separation into "shale" and banded iron formation is a clear and consistent one. Although the change from one rock-type to the other may take place gradationally over a few feet at the edges of the thicker bands, in the thinner "shales" the edges are sharply definable. Within the "shales", although lithology is variable, there is no tendency for confusion with or gradation into banded iron formation. The term "shale" is used within quotation marks because it is used for convenience to cover a number of differing types. The bulk of the material is very fine-grained, black, green, grey or brown shale which may be highly fissile along the bedding or almost massive. Similarly there may be conspicuous fine colour banding. The chemical analyses available suggest that this wide range of types reflects a correspondingly wide range in mineral composition, and a variety of iron-rich phyllosilicates are probably the chief constituents. An X-ray study of these shales is planned. The green shale grades into tough green carbonate which in core is difficult to distinguish from massive shale. (At the surface the dolomite is yellow-weathering). White chert bands, mostly 1-2 inches thick, sharply divided from the dark shales, are common and vary in abundance. Thus "shale" refers to "shale with subordinate cherts and carbonate".

The sharply defined base of a breccia with angular shale and chert fragments up to several feet long, lies between 2 and 10 feet above the base of the fourth "shale", or Calamina Member (see "Stratigraphy" below). The breccia usually grades into shale over about 3 feet, with one or two thinner graded beds following it before undisturbed shale finally appears. In the seventh "shale" angular pieces of shale and other material about an inch across occur over about 3 feet without obvious grading. At both levels white-rimmed spheroidal bodies about a millimetre across are present in the breccia. These breccia bands are the only sign of irregularity of stratification throughout the part of the Brockman Iron Formation studied. No detailed work has yet been carried out on them and they are not reported on further here.

Miscellaneous Definitions

It is convenient to define terms for the three main scales on which the Brockman Iron Formation may be described as "banded". These are:

1. Gross variations in lithology from "shale" to banded iron formation.

2. Banding defined by changes from "chert" to "carbonate" or "magnetite" within the banded iron formation proper and which are internally consistent and which are named after the predominant mineral of the band. Such bands are typically ¼ inch to 1 inch thick.

3. Fine banding within individual cherts of scale 2 above. It appears as a rhythmic alternation of stripes usually richer or poorer in carbonate or stilpnomelane and usually has between 2 and 5 (double) stripes to a millimetre.

For convenience I propose to refer to these three scales as "macrobanding", "mesobanding" and "microbanding", and to the bands themselves as "macrobands", "mesobands" and "microbands". Thus a chert mesoband may have internal microbands and be part of a macroband. The term "band" used alone may refer to any of these three types but is only used in a context where the meaning is apparent. Other types and scales of banding are present, and are noted below, but are of minor importance.

The term *chert* in this report denotes a rock with a matrix of finely crystalline (almost invariably in the range 5-30μ) quartz. Cherts of iron formation are so different from normal sedimentary or metamorphic quartzite that the term seems preferable.

The term *riebeckite* is applied at Wittenoom to massive blue mesobands made up of randomly interlocking riebeckite needles. Such bands are referred to in South Africa as *mass-fibre* bands.

The term *fibre* is applied at Wittenoom to mesobands of fibrous riebeckite with a common orientation nearly normal to the stratification. *Crocidolite, cross-fibre* or *blue asbestos* are synonyms.

A single mesoband of crocidolite is referred to as a *band,* or mesoband. A group of bands that can be mined together constitute a *seam.* A riebeckite-bearing stratigraphic thickness with which a seam or seams may be associated is called a *riebeckite zone.* These terms have the following equivalence with those in use in South Africa (Cilliers, 1961, p. 28):

South Africa	Western Australia
seam or band	band or mesoband
reef	seam
horizon	riebeckite zone

A Western Australian riebeckite zone is not the precise equivalent of the South African asbestos horizon, since one is defined by riebeckite and the other by asbestos. This is more of a geological accident than an indication of fundamental differences in the two; both terms denote a stratigraphic thickness in which riebeckite (*sensu lato*) is exceptionally abundant.

In South Africa (Cilliers, 1961, p. 16) "zone" is used as a major stratigraphic unit in a manner which would not be admissible under the Australian Code of Stratigraphic Nomenclature. It would be the equivalent of either a Formation or a Group. It is also used in South Africa with reference to weathering.

STRATIGRAPHY

General

A vertical section of the lowermost 750 feet of the Brockman Iron Formation in the Wittenoom-Yampire area, constructed solely from borehole information, is shown in the right hand column of Plate 32. The salient features are:

1. An alternation of banded iron formation and "shale" macrobands, two of which have the status of members.

2. Two riebeckite zones with centres roughly 150 feet and 450 feet above the base.

3. Three main fibre seams below the lower riebeckite zone. The upper and lower fibre seams are those currently mined at the Colonial Mine.

This section was constructed as follows: From the base to the shale below the lower fibre seam information is entirely from Y1, the only hole to penetrate to the Mt. McRae Shale. The boundary between the two formations is transitional, and the base of the Brockman Iron Formation will be defined later within the range shown on Plate 32. Where the base is referred to above it means the lowest possible position. From this shale upwards for about 366 feet the macrobands shown have the mean thicknesses of a number of holes. These thicknesses, together with the range of thickness and the number of holes used to determine the mean, are shown in the table to the right of the column. Each "shale" and b.i.f. macroband is numbered for subsequent reference. Above "shale" 16 information is solely from Hole 63.

Nomenclature

Two local names are to be formally defined by G. R. Ryan and are for field use on a regional scale. The Calamina Member is the fourth "shale" macroband and the Joffre Member is the fifteenth "shale" macroband of this report (Plate 32). Other equivalences between the nomenclature of this report and that of A. B. A. geologists at various times are:

This report	Local Wittenoom usage
Third fibre seam	Knapping seam
No equivalent term	Knapping seam marker
First " shale "	Lower seam marker
Second " shale "	Upper seam marker
Upper riebeckite zone	Upper Yampire Zone Upper Yampire Series
Lower riebeckite zone	Yampire Zone Yampire Series

Lateral Correlation

Good lateral correlation at the macroband scale is evident from a glance at the A.B.A. graphic logs.* In the core from below the third "shale" and in the true-scale logs from a selected level within the lower riebeckite zone (see "Plan and Progress of Work") there is spectacular continuity on the mesoband scale, to an extent that unlabelled vertically sawn half-cores at the same stratigraphic level from different holes could be accepted as coming from a single hole. Briefer examinations at other levels show that lateral continuity at mesoband scale is, within the greatest distance between two cored holes (15 miles), effectively perfect, and that in the whole 366 feet of the central part of the right-hand column of Plate 32, of which a number of cores are available, no discontinuity of mesobanding (apart from the "podding" mentioned later) exists in the banded iron formation parts. Although no close study has been made of the cherts within "shales" my impression is that their continuity is much less perfect.

On a wider scale, a single chert mesoband about an inch thick within the Mt. Sylvia Iron Formation and some 400 feet below the base of the Brockman Iron Formation, has been observed to be stratigraphically continuous for at least 150 miles along the northern face of the Hamersley Range.

Thickness Variations (large-scale)

The table in Plate 32 shows that the part of the Brockman Iron Formation between about 100 feet and 466 feet above the base, from the base of the first "shale" to the top of the sixteenth "shale," has a mean thickness of 366.4 feet. Of this thickness 107.5 feet (or 29.3%) consists of "shale" in sixteen macrobands of mean average thickness 6.7 feet, and 258.9 feet (or 70.7%) is banded iron formation in 15 macrobands, alternating with the "shales," of mean average thickness 17.3 feet.

To study thickness variation between and within holes this part of the formation was divided into 15 *sections* between "shale" centres. The lower 11 of these sections, between the centres of the first and twelfth "shales" are common to 12 holes and for statistical uniformity attention is mainly confined to these in this report.

The mean total thickness of sections 1-11 for all 12 holes is 249.1 feet, with a range of individual values from 233 feet (or —6.5% of the mean; Hole 40) to 258 feet (or +3.6% of the mean; Hole 33). In all 12 holes there is thus an extreme thickness range of 25 feet, or 10.1% of the mean. The mean deviation is 2.5%. Regarding each drill core as a local sample of stratigraphic thickness, three main questions arise from these figures:

1. Does the regional distribution of thickness allow the construction of a simple isopach pattern?

2. In a thick† hole is the thickness evenly distributed internally?

3. Is the thickness variation mainly due to variations in the thickness of the constituent "shales", or of banded iron formation macrobands, or to both?

The answers to these questions, numbered as above, are:

*The nomenclature of rock-types in these logs differs slightly from that used here; these differences are not important, and are not referred to again.

†*thick* and *thin* holes or sections refer to holes or sections whose thickness is above or below the mean for all holes.

1. No simple isopach pattern fits the areal thickness distribution. In some instances (Holes 67, 68, 69) a group of close holes shows a thickness range little short of the total range. It is certain that any major regional variation in thickness over the Wittenoom-Yampire area is so effectively hidden by minor local fluctuations that an impossibly close pattern of sampling would be necessary to detect it.

2. This is a more difficult question. In Table 1 are shown, for the 12 holes used for thickness study, the number of separate sections less than, greater than, or equal to the mean for that section, and the terminal* deviation of the total from the mean at that level. In a general way the terminal thickness of any hole is a reflection of the number of sections above and below the mean thickness of each section. Some interesting exceptions to this are: Hole 33, which in spite of a terminal percentage of 2.7 above the mean has as many constituent sections at or below the mean as it has above; and Hole 29, which has the same distribution of sections above and below the mean as Hole 33, but has a terminal thickness below the mean.

Table 1

SUMMARY OR INTERNAL THICKNESS DISTRIBUTION IN 12 HOLES

1	2	3	4	5	6
Hole No.	Number of Sections				Terminal Per cent. Deviation from Mean
	Above Mean	Below Mean	At Mean	Total	
33	7	6	1	14	+2·7
75	6	4	1	11	+2·8
49	10	5	0	15	+2·3
27	8	5	0	13	+2·1
28	6	6	0	12	+1·4
51	6	7	0	13	—0·2
62	7	6	0	13	+0·1
29	7	6	0	13	—0·5
61	6	8	1	15	—0·5
63	6	8	1	15	—1·9
46	3	10	0	13	—4·0
40	2	9	1	12	—5·4

There is no regular alternation or grouping in the holes of sections above and below the sectional means. Of 147 sectional contacts in this study 81 show a change (i.e. below the sectional mean to above it, or vice versa) and 66 show no change. The equivalent percentages, 55 and 45, show that the chances are very nearly equal that a section thicker than the sectional mean will be succeeded, or underlain, by a section above or below its sectional mean.

At present it seems that the gross variations in thickness between holes can be accounted for entirely by a random stacking of thick and thin sections, a thick hole being the result of a fortuitous succession of thick sections, and vice versa. The sedimentational significance of this is that each section, considered as a sedimentary unit, varies areally in thickness in a way unrelated to preceding sections. No simple regional pattern should be produced and it has been seen that this is so.

It is assumed here that the present thicknesses of the rocks are directly related to the original thicknesses of deposited material. It will be shown later that extreme compaction has probably taken place, and it may be that present thicknesses are controlled more by compaction than by deposition. This is a problem for future attention.

3. It is theoretically possible for the thickness variations discussed to be controlled mainly or entirely by either one of the two macroband types involved in each section ("shale" or banded iron formation) or to be contributed to by both types equally. In Table 2 are shown, over the range of the 11 lowermost sections only ("shales" 1-12), for the 12 holes used in Table 1, the total thickness (column 2), the "shale" and b.i.f. thickness (columns 3-6), and the ratio of b.i.f. to "shale".

*terminal here means at the top of the highest section in the hole measured upwards from the centre of the first "shale."

It is clear from this table that the relationship between total thickness and "shale" thickness is highly erratic.

Although the upper six (thickest) holes have a mean total thickness of 255 feet and a mean "shale" thickness of 83 feet, and while the lower six (thinnest) holes have equivalent thicknesses of 243 feet and 88 feet (in other words greater thickness, less "shale") the variation within these two groups is so great (e.g. the thinnest hole has the least "shale") that it is of doubtful significance. On this point one can only say that although there is some suggestion that hole thicknesses are related more to constituent b.i.f. thicknesses than to "shale" thicknesses, more information is needed on the precise correlation of "shale"/b.i.f. boundaries. It may be that logging inconsistencies contribute largely to the confusion.

Table 2

SUMMARY OF THE CONTRIBUTION TO TOTAL THICKNESS VARIATION OF "SHALE" AND BANDED IRON FORMATION

1	2	3	4	5	6	7
Hole No.	THICKNESS					Ratio B.I.F. / " Shale "
	Total (feet)	" Shale "		B.I.F.		
		Feet	Per cent.	Feet	Per cent.	
33	258	87	34	171	66	2·0
75	256	93	36	163	64	1·8
49	256	88	34	168	66	1·9
27	255	73	29	182	71	2·5
28	252	82	33	170	67	2·1
51	252	73	29	179	71	2·5
62	250	89	36	161	64	1·8
29	248	86	35	162	65	1·9
61	248	95	38	153	62	1·6
63	243	90	37	153	63	1·7
46	238	87	37	151	63	1·7
40	233	69	30	164	70	2·4

Thickness Variation (small-scale)

It is clear from the preceding discussion that sample-size is vitally important in studying thickness variation. It is not yet known, for example, what relationship the thickness of the studied (mean) 249.1 feet has to the total thickness of the Brockman Iron Formation at the site of each hole; that is, whether a 250 foot sample of a 2,000 foot formation is an adequate one. On a smaller scale it is clear that a single section has no value as an index of the thickness of all 11 sections between the first and twelfth "shales" in any hole. Three further questions now arise:

1. What is the relationship between sample-size and variability from hole to hole?

2. What is the least thickness that will give a reasonably reliable indication of gross thickness?

3. Do either "shale" or b.i.f. macrobands tend to be more consistent internally than the other?

These questions can be less reliably answered than the preceding three. In Table 3, in which all the figures relate to the 12 holes of Tables 1 and 2, the mean values of each section and their mean deviations are given (columns 2 and 3) together with the corresponding cumulative figures for successively larger groups of sections from the first "shale" upwards. The mean of column 3 is 5.8; from this and from the upward diminution of values in column 6 it is clear that smaller samples show a higher percentage mean deviation. The values in columns 2 and 3, and of columns 5 and 6 are plotted against each other in Figure 1, in which the smoothed (exponential) curve suggests that a sample of 100 feet gives a mean deviation little higher than a sample of 250 feet. Ideally, all possible combinations of sections should be included on this figure, and standard deviations would be preferable to mean deviations (here and elsewhere in this paper) but time and equipment have not been available for these calculations.

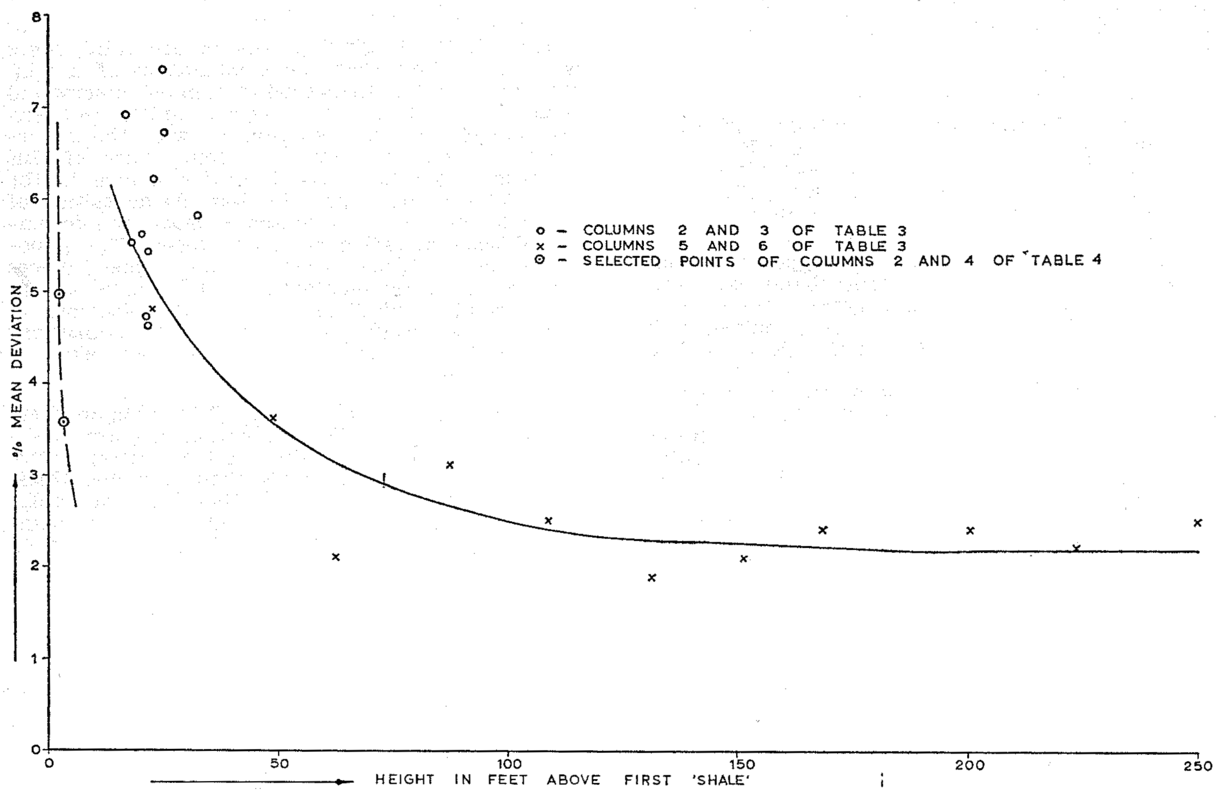


Figure 1—Graph relating mean deviation and stratigraphic sample thickness in the lower part of the Brockman Iron Formation in the Wittenoom-Yampire area.

At a smaller scale the true-scale logging of about 3 feet from within the second b.i.f. macroband (see "Plan and Progress of Work" above) provides further data. In this thickness 35 easily correlatable exact levels (mesoband boundaries) were marked and measured. In general, levels 1-16 (from the top down) are free of riebeckite and occupy about 17 inches, levels 16-24 occupy about 10 inches, of which about half is riebeckite, and levels 24-35 are free of riebeckite and occupy 11 inches. Exact means, with the number of holes used and mean deviations are given for the whole and different parts of this thickness in Table 4.

Table 3

VARIATION OF MEAN DEVIATION WITH SIZE OF STRATIGRAPHIC SAMPLE

1	2	3	4	5	6
Separate Sections			Cumulative Figures from the Bottom Upwards		
Section	Mean Thickness (feet)	Mean Deviation Per cent.	Section	Mean Thickness (feet)	Mean Deviation Per cent.
"Shales" 11–12	25·6	6·7	"Shales" 1–12	249·1	2·5
"Shales" 10–11	23·1	6·2	"Shales" 1–11	223·5	2·2
"Shales" 9–10	32·1	5·8	"Shales" 1–10	200·4	2·4
"Shales" 8– 9	17·0	6·9	"Shales" 1– 9	168·3	2·4
"Shales" 7– 8	20·1	5·6	"Shales" 1– 8	151·3	2·1
"Shales" 6– 7	21·9	5·4	"Shales" 1– 7	131·2	1·9
"Shales" 5– 6	21·7	4·7	"Shales" 1– 6	109·3	2·5
"Shales" 4– 5	24·8	7·4	"Shales" 1– 5	87·6	3·1
"Shales" 3– 4	21·9	4·6	"Shales" 1– 4	62·8	2·1
"Shales" 2– 3	18·4	5·5	"Shales" 1– 3	40·9	3·6
"Shales" 1– 2	22·5	4·8	"Shales" 1– 2	22·5	4·8

Table 4

VARIATION OF MEAN DEVIATION WITH THICKNESS OF SAMPLE WITHIN BANDED IRON FORMATION

1	2	3	4
Stratigraphic Thickness	Mean Thickness (inches)	Number of Holes	Mean Deviation Per cent.
Levels 1–35	37·52	18	3·57
Levels 1–16	16·93	20	4·84
Levels 16–24	9·64	21	7·05
Levels 24–35	10·88	21	5·24
Levels 1–16 and 24–35 (all riebeckite-free)	27·74	19	4·94
Levels 15–16 (one mesoband)	0·70	22	24
Levels 24–25 (one mesoband)	0·54	22	39

Two points from this table are included on Figure 1: that for levels 1 to 35 (the lower one on the graph) and that for (1 to 16) + (24 to 35). The measurements show that the 3 feet of b.i.f. chosen has a percentage mean deviation through all the available holes equivalent to that of a 20-30 foot stratigraphic sample which includes shales.

From the data presented the following answers can now be suggested for the questions above:

1. As the sample size decreases from 250 feet the mean deviation shows little change until about 100 feet, after which it increases rapidly.

2. About 100 feet, or any five sections, will give an index of thickness that will be little improved by greater measurement.

3. Within b.i.f. there is greater lateral consistency of thickness than in sections which include b.i.f. and shale.

A test of correlation between the logged 3 feet of the second b.i.f. macroband and the total thickness of the macroband would be interesting but the graphic logs are not reliable to a greater accuracy than whole feet, and this is insufficient for the purpose.

Rhythmic Sedimentation

From Plate 32 and from the sectional thicknesses given in Table 3, it is apparent that the Brockman Iron Formation has a strikingly regular alternation of "shale" and banded iron formation. The average mean sectional thickness (15 sections) is 24.0 feet, with a range of 17.0 to 32.1 feet.

If it be supposed, as a working hypothesis, that a neighbouring "shale"/b.i.f. macroband pair constitutes a unit of cyclic sedimentation then either the "shale" above or below could be combined with each b.i.f. to comprise such a unit. If it is then supposed that units have constant thickness two results would be expected: the proper combination would show a smaller total range of thickness and each individual unit would vary less between holes. In Table 5 the mean thicknesses, range and limits, and standard deviations (numerical and as percentage of mean) are given for b.i.f. macrobands with their underlying "shales" (columns 1-5) and for the same b.i.fs. and their overlying "shales" (columns 6-10). The mean of column 2 is 22.6 feet, with a range of 13.6 to 32.2 feet while the mean of column 7 is 22.8 feet, with a range of 15.7 to 30.7 feet. The means of columns 5 and 10 are 10.5 and 7.5 respectively.

Thus, if the original postulates are valid, there is an indication that the combination of a b.i.f. macroband with its overlying "shale" macroband is more properly regarded as a complete sedimentary entity than the combination with the underlying "shale". The principal importance of this hypothesis is that it could provide a clue to the origin of iron formation, in that the deposition of a "shale" is a natural consequence of iron formation deposition rather than vice versa. The hypothesis also indicates that the most likely places for breaks in sedimentation to be sought are at the tops of "shales" rather than the bottoms. A comparative study of "shale"/b.i.f. transitions above and below "shales" should be undertaken on the A. B. A. cores.

Just above the twelfth "shale" macroband there is a remarkably regular alternation of chert mesobands about 5 inches thick separated by softer (QIO, see below) mesobands about 2 inches thick. There are at least nine alternations here, so regular as to be immediately recognisable in the cliffs. This is an exceptional type of rhythmic regularity which has not been seen elsewhere.

Table 5

SUMMARY OF TWO POSSIBLE MODELS OF RHYTHMIC SEDIMENTATION

Combinations of Banded Iron Formations with Underlying Shales

1	2	3	4	5
"Shale" + B.I.F. No. No.	Mean Thickness (12 Holes) (feet)	Range and Limits (feet)	Standard Deviation: Numerical Value	Standard Deviation: %
11 + 11	32·2	23–35(12)	3·2	9·9
10 + 10	19·8	15–29 (14)	3·6	18·2
9 + 9	34·4	27–40 (13)	3·8	11·1
8 + 8	13·6	10–17 (7)	2·3	16·9
7 + 7	20·7	18–22 (4)	1·4	6·8
6 + 6	29·0	27–32 (5)	1·3	4·5
5 + 5	12·7	10–15 (5)	1·3	10·2
4 + 4	29·0	26–32 (6)	2·1	7·2
3 + 3	17·4	15–22 (7)	1·8	10·3
2 + 2	18·7	16–21 (5)	1·4	7·5
1 + 1	22·3	20–25 (5)	1·7	13·1

Combinations of Banded Iron Formations with Overlying Shales

6	7	8	9	10
"Shale" + B.I.F. No. No.	Mean Thickness (12 Holes) (feet)	Range and Limits (feet)	Standard Deviation: Numerical Value	Standard Deviation: %
12 + 11	18·8	16–21 (5)	1·6	8·5
11 + 10	27·4	25–29 (4)	1·3	4·7
10 + 9	30·4	29–32 (3)	0·9	3·0
9 + 8	20·6	16–26 (10)	2·5	12·1
8 + 7	19·3	16–23 (7)	1·7	8·8
7 + 6	15·7	13–18 (5)	1·6	10·2
6 + 5	30·7	28–34 (6)	1·7	5·7
5 + 4	20·3	17–22 (5)	1·5	7·5
4 + 3	25·7	24–29 (5)	1·5	5·8
3 + 2	18·7	14–20 (6)	1·7	9·1
2 + 1	22·7	20–27 (7)	1·8	7·9

The Lower Riebeckite Zone

The A. B. A. graphic logs, at a scale of 10 feet to an inch, show clearly that a lower riebeckite zone, in which massive blue riebeckite mesobands are concentrated, is almost entirely confined between the second and fourth "shales"; in only a few holes do riebeckite bands occur outside these limits. On the other hand these large-scale logs seemed to show little regularity in the distribution of riebeckite within these limits and negligible correlation of riebeckite bands. In 18 holes the lower riebeckite zone was therefore re-examined and logged for graphic representation at a scale of 1.8 feet to an inch. In view of the known excellence of mesoband correlation the principal questions which it was hoped to answer by this, apart from the simple estimation of mean riebeckite content (Plate 32; left hand column) were:

1. Can riebeckite mesobands be correlated between holes?

2. If they can be correlated, and if a band is absent from a particular hole, is it represented by a break in mesoband sequence or by some other mesoband type?

3. Does there tend to be a constant total amount of riebeckite in any one hole, but unevenly distributed between the upper and lower parts of the zone (above and below the third "shale"), or is a small amount of riebeckite in the lower part of the zone usually associated with a small amount in the upper part?

4. Is there any simple areal pattern in the distribution of riebeckite?

5. Is there any correlation between riebeckite thickness and stratigraphic thickness of the third and fourth banded iron formation macrobands?

All these questions were answered. The answers are given below, numbered as above, with a brief summary of the data where appropriate:

1. After logging of the riebeckite mesobands and the marginal and central "shales" of the riebeckite zones the logs were arranged side-by-side using the third "shale" as a datum. The scales of plotting of the banded iron formation macroband above and below were adjusted for variations in stratigraphic thickness. From the resultant plot it was apparent that the development of massive riebeckite mesobands was confined to 15 main levels and the mean thickness of massive riebeckite mesoband was close to 3 inches. To give a more objective assessment of the distribution a vertical histogram was constructed summarising the total riebeckite content at successive small vertical intervals of the zone. The irregular appearance of the large-scale logs is due to a haphazard distribution of the riebeckite between these principal 15 available levels. These are shown on Plate 32, together with the mean and ranges (inches of riebeckite) for the two parts and the whole of the lower riebeckite zone. Some of these levels are more persistent than others, notably the lower three in both the upper and lower banded iron formation macrobands, but no absolute rules can be deduced for the preferred order of appearance of riebeckite in them. It must be emphasised that these massive riebeckite bands represent the bulk of the riebeckite in the zone, although no thin section from within the zone would lack a few hairs of amphibole.

Summarising the answer to the first question: the riebeckite mesobands in which the bulk of the riebeckite of the lower riebeckite zone is concentrated are confined to 15 main levels within the zone, and are easily correlatable between holes.

2. If there is no riebeckite at a potential riebeckite level it is invariably represented by a chert mesoband, usually 2-3 inches thick, of flat-modified type (see "Petrography" below). G. R. Ryan has suggested the name "riebeckite-prone" cherts for these.

3. There is no significant correlation between riebeckite content above and below the third "shale." Table 6 shows that a hole with little riebeckite below the "shale" may have abundant riebeckite above and vice versa; or there may be abundant riebeckite above as well as below, or only a little. From the means of Plate 32 the upper part of the zone has 14.1% of riebeckite while the lower has 9.1% but the erratic nature of the distribution is shown by the fact that in several holes there is more riebeckite below than above.

4. There is no simple areal pattern in the distribution of riebeckite. Closely spaced holes vary widely in riebeckite content.

5. There is no correlation between rieckbite content and stratigraphic thickness.

Table 6

RIEBECKITE CONTENT OF THE LOWER RIEBECKITE ZONE*

1	2	3	4
Hole No.	Riebeckite Thickness (inches)		
	Above Third "Shale"	Below Third "Shale"	Total
22	23·5	10·0	33·5
27	22·5	19·0	41·5
28	24·5	29·5	54·0
33	32·5	19·5	52·0
34	18·5	25·0	43·5
40	27·5	0·0	27·5
46	27·5	16·5	44·0
49	37·5	42·5	79·5
59	Incomplete	9·0	Incomplete
60	26·5	8·5	35·0
61	23·0	39·5	62·5
62	20·0	6·0	26·0
67	41·5	21·5	63·0
68	16·0	19·0	35·0
69	14·0	12·0	26·0
73	26·5	10·5	37·0
75	41·0	19·0	60·0
81	29·0	26·0	55·0

*The thicknesses in columns 2, 3 and 4 were obtained by adding together the thicknesses of massive mass blue riebeckite mesobands and adding on half the thicknesses of mesobands partially replaced by riebeckite. The resultant figures, while giving a reasonably accurate comparison between the holes, probably give generally high estimates for the absolute quantities of riebeckite present.

There is ample petrographic evidence that massive riebeckite bands result from the late metasomatic volume-for-volume replacement of a limited number of "riebeckite-prone" cherts within the riebeckite zone. Where an unreplaced riebeckite-prone chert is represented in another hole by a riebeckite band the latter is usually thicker than the equivalent chert. This is partly because the replacement extends up and down into neighbouring mesobands. The replacement usually extends further below the chert than above it. It is possible also that thicker cherts were more liable to replacement, but more evidence is needed here. Replacement of any or all of the 15 main riebeckite-prone cherts of the lower riebeckite zone appears to have taken place in a haphazard manner with no obvious control. Soda is the only major constituent needed for conversion of banded iron formation to riebeckite and connate water seems to be an obvious source for this. By the nature of things it will always be impossible to know whether the replaced riebeckite-prone cherts had some essential difference which initiated the crystallisation within them of riebeckite, or whether replaced and unreplaced cherts were at one stage of diagenesis identical, but connate water was available only in some parts of the rocks, where the cherts are now riebeckite.

I am indebted to G. R. Ryan for pointing out that Plate 32 shows a strong correlation between riebeckite content of banded iron formation and the b.i.f./"shale" ratio over a restricted vertical range; the two riebeckite zones occur where this ratio is greatest.

The Upper Fibre Seam

True-scale logging of this seam between two correlatable levels at top and bottom has shown that although fibre is more common towards the top of the seam there is very much less correlation between fibre mesobands. Where fibre mesobands are absent laterally, they are represented by gaps in mesoband sequence. This work is still in progress and is therefore reported on only briefly, but it seems clear that fibre mesobands are dilatational, in marked contrast to the metasomatically formed riebeckites. As has been noted by previous authors, a pre-existing magnetite band is necessary as a seeding layer for the growth of the crocidolite.

No correlation whatsoever between fibre content and riebeckite content is present from the data available so far.

PETROGRAPHY

The following are provisional notes on the petrography of the banded iron formation macrobands only.

Classification of Mesobands

If any attempt is made to expand on the very simplest petrographic description of banded iron formation the range of textural detail becomes so varied as to defy analysis. It has already been noted that essentially the rock consists of a succession of internally consistent mesobands defined by changes in mineralogy and texture, and the first step is to attempt a classification of these. If a strictly qualitative mineral content classification be made, and there are n minerals, then there are $2^n - 1$ possible types of band, ignoring possible textural and quantative subdivisions. There are 13 minerals known to me to be present, listed below:

1. Oxides—
   - (a) of silica—Quartz
   - (b) of iron—Magnetite
2. Sulphide—Pyrite
3. Carbonates—
   - Ankerite-Dolomite
   - Siderite
   - Calcite
4. Phosphate—Apatite
5. Silicates—
   - Riebeckite
   - Stilpnomelane
   - Feldspar
   - Unidentified amphibole
   - Unidentified phyllosilicate

With a potential 8,111 different mesoband types this classification of mesobands is clearly inadequate. Fortunately it is possible to classify the mesobands into a comparatively small number of main types, and although some of these are gradational the following classification is useful in practice:

1. Chert
2. Quartz-iron oxide (abbreviated to QIO)
3. Magnetite
4. Stilpnomelane
5. Carbonate—
   - (a) Siderite
   - (b) Ankerite
   - (c) Calcite
6. Riebeckite—
   - (a) Mass-fibre
   - (b) Crocidolite

This is simply a quantitative mineral classification based on the principal constituent mineral or minerals in each band.

No properly measured estimates of the relative abundance of these types has been made, but there can be no doubt that the first three types constitute 90% by volume of the rock, and the first two about 80%, except within riebeckite zones, where for example the lower riebeckite zone contains an average 11.5% of mass-fibre riebeckite. Only a small proportion of the estimated total 35% of magnetite in banded iron formation would be contained within magnetite mesobands.

Macroscopic Petrography

Chert. The principal mineral content of chert bands lies mainly in the following ranges:

Quartz	50 - 80%
Magnetite	0 - 20%
Carbonate	20 - 30%

Cherts are pale in colour, and are usually of even thickness and lithology. They reach a thickness of 5 inches but this is unusual and ½ - 2 inches is more common. They are characteristically homogeneous internally, except for the regularly striped microbanding which is almost always present. This even alternation of laminae about 0.2 - 0.5 mm thick, defined by slight colour variation is an important and characteristic feature of almost all cherts.

Bands whose thickness is variable may be divided into those in which continuity is maintained and those which are discontinuous. Irregular thickness variation involving contortion with dips up to 40° is rare and usually associated with exceptional carbonate content. Thickness variation not involving dip of microbanding, and caused by irregular transgressive incursion of magnetite-rich material in both top and base of the band is very rare but minor wavy incursions of neighbouring bands involving truncation of the microbanding is quite common. There are several varieties of actual discontinuity. Thin cherts may appear as finely tapering lenticles enclosed in dark QIO material. In such groups there is usually overlap of gaps such that some bands at least are present at any given point. Alternatively the discontinuity may involve the comparatively abrupt truncation of cherts up to 2½ inches thick, with considerable disturbance of the enclosing QIO.

Most commonly the discontinuity in chert bands falls between these two extremes, and a number of lenticles of elongation between 2:1 and 6:1, with intervening gaps about half their length. In this common type of "podding" or "pinch-and-swell structure" the chert edges are often pink-stained and the curved margins meet at about 30°. Pink-staining is not confined to the edges of discontinuous pods. It is a common feature usually about 1-2 mm thick at top and bottom of even chert bands and a local thickening and coalescence of upper and lower pink-staining is often associated with a thinning of the whole chert band. Less commonly, pink-staining is present at top or bottom only of a chert, as a median band, over the whole of a band or in a very clear pink/white definition of the internal microbanding. It is always associated with the conversion of stilpnomelane to fine hematite platelets. Very exceptionally the individual pods may be small and spheroidal or even ellipsoidal with the long axis vertical. In such cases discontinuity is very marked and it may not be possible to follow the original band.

Quartz-iron oxide (QIO). Typically this mesoband type contains:

Quartz	35%
Magnetite	45%
Carbonate	10%
Stilpnomelane	10%

It is a brownish-grey material, often very finely and streakily microbanded, and is gradational into the less pure magnetite bands.

QIO is the characteristic enclosing material of podded cherts, and bands of it vary from almost nothing to about 3 inches. It is usually striped by "sub-bands" caused by relative paucity or abundance of the irregular magnetite microbands. Apart from mineral content the most distinctive difference between QIO and chert mesobands is the absence in the former of the extremely regular alternation of microbands characteristic of the cherts.

Magnetite. There is a gradation from magnetite-rich QIO mesobands to almost pure magnetite mesobands, and the distinction between them is at this stage subjective. Magnetite mesobands are rarely very thick; half an inch is exceptional and the mean would probably be less than a quarter of an inch.

Stilpnomelane. Mesobands with stilpnomelane as the most abundant mineral are thin and rare. They are dark green and of minor interest in the petrography of banded iron macrobands, although shale macrobands may prove to have stilpnomelane as a major constituent.

Carbonates. Pure carbonate bands are not abundant within banded iron macrobands. Green bands consisting almost entirely of fine-grained siderite occur in a few places in the section studied and are stratigraphically among the most consistent of all mesobands. Calcite and dolomite occur as sub-bands bordering chert or QIO mesobands but are never abundant. The occurrence of dolomite-ankerite and siderite within chert and QIO bands is described below.

"Riebeckite" or "Mass-Fibre." The conspicuously blue bands logged by A. B. A. as riebeckite represent other mesoband types replaced to a variable extent by riebeckite. This appears to be volume-for volume metasomatic replacement without structural disturbance of the rock, since ghost mesobands of chert and magnetite are not only clearly recognisable in some of the less completely altered riebeckite bands but their identity as such is confirmed by correlation with other holes in which these particular mesobands are unaffected. This dates the riebeckite as subsequent to the evolution of the main mesoband types by compaction (see below).

Crocidolite. Mesobands of fibrous riebeckite always represent a minor part of the total thickness of the Brockman Iron Formation, even in the mined fibre seams. I have done insufficient work on fibre mesobands as yet to record it in this report.

Microscopic Petrography and Diagenetic Evolution

From the lateral structure of certain chert pods (Figure 2), it is clear that the chert and a smaller vertical thickness of the adjacent QIO material are stratigraphically equivalent, and it seems likely that QIO has developed from chert by post-depositional modification, or diagenesis. The

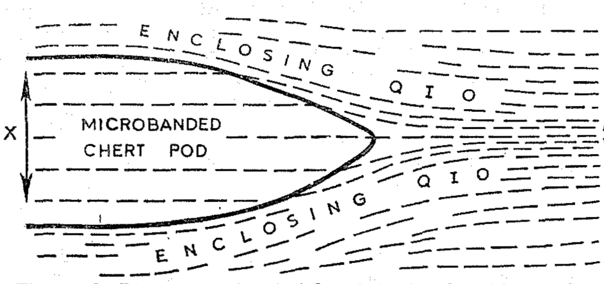


Figure 2—Diagrammatic sketch of textural evidence for equivalence of a greater thickness (X) of podded chert with a lesser thickness (Y) of QIO based on continuity of microbanding. The broken lines within the chert represent lines of ankerite rhombs; those in the enclosing QIO may represent either siderite-rich or magnetite-rich bands.

gradation between QIO and magnetite bands may develop as a result of a more extensive operation of the same process, and from this train of thought I tried to set up a model for a primitive material whose modification during varying diagenetic histories would account for much of the textural and compositional variety. Whatever the nature of such a primitive material may have been at the time of its deposition, and whatever the mechanism of its formation, it is convenient to assume that the least modified representatives of it that are now preserved are chert mesobands with coarse microbanding and that other varieties of chert and QIO were derived from this by diagenesis. The fineness and preservation of the microbanding are indices of the degree of modification. It is not possible to know to what extent present petrographic transitions represent a direct line of descent; two stages of a supposed transition may both be modified derivatives of two entirely different materials which, although derived one from the other, lost their potential to transform during subsequent modification. This concept is largely academic but it is useful to keep at the back of one's mind. The following petrographic account, then, is based on a supposed sequence of diagenetic modification of a primitive material as a means of resolving some of the complexities of the rock:

Primitive Chert. In the least modified cherts there is complete stratigraphic continuity and the microbanding is conspicuous and comparatively coarse. It is defined by ankerite bands about 0.25 mm thick, made up of a virtually continuous mosaic of rhombs about half this dimension across, alternating with bands of chert with an irregular quartz mosaic of average grain diameter about 5μ. Within the quartz are thin green streaks of stilpnomelane flakes. These have only a crude parallel orientation and the actual flake boundaries are difficult to distinguish. There may be 3-6 discontinuous and anastomosing streaks in each chert microband.

In one unusual example ankerite microbands 0.75 mm thick, within which the average grain diameter is still close to 0.125 mm, alternate with discontinuous quartz bands only about 0.2 mm thick, giving a microband (both alternations) thickness of nearly 1mm. The stilpnomelane here is clotted rather than streaky.

A primitively microbanded "chert" with about equal proportions of quartz and ankerite in regularly alternating layers about 0.5 mm thick is regarded as parental to the modifications described below. Two types of modification are distinguishable: "flat modification," in which the chert thickness is evenly reduced and is petrographically altered evenly; and "podded modification," in which compression is uneven, and the end products are chert and QIO. Chert augen remaining within QIO are usually also modified to a variable extent, and such modification has many features in common with flat modification, which is dealt with first.

The different factors which, to some extent simultaneously, are involved in the "flat" diagenesis of a primitive chert are:

1. Stilpnomelane is leached to hematite platelets about 5μ across which develop from finer "dust" left immediately after alteration of the stilpnomelane.
2. The carbonate bands decrease in thickness, the ankerite rhombs become discontinuous with the intermediate quartz mosaic slightly finer than that of the originally stilpnomelane-bearing microbands, the rhombs finally become hollow (with the cores quartz-filled) and siderite appears in association with them, in smaller rhombs.
3. The microbanding gradually becomes finer and its continuity more difficult to follow.
4. Concertina-shaped lines (or plates?) of solid magnetite which have crystal faces along the edges appear. These are referred to as "extended octahedra." They are characteristically discontinuous and patchily distributed, but very frequently there is a tendency for concentration in vertical stacks, like a pile of plates, with alternating vertical gaps. The last feature mentioned is also present at an earlier stage, when it is defined by the preferential concentration of hematite after stilpnomelane.

Whereas in the flat-modification the whole primitive mass ends up as a homogenous squashed relic of the original material reduced to perhaps 20% of its former volume, in podded modification a differentiation into modified chert and QIO is involved. The modification of the chert in the pod follows much the same lines as in flat modification as far as stilpnomelane and carbonates are concerned, except that it is rare for stilpnomelane to be preserved in a pod. On the other hand there is comparatively little microband compression in chert pods, except where they are pink-stained, and virtually no magnetite growth, although a few octahedra are very occasionally present. In one particularly good example on which the microbanding of the QIO can be followed clearly, some 7 mm of chert are represented by about 1.5 mm of QIO. The pink-stained chert edges are caused by removal of carbonates and silica from the modified chert of the pod and the resultant concentration of the fine jaspery hematite from the originally stilpnomelane-bearing microbands.

Quartz-Iron

Oxide (QIO). It has already been pointed out in one example that 7 mm of chert reduce to about 1.5 mm of QIO; here, the chert would have about 30 microband alternations. It is to be expected therefore that the microbanding of QIO will be on a very small scale, nor is it surprising that after this extreme compression its continuity is often difficult to discern. As many as 20 vaguely defined streaks of hematite may be present in a thickness of 0.5 mm, giving a microband width of 0.025 mm. The mineral content of QIO has already been given. There is a general matrix of siderite (a little dolomite may be present) of average grain diameter 15 μ, quartz of the same grain size, rarely forming a continuous mosaic, and stilpnomelane flakes again of about the same length, with parallel streaks of platy hematite. Extended magnetite octahedra exactly like those of the flat-modified cherts are commonly present, and it seems clear that the growth of magnetite was a general, pervasive, late phenomenon in which the magnetite crystallised through the rock in the best local environment. Where the chert had not differentiated the magnetite grew in the chert, but preferentially in the ex-stilpnomelane-bands, and where the chert had differentiated (podded) it grew in the QIO differentiate. This time of growth is supported by the textural relationship of magnetite octahedra to the microbanding: the general streakiness of the matrix is sharply cut off against the edges of the octahedra.

Another common feature of QIO is the presence of quartz augen about 0.5 mm across, often cored with carbonate and associated with magnetite, around which the mircobanding "flows" smoothly. These clearly represent carbonate rhombs pseudomorphed by quartz. It is not clear whether the replacement was before or after compression.

It is difficult to know whether the pink staining represents a late modification of the edges of the chert pods unconnected with the main "chert-to-QIO" transition, or whether it represents an intermediate stage in this transition. If the latter, then it is noteworthy that the siderite of the QIO represents a new generation of carbonate, and is not simply the chert siderite concentrated by removal of the enclosing silica. Its generally finer grain would support this concept.

CONCLUSIONS AND DISCUSSION

Thanks to a uniquely valuable collection of drill cores more data on the internal stratigraphy and petrography of a Precambrian banded iron formation are presented in this report, than have been available in the whole of the extensive previous literature of this puzzling rock. At the start of this report three questions were put as a summary of the objectives of the work. Progress on answering these, together with speculation beyond the evidence presented and ideas for future work, are now summarised.

Three distinct type of banding in the Brockman Iron Formation have been described. Each of these needs an explanation. It has been postulated that all the common mesoband types are derived from one of them—the primitive or coarsely microbanded chert—by diagenetic modification. The common QIO mesoband material is supposed to represent only 20-25% of the volume of its parent chert, and many magnetite bands may represent a more advanced stage of the same process. Thus massive removal of material, presumably in solution in connate water expelled during compaction, is envisaged. Selective analyses of mesobands will show whether this hypothesis is chemically tenable, and indicate the composition of the material removed. If this hypothesis is adopted the problem arises of how the mesobands become defined; any answer to this involves discussion of the nature of the original deposition and of the microbanding.

In common with almost all other workers on Precambrian banded iron formations, I find the spectacular lateral continuity on a minute scale, the lack of any internal textural evidence of detrital origin, and the curious and distinctive chemistry jointly persuasive of an origin for these rocks by chemical or biochemical precipitation. The depth of water is uncertain, but it was probably even all over the basin and was amazingly still. Silicia and ankerite in alternate thin regular layers now form the primitive chert. It is possible that these two materials were precipitated, but equally likely that the silica was in a hydrous gelatinous form and that the ankerite was previously represented by a water-rich mixture of calcium and magnesium carbonates and ferric hydroxide. But it is not certain that the microbanding originated during deposition at all; it may represent some form of liesegang differentiation at shallow depth in a mixed gelatinous sheet. There is an extensive speculative literature on the depositional chemistry of iron formation which there is not space to review or add to here, but one point of microband thickness is worth noting. Allowing for compaction of the order suggested, there are some 35,000 microband pairs in each macroband of the Brockman Iron Formation. If these are supposed to reflect annual changes of depositional chemistry, and an arbitrary 15,000 years are allowed for the associate "shale" macroband, then each cyclic unit represent 50,000 years, and the deposition of the 360 feet of 15 sections studied in detail would occupy some 750,000 years, with a depositional rate of about a foot (of present b.i.f.) every 2,000 years. This seems an acceptable depositional model. A striking feature of the microbanding is its regularity and evenness. A diurnal origin of microbanding would give a high rate of deposition, while any longer time would have to have a regularity absent from any possible cyclic controls of geological environment that are known so far.

Returning now to the question of mesoband origin the problem is one of deciding, if each microband pair represents one year's accumulation of two precipitate types, and if mesoband types are diagenetic differentiates of the resultant material, why particular levels should be modified by diagenesis to different degrees. More information is required here on the numbers of microbands in the different chert types. The commonest type of primitive chert, for example, is about half an inch thick with ten microband pairs; this type commonly lies between magnetite mesobands. On the other hand flat-modified cherts up to 5 inches thick occur with about 350 microbands, and have only very slight internal variation. How does the variety of types arise if the original material is homogeneous? Is the hypothesis fundamentally wrong? Were there breaks in deposition? Were there slight chemical, physical or even thickness differences from time to time, which later exerted an important control over diagenesis? The small-scale rhythmic sequence of cherts about 5 inches thick, referred to above, may help with these problems, none of which are answered.

At the macroband scale the most obvious hypothesis is intermittent (50,000 years, if the hypothesis above is true) sinking of the basin, with depth and proximity to the shoreline the depositional controls. But it is not clear how the two macroband types correspond to particular condition, nor why there is virtually no gradation between the two types. If sudden sinking caused a change from one to the other, gradual sedimentation would not involve an equally sudden change back. As noted above, more comparative work is needed on "shale" tops and bottoms. However, it seems certain, from the comparative uniformity of the Brockman Iron Formation throughout its great thickness, that the basin must have sunk steadily, and sinking still seems the most likely microband control.

G. La Berge (pers. comm.) has suggested a correlation between vulcanicity and shale but the rhythmic alternation of the two man rock types seems too regular for this to be likely.

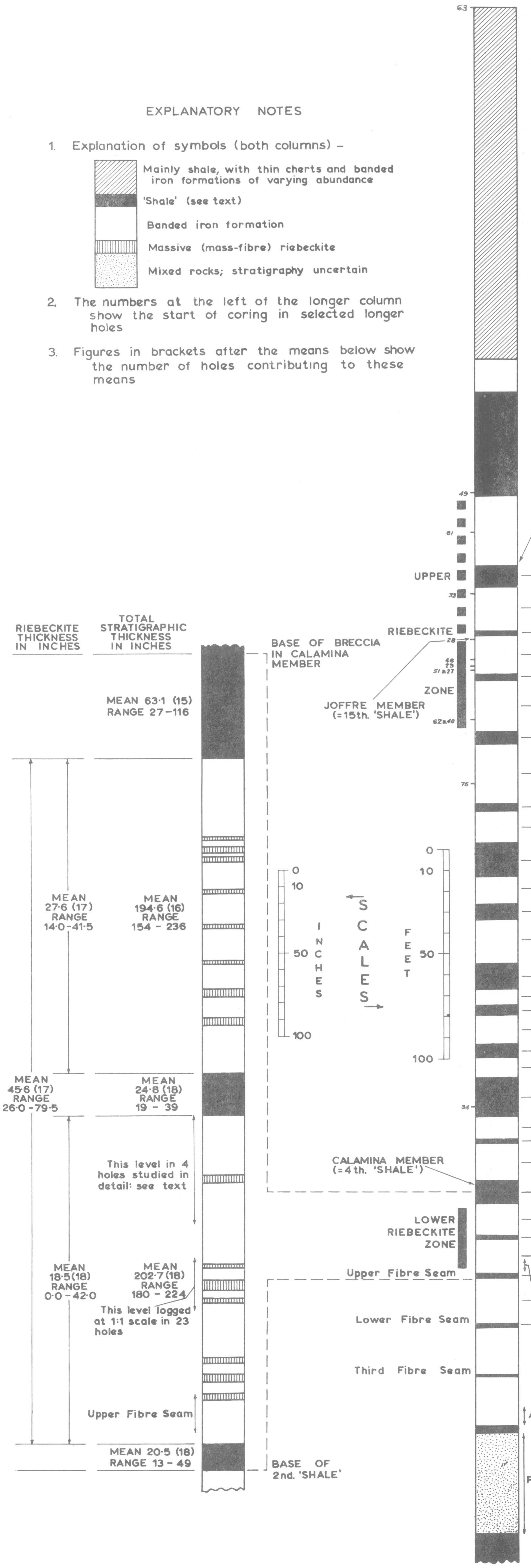
Passing on to the second and third questions, the evidence is now overwhelming that massive (mass-fibre) riebeckite and the economically important cross-fibre riebeckite, or crocidolite, are totally different in origin. Massive riebeckite forms at a late stage of diagenesis of the banded iron formation by metasomatic volume-for-volume replacement of particular "riebeckite-prone" cherts and their adjacent mesobands, probably by the addition of soda from connate water, in an erratic manner. The controls of the process are not known. Crocidolite macrobands are dilatational veins which used a pre-existing magnetite mesoband as a seeding layer. Although it is likely the crocidolite formed still later than the massive riebeckite, which is otherwise the last mineral in the rock to crystallise, it is uncertain to what extent the actual materials of the crocidolite (principally the soda) were derived from pre-existing riebeckite, or were, as in the case of the massive riebeckite, derived from connate water still present.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SUMMARY OF THE INTERNAL STRATIGRAPHY OF THE LOWER PART OF THE BROCKMAN IRON FORMATION IN THE WITTENOOM - YAMPIRE AREA

EXPLANATORY NOTES

1. Explanation of symbols (both columns) -
   - Mainly shale, with thin cherts and banded iron formations of varying abundance
   - 'Shale' (see text)
   - Banded iron formation
   - Massive (mass-fibre) riebeckite
   - Mixed rocks; stratigraphy uncertain
2. The numbers at the left of the longer column show the start of coring in selected longer holes
3. Figures in brackets after the means below show the number of holes contributing to these means



MEAN THICKNESS IN FEET OF NUMBERED 'SHALE' AND BANDED IRON FORMATION MACROBANDS BELOW THIS LEVEL TABULATED HERE

'SHALES'

No.	MEAN	NUMBER OF HOLES USED FOR MEAN	RANGE OF THICKNESS
16	10·3	3	8 – 12
15	2·0	4	2 – 2
14	2·4	9	1 – 3
13	5·6	11	4 – 7
12	2·8	12	1 – 6
11	16·3	12	9 – 20
10	7·8	12	4 – 12
9	11·8	12	6 – 17
8	4·8	12	2 – 8
7	6·2	12	4 – 10
6	19·6	12	16 – 22
5	1·6	12	1 – 3
4	10·3	12	6 – 13
3	2·1	12	1 – 4
2	2·1	12	1 – 3
1	1·8	12	1 – 4

BANDED IRON FORMATIONS

No.	MEAN	NUMBER OF HOLES USED FOR MEAN	RANGE OF THICKNESS
15	20·7	3	19 – 22
14	19·0	4	18 – 20
13	25·0	9	24 – 26
12	28·5	11	27 – 30
11	15·9	12	12 – 18
10	12·0	12	9 – 16
9	22·7	12	18 – 25
8	8·8	12	6 – 15
7	14·6	12	12 – 16
6	9·4	12	8 – 13
5	11·1	12	9 – 12
4	18·7	12	16 – 21
3	15·3	12	13 – 18
2	16·6	12	13 – 18
1	20·6	12	19 – 24

REFERENCES

Cilliers, J. J. Le R., 1961, The nature and origin of the rocks of the Lower Griquatown Stage and the associated deposits of amphibole asbestos in the northern Cape, with special reference to the Koegas-Prieska area: D. Sc. Thesis, Pretoria University.

Leggo, P. J., Compston, W., and Trendall, A. F., 1965, Radiometric ages of some Precambrian rocks from the North-West Division of Western Australia: Geol. Soc. Australia Jour., v. 12, pt. 1.

MacLeod, W. N., de la Hunty, L. E., Jones, W. R., and Halligan, R., 1963, A preliminary report on the Hamersley Iron Province, North-West Division: West. Australia Geol. Survey Ann. Rept. 1962.

LOWER PERMIAN FOSSILS FROM OUTCROPS IN THE PERTH BASIN, NEAR ARRINO

by H. S. Edgell

ABSTRACT

Lower Permian megafossils are identified and described from a surface locality in the Perth Basin, 3 miles west of Arrino. They include Artinskian brachiopods and pelecypods indicative of the Mingenew Formation.

In the vicinity of Arrino a narrow Permian fault block lies just west of the Urella Fault where strata had previously been assigned to the Lower Cretaceous. This megafossil assemblage constitutes the southernmost surface occurrence of marine Permian strata yet known in the Perth Basin.

INTRODUCTION

Surface exposures at a locality 3 miles west of Arrino have yielded an interesting assemblage of megafossils. These were collected by D. C. Lowry in 1964. They occur as poorly preserved external and internal casts on fossiliferous slabs of ferruginous silty sandstone.

This surface material was submitted in July, 1964 for age determination and identification of the megafossils. Despite its relatively poor preservation, the distinctive nature of the megafauna has enabled the outcrops to be assigned to the Lower Permian.

Several species of brachiopods can be distinguished in this collection. They include *Aulosteges baracoodensis, Chonetes pratti* and *Neospirifer musakheylensis* var. *australis.* The pelecypod *Aviculopecten subquinquelineatus* is also commonly represented together with occasional *Chaenomya? nuraensis.*

The significance of this faunal assemblage is that it proves the existence of Lower Permian strata in an area formerly thought to be underlain by Lower Cretaceous sediments of the upper Yarragadee Formation. This age determination shows that large scale faulting exists in the Arrowsmith River area on the eastern edge of the Perth Basin.

OCCURRENCE

The fossils described here are poorly preserved on blocks of ferruginous sandstone. They were collected from a hillside 3 miles west of Arrino (see Plate 33), where they occur in loose surface material and also in somewhat obscured outcrop. There is considerable lateritization of surface sediments at this locality, and the largest block collected (about 6 inches square) consists of ironstone with many fossil casts. Three smaller samples collected from the same locality consist of yellow to mauve, medium-grained, silty, micaceous sandstone with frequent pelecypod and brachiopod casts. These rocks have once been calcareous sandstone but are leached, so that only impressions of the shell material now remain.

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GEOLOGICAL BACKGROUND

A significant fault known as the Urella Fault, is just east of the megafossil locality. This fault is a major north-northwest trending offshoot of the Darling Fault. The throw of the Urella Fault is not yet known, but it would appear to be considerable and sufficient to wedge a block of Permian strata to the surface in an area of Lower Cretaceous sediments. Thus there is evidently a strip of Lower Permian sediments with megafossils situated west of the Urella Fault. These Late Palaeozoic beds lie between Precambrian granitic gneiss at Arrino itself and Lower Cretaceous siltstone some 5 miles west of the town. Evidently a large fault separates the previously unknown area of Permian strata from Lower Cretaceous sediments to the west. However, the area to the west of Arrino is of low relief, being mostly covered by soil or alluvium with few natural outcrops.

PALAEONTOLOGICAL DATA

The fossils represented as impressions on these strongly ferruginous sandstone specimens include productids, spiriferids and several species of pelecypods. The various species identified are described in detail below.

TAXONOMY AND FOSSIL DESCRIPTIONS

Phylum: BRACHIOPODA.

Superfamily: PRODUCTACEA Waagen 1884.

Family: CHONETIDAE Bronn 1862.

Genus: CHONETES Fischer 1837.

Species: PRATTI Davidson 1859.

(see Plate 34, Fig. 2)

Chonetes Pratti Davidson, The Geologist 1859, p. 116, pl. 4, figs. 9-12.

Chonetes Pratti Davidson, Bullen Newton, 1892, Geol. Mag., v. 9, no. 3, p. 542, pl. 14

Chonetes Pratti Davidson, Etheridge jr., 1903, West. Australia Geol. Survey Bull. 10, p. 23.

Chonetes Pratti Davidson, Etheridge jr. 1907, West. Australia Geol. Survey Bull, 27, p. 19-25, pl. 8, fig. 2; pl. 9, fig. 7; pl. 10, fig. 2.

Material: Four internal casts, principally of the ventral valve, under the registered numbers G.S.W.A. F5285a, F5285b, F5287 and F5288. The internal casts are mostly ferruginised and preserved in fine, decalcified, micaceous sandstone.

Diagnosis: A species of *Chonetes* distinguished by a rather wide hinge line and tendency for the shell to become alate. Four long hinge line spines on each side of the beak. Well defined medium septum in ventral valve and shallow ventral sinus.

Description: The outline of the shell is generally semicircular with a straight hinge line. It is of small size and moderately concavo-convex in profile. Dimensions of the figured specimen are: width = 12 mm; length = 8 mm; depth = 3 mm. The ventral valve has slight ears at the hinge extremities and there is a poorly marked sinus at the anterior margin. There are four long spines on the ventral hinge projecting upwards and outwards on either side of the beak.

Ornamentation of the shell consists of fine radial ribbing. About 40 to 50 fine ribs or costellae occur on a ventral valve of 12 mm width. The internal cast of the ventral valve shows a well marked median septum extending over slightly more than half the shell length. Short thick crura are situated under the ventral hinge on each side of the umbonal cavity. Numerous punctae occur on the internal surface of the ventral valve. Only a few broad growth lines are evident towards the anterior margin of the shell.

Relationships: Typical specimens of the species *Chonetes pratti* Davidson from the Irwin River and Wooramel River districts are larger than those described here and also have a more definite ventral sinus. However, they exhibit a considerable range in size. Smaller specimens of the species from well-preserved material display characteristics identical to those seen in the internal casts collected near Arrino.

There is a close resemblance between these specimens of *Chonetes pratti* Davidson and C. *granulifer* Owen from the Pennsylvanian of North America. Both have a wide hinge with alate cardinal extremities. In the latter, however, the ornamentation is more detailed consisting of very fine costellae, and hinge line spines are more numerous amounting to ten on each side of the beak. The interiors of the ventral valves in these species have short, well-marked crura and very numerous, raised punctae. On the inside lateral and anterior parts of both valves these punctae appear as short tubular spines.

Stratigraphic Distribution: This species is commonly encountered in Lower Permian marine formations in the Perth, Carnarvon and Canning Basins. In the Perth Basin it is found abundantly in the Fossil Cliff Formation. Dwarfed forms also occur as high as the Carynginia Formation. The stratigraphic interval comprising these formations is considered to be entirely within the Artinskian Stage of the Lower Permian (see McWhae and others, 1958; Glenister and Furnish, 1961).

Chonetes pratti also occurs abundantly in corresponding formations in the Carnarvon Basin, particularly the Callytharra Formation, as well as in the Poole Sandstone and Noonkanbah Formation of the Canning Basin. All these strata are of Early Permian age, being dated as Artinskian on ammonoid evidence. The highest stratigraphic horizon at which this species has been found is the Lightjack Member of the Liveringa Formation considered to be Late Artinskian to Kungurian in age (Thomas, 1958). A review of known occurrences of *C. pratti* in Western Australia shows that it is found only in Lower Permian strata.

Superfamily: PRODUCTACEA Waagen 1884.

Family: PRODUCTIDAE Gray 1840.

Genus: AULOSTEGES Helmersen 1847.

Species: BARACOODENSIS Etheridge, Jr., 1903.

(See Plate 34, fig. 3.)

Aulosteges baracoodensis Etheridge, Jr., West Australia Geol. Survey Bull. 10, p. 22, pl. 2, figs. 1-20.

Aulosteges baracoodensis Etheridge, Jr., revised Hosking, Royal Soc. West. Australia Jour., v. 19, p. 33, pl. 1, figs. 1a-c; pl. 2.

Aulosteges baracoodensis Etheridge, Jr., revised Coleman, Bur. Min. Resour. Aust. Bull. 40, p. 36-38, pl. 1, figs. 1, 3, 4 and 6.

Material: External cast of most of one ventral valve under the registered number G.S.W.A. F5291. The external impression is well preserved in a highly ferruginized rock and shows much detailed ornamentation.

Diagnosis: Large species of *Aulosteges,* subquadrate in outline, ornamented with very numerous small sub-erect and reclined, spine bases giving a somewhat striate appearance.

Description: The specimen preserved represents a large productid with a subquadrate outline. The ventral valve has a width of 60 mm and a length of at least 50 mm, although the anterior margin of the shell is not preserved. Maximum thickness of the shell is about 35 mm.

There is a strong blunt umbo on the ventral valve, flanked by weakly developed ears. A broad sinus is also developed on this valve. Most distinctively the shell possesses fine ornamentation consisting of many elongate spine bases and some which are small and erect. This gives the shell a closely ribbed appearance with ribs about 1 mm apart. Concentric growth rings are faintly developed.

Relationships: Aulosteges baracoodensis Etheridge Jr., is distinguished from *A. spinosus* Hosking by its larger size, more quadrate outline and less prominent spines. A similar shaped form of *Aulosteges* known as *A. lyndonensis* has less frequent and finer spines than *A. baracoodensis.* Finally comparison with topotypes of *A. baracoodensis* and a hypotype figured by Etheridge Jr. (West. Australia Geol. Survey Bull. 58, p. IV, fig. 11) shows that the specimen from Arrino belongs to that species.

Stratigraphic Distribution: All specimens of *Aulosteges baracoodensis* are from Lower Permian strata, particularly in the Perth and Carnarvon basins of Western Australia. At the type locality Baracooda Pool, Arthur River, in the Gascoyne district the species occurs in the Callytharra Formation of Artinskian age. Corresponding beds of the Fossil Cliff Formation in the Irwin River district also contain this distinctive productid.

Superfamily: SPIRIFERACEA Waagen 1883.

Family: SPIRIFERINAE Schuchert 1913.

Genus: NEOSPIRIFER Fredericks 1919.

Species: MUSAKHEYLENSIS Davidson 1862.

Variety: AUSTRALIS FOORD 1890.

(See Plate 34, Fig. 1.)

Synonomy:

Spirifer fasciger on Keyserling 1846, Wissensch, Beobacht, auf einer Reise in das Petschoraland im Jahre 1843 p. 229, Tab. 8, figs. 3, 3a, 3b.

Spirifera Moosakhailensis Davidson 1862, Geol. Soc. London Quart. Jour. v. 18, p. 28, pl. 2, fig. 2a-c.

Spirifera Musakheylensis Waagen, 1883, Pal. Indica, Ser. 13, Salt Range Fossils, Fasc. 4, no. 2, p. 512, pl. 55.

Spirifera Musakheylensis var. *australis* Foord, 1890, Geol. Mag. v. 7, p. 147-149, pl. 7, fig. 2 and ? pl. 5, fig. 12.

Spirifer musakheylensis var. *Australis,* Foord; in Hosking 1931, Royal Soc. West. Australia Jour. v. 17, p. 23-24, pl. 7, figs. 1-3.

Neospirifer musakheylensis (Davidson) var. *australis,* Foord, this paper.

Material: One external cast of the ventral valve preserved with details of ornamentation and outline as an ironstone impression, under the registered number G.S.W.A. F5292.

Diagnosis: A moderately large spiriferoid with a transversely rhomboidal outline and moderately convex valves. Distinctively ornamented by numerous small ribs in groups of larger plications and traversed by numerous conspicuous growth lines.

Description: The shell has a width of approximately 70 mm and a length of 40 mm. It has somewhat rounded lateral extremities and is subrhomboidal in outline. There is a wide, plicate sinus in the ventral valve and from four to five major ribs on each of the lateral slopes. Numerous smaller ribs appear faintly on the major ribs. This pattern of double ribbing is intersected by very numerous, sharp, projecting growth laminae. There are not more than two concentric frill laminae per millimetre.

Relationships: The specimen examined does not show details of the umbo or hinge line. On the basis of shape and size it is very similar to hypotypes in the palaeontological collections of the Geological Survey of Western Australia. The numerous ribs crossed by prominent growth lines are a common characteristic. However, small plications on the larger ribs are more numerous and more prominent on well preserved specimens.

"Spirifer" (Neospirifer) hardmani Foord shows a resemblance to the Arrino material in overall size and shape, although it is slightly more quadrate. In addition, *N. hardmani* has numerous evenly developed, radiating ribs and these are not plicated or intersected by prominent growth laminae.

Hosking (1931, p. 23) has stated "there remains no doubt that *S. fasciger* and *S. musakheylensis* are identical and that Keyserling's name takes precedence." In the absence of comparative material from the Salt Range representing *Neospirifer fasciger Keyserling* I have referred our specimen to Foord's variety which is commonly known in Australian literature and collections.

Although originally assigned to the genus *Spirifera* by Davidson (1862) and later to *Spirifer* by Hosking (1931) the form figured by Foord (1890) is undoubtedly a *Neospirifer* in modern spiriferoid nomenclature. It has the general large transverse outline and possesses the characteristic fasciculate ribbing. The specimen examined is thus referred to here as *Neospirifer musakheylensis* Davidson var. *australis* Foord.

Stratigraphic Distribution: The type locality of *Neospirifer musakheylensis* var. *australis* is given by Foord as the Gascoyne River. Although this is not a specific reference almost identical hypotype material is figured by Hosking (1931, pl. 7, fig. 1) and comes from ½ mile west of Callytharra Springs in the Callytharra Formation. The age of this very fossiliferous formation is known to be early Artinskian. Other occurrences of this spiriferoid are all from lower Permian strata. These include the Byro Group at Byro Station, Lower Murchison River district and the Callytharra Formation, 20 miles north of Barrabiddie, in the Minilya River district. *Neospirifer musakheylensis* is also recorded from the Lower Permian Noonkanbah Formation in the Christmas Creek area of the Canning Basin (Wade, 1924).

Phylum: MOLLUSCA.

Class: PELECYPODA Goldfuss.

Superfamily: GRAMMYSIACEA.

Family: PHOLADOMYIDAE Gray.

Genus: CHAENOMYA Meek 1865.

Species: NURAENSIS Dickins 1963.

Synonomy:

Chaenomya sp. nov. Dickins 1957, Bur. Min. Resour. Aust. Bull. 41, p. 29, pl. 4, figs. 10-12.

Chaenomya? nuraensis Dickins 1963, Bur. Min. Resour. Aust. Bull. 63, pp. 52-53, pl. 6, figs. 10-14.

Material: Two external impressions of the right valve of this pelecypod are preserved in leached, silty sandstone, under the registered numbers G.S.W.A. F5286a and F5286b.

Diagnosis: Elongate sub-rhomboidal shell with long posterior part. Umbo broad, sub-erect. Posterior dorsal edge almost straight making a narrow obtuse angle with the rounded posterior margin. Dorsal part of anterior margin short and oblique to shell length.

Description: The outline in this species is traversely elongate and very inequilateral with a high and long posterior part. There is a very broad umbo and a short anterior area. The shell is marked by its almost straight postero-lateral margin, which makes a broad angle with the rounded postero-ventral margin. A short and slightly oblique anterior margin is present. Of moderate size and no great thickness the valves show numerous lightly marked growth lines. There is probably a slight posterior gape. Typical shell dimensions are: length = 35mm; height = 20 mm; thickness = 5 mm.

Relationships: In casts of this pholadomyid type shell identical characteristics can be seen to those described by Dickins (1963) for the species *Chaenomya? nuraensis.* However, his original description of this species is based on casts of one valve. Conjoined or separate valves have not been studied and assignment to the genus *Chaenomya* is as yet provisional.

Stratigraphic Distribution: This species has been found in Western Australia only in the Carrandibby Formation, in the Wooramel River district and in the Nura Nura Member, in the Fitzroy River area. Both these stratigraphic units are Lower Permian and correlative with the Fossil Cliff Formation of Artinskian age in the Perth Basin.

Superfamily: PECTINACEA Reeve.

Family: AVICULOPECTINIDAE Etheridge Jr. Emend. 1906.

Genus: AVICULOPECTEN McCoy 1851.

Species: SUBQUINQUELINEATUS McCoy 1847.

(See Plate 34, fig. 4.)

Synonomy:

Pecten comptus Dana (non McCoy) 1847, Am. Jour. Sci., v. 4, p. 160.

Pecten sub-5-lineatus McCoy 1847, Ann. Mag. Nat. Hist., v. 20, p. 295, pl. 17, fig. 1.

Aviculopecten subquinquelineata McCoy, Etheridge, Jr., 1880, Royal Phil. Soc. Edinburgh Proc., v. 5, p. 297, pl. 15, fig. 52.

Deltopecten subquinquelineatus (McCoy), Etheridge Jr., 1907, West. Australia Geol. Survey Bull. 27, p. 22-23, pl. 5, figs. 1-3.

Deltopecten subquinquelineatus (McCoy) var. *comptus* Dana, Fletcher 1929, Aust. Museum Rec., v. 17, no. 1, p. 23, pl. 13, figs. 1-4.

Material: Two partly preserved, external casts of the left valve under the registered numbers G.S.W.A. F5293 and F5284.

Diagnosis: Pectiniform, nearly equilateral, biconvex; cardinal margin auriculate and slightly less than maximum width. Radial ribs increasing by intercalation.

Description: Casts of the shell show that it is truncato-orbicular in outline with well-developed ears and almost equilateral. Its maximum width lies about midway between the umbo and the rounded, ventral commissure. Ornamentation consists of from 15 to 25 primary ribs with numerous, fine ribs intercalated ventrally. Growth lines are not prominent and are widely spaced.

Relationships: Aviculopecten subquinquelineatus cannot be assigned to the genus *Deltopecten* as its ornamentation does not consist solely of large radiating ribs. It has in addition many finer ribs intercalated towards the ventral margin. There is no doubt that the species has been incorrectly referred to *Deltopecten* in Western Australia literature since 1907. Comparison with hypotype specimens of *A. subquinquelineatus* figured by Etheridge (1907) and now in the palaeontological collection of the Geological Survey shows that the Arrino specimens are almost indistinguishable in size, shape and nature of ribbing.

Specimens from the Wooramel River district, figured by Hosking and named *Deltopecten subquinquelineatus* var. *comptus* Dana also show similar characteristics to our material. They are definitely *Aviculopecten* with ribbing arranged in ranks, and probably belong to the species *A. subquinquelineatus* McCoy but cannot be referred to the variety *comptus* Dana. It has been pointed out by Etheridge (in Jack and Etheridge, 1892) that Dana's name of *comptus* was preoccupied by McCoy for another species from the Carboniferous of Ireland.

Stratigraphic Distribution: Known occurrences of *Aviculopecten subquinquelineatus* in Western Australia are all from Lower Permian beds. It is recorded abundantly from the Madeline Formation in the basal part of the Byro Group, lower Murchison River district and from the Mingenew Formation about 1½ miles east of Mingenew, Perth Basin. Both these formations are of Artinskian age. There is a marked similarity in the limonitic sandy lithology of the Mingenew Formation and that of the outcrop material from Arrino. Materials from both localities contain abundant *A. subquinquelineatus* with almost identical, fine, intercalated, radial ribbing.

FACIES

The presence of large productid and spiriferoid brachiopods as well as pholadomyid and pectiniform pelecypods in the megafauna near Arrino provides good evidence of depositional conditions. They indicate that the strata were formed in a shallow marine environment possibly in the inner neritic zone. The rocks in which the Arrino fossils are found confirm this view since they are poorly sorted micaceous sandstones now largely ferruginized due to weathering. The original nature of the rock has been a very fossiliferous calcareous silty sandstone.

GEOLOGICAL AGE

All the megafossil species identified are known to be confined to Lower Permian formations in Western Australia. These formations are richly fossiliferous and are known to be of Artinskian age on the basis of their brachiopod, pelecypod and ammonoid faunules. There is no doubt that the fossil material is Early Permian and Artinskian according to recent correlations (McWhae and others, 1958; Furnish and Glenister, 1961: Dickins, 1963).

CORRELATION

The megafauna indicates a general correlation with formations such as the Mingenew Formation, Fossil Cliff Formation, Callytharra Formation and the Nura Nura Member of the Poole Sandstone. These are all very fossiliferous, Lower Permian rock units well known in the stratigraphy of Western Australia. They are considered to be stratigraphically equivalent, with the exception of the Mingenew Formation. In recent studies Dickins (in McWhae and others, 1958; in McTavish, 1961; Dickins, 1963) has shown that this enigmatic formation is approximately correlative with the Madeline Formation of the Wooramel River and the lower part of the Byro Group in the Kennedy Range.

Investigation of the known vertical ranges of megafossils collected near Arrino show that they are mainly recorded from beds younger than the Fossil Cliff Formation. Thus, the pelecypod *Aviculopecten subquinquelineatus*, which occurs so abundantly in the Arrino megafauna is known principally from the Madeline Formation, in the lower Byro Group and from the Mingenew Formation itself. In the latter beds *A. subquinquelineatus* is commonly preserved as casts. These occur in a ferruginous silty sandstone almost identical in lithology with the fossiliferous samples collected in the Arrino area.

A recent water bore, Arrowsmith River No. 5, also encountered Lower Permian strata between the sampled depths of 90 feet and 120 feet. This bore is approximately 3 miles west of Arrino. The samples of dark grey claystone were examined palynologically and found to contain the characteristic *Nuskoisporites gondwanensis* Assemblage. This is typical of the Lower Permian and the strata examined from this bore belong to the Holmwood Shale. A few miles further to the west numerous bores for water in the Arrowsmith River area have reached the Lower Cretaceous Yarragadee Formation at shallow depths. At Arrino itself and in a belt north-northwest of the town Precambrian rocks are present.

CONCLUSIONS

At a locality some 3 miles west of Arrino scattered outcrops of ferruginous silty sandstone have yielded a distinctive Lower Permian megafauna. This consists of the brachiopods *Aulosteges baracoodensis, Chonetes pratti* and *Neospirifer musakheylensis* var. *australis* as well as the pelecypods *Chaeomya? nuraensis* and *Aviculopecten subquinquelineatus*. All these species are known only from the Lower Permian and are confined to strata of Artinskian age.

Identification of this fossil assemblage has considerable geological significance. It shows that Lower Permian strata occur at the surface a few miles west of Arrino in an area previously thought to be underlain by Lower Cretaceous sediments. This is the southernmost surface occurrence of Permian strata known in the Perth Basin west of the Urella Fault.

The ferruginous sandstone in which the fossils are found can be assigned to the Mingenew Formation. It is correlative with the lower Byro Group of the Carnarvon Basin, or approximately with the Caryngina Formation of the Perth Basin Permian sequence.

Lower Permian outcrop and subsurface sediments just west of Arrino are situated in a narrow north-northwest trending fault block bounded by Precambrian rocks to the east and Lower Cretaceous sediments to the west. This block is downthrown by the Urella Fault against Precambrian rocks to the east. Another major fault 4 miles west of Arrino allows Lower Cretaceous strata to be downthrown at least 6,000 feet against this narrow Permian fault block. The Mingenew formation at its type locality some 1½ miles east of Mingenew is bounded by similar faults and is probably in the same fault block as the Arrino megafossil locality.

Palaeontological evidence of the Lower Permian Mingenew Formation just west of Arrino provides a further indication of the strong fault pattern which dominates geological structure in the Perth Basin.

REFERENCES

Dickins, J. M., 1957, Lower Permian pelecypods and gastropods from the Carnarvon Basin, Western Australia: Bur. Min. Resour. Aust. Bull. 41, 74p., 10 pls.

Dickins, J. M., 1963, Permian pelecypods and gastropods from Western Australia: Bur. Min. Resour. Aust. Bull. 63, 202p., 26 pls.

Etheridge, R., Jr., 1903, Palaeontological contributions to the geology of Western Australia, Descriptions of Carboniferous fossils from the Gascoyne District, Western Australia: West. Australia Geol. Survey Bull. 10, 41p., 6 pls.

Etheridge, R., Jr., 1907, Palaeontological contributions to the geology of Western Australia, Fossils from Mingenew, Irwin River Coalfield, collected by Mr. E. S. Simpson, Mineralogist and Assayer: West. Australia Geol. Survey Bull. 27, pt. 3, p. 19-25, pls. 3-5.

Foord. A. H., 1890, Notes on the palaeontology of Western Australia I: Geol. Mag. n.s., v. 7, p. 145-155, pls. 6-7.

Glenister, B. F. and Furnish, W. M., 1961, The Permian ammonoids of Australia: Jour. Palaeont., v. 35, no. 4, p. 673-736, pls. 78-86, 17 text figs.

Hosking, L. F. V., 1931, Fossils from the Wooramel District, Western Australia: Royal Soc. West. Australia Jour., v. 17, p. 17-52, pls. 3-13, 5 text figs.

McTavish, R. A., 1961, Completion report on bore B. M. R. 10A, Beagle Ridge, Western Australia: Bur. Min. Resour. Aust. Rec. 1960/127 (unpublished).

McWhae, J. R. H., Playford, P. E., Lindner, A. W., Glenister, B. F., and Balme, B. E., 1958, The stratigraphy of Western Australia: Geol. Soc. Australia Jour., v. 4, pt. 2, 161 p.

Playford, G., 1959, Permian stratigraphy of the Woolaga Creek area, Mingenew District, Western Australia: Royal Soc. West. Australia Jour., v. 42, pt. 1.

Wade, A., 1924, Petroleum prospects, Kimberley District of Western Australia and Northern Territory: Commonwealth Parl. Paper No. 142, 1923-1924, 13 pls.

TECHNIQUES IN THE RECOVERY OF SPORES AND POLLEN FROM SURFACE SEDIMENTS

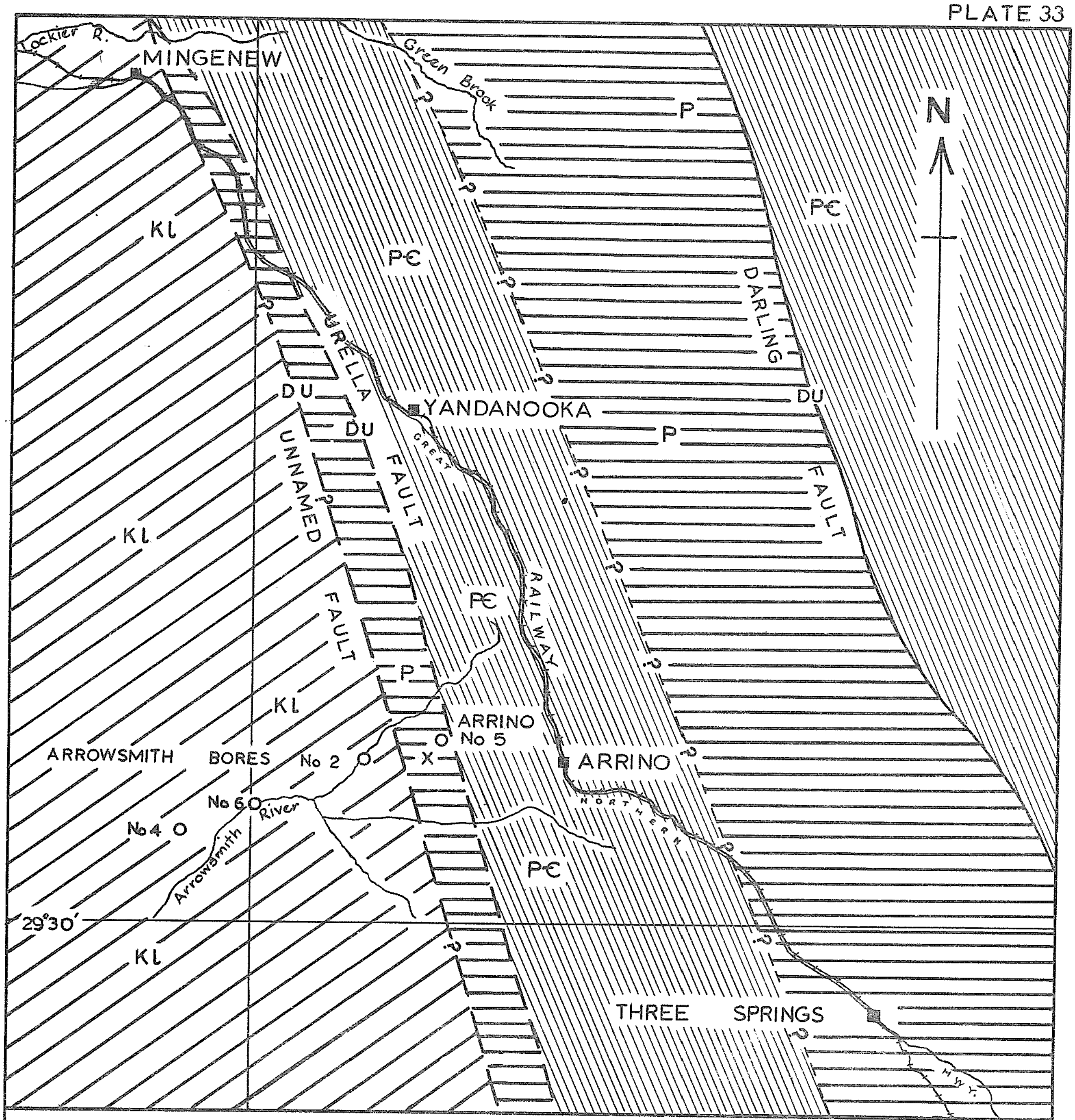
By H. S. Edgell

ABSTRACT

Palynological techniques are described by which spores and pollen may be recovered from surface samples of various lithological types. These methods involve limited oxidation and base treatment as well as controlled heavy liquid separation. They have been used in the laboratory of the Geological Survey of Western Australia during the last three years and have provided useful data for the majority of outcrop samples submitted.

INTRODUCTION

In earlier palynological investigations in Western Australia the study of surface samples has been avoided. This is because simple preparation of some outcrop samples yielded no spores or pollen grains and it was held that surface weathering had effectively destroyed any determinable palynomorphs. The more favourable dark, argillaceous or carbonaceous subsurface samples have



LEGEND

Megafossil Locality	X
Water Bore	O
Lower Cretaceous (KL)	
Permian (P)	
Precambrian (PЄ)	

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

SKETCH MAP OF SOLID GEOLOGY IN THE ARRINO —— MINGENEW AREA

SCALE OF MILES

4 0 4 8

To Accompany Report By H.S. Edgell 1964

Fig. 1: *Neospirifer musakhleyensis* var. *australis* Foord (x1)
External cast of ventral valve, from 3 miles W. of Arrino.

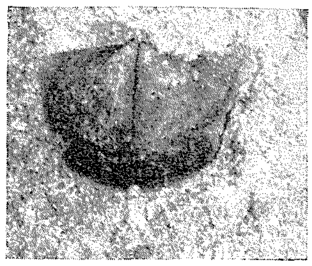


Fig. 2 *Chonetes pratti* Davidson (x2½)
Internal cast of ventral valve, from three miles W. of Arrino.

Fig. 3 *Aulosteges baracoodensis* Etheridge, Jr. (x1)
External cast of ventral valve, anterior view from 3 miles W. of Arrino.

Fig. 4 *Aviculopecten subquinquelineatus* McCoy (x1)
External cast of valve, from 3 miles W. of Arrino.

been primarily selected in past work. While these certainly provide the most diverse microfloral assemblages, such ideal lithologies are often unavailable. This is most commonly the case with outcrop material or samples from shallow depths where it may be critical to know the age, facies and formation represented. Palynological age determinations of this type are of particular value in the construction of regional maps and in hydrological investigations. In the latter case there is often a major interest in shallow, less saline aquifers as well as in the age and distribution of intake beds.

MATERIAL

Methods applied in the recovery of spores and pollen from surface samples vary widely according to the type of lithology. Certain kinds of surface weathering or shallow leaching may entirely remove all initial carbonaceous material from a sediment. This includes the complex but highly acid resistant organic sporine or sporopollenine which forms the walls of spores and pollen grains. The effect of weathering appears to take place down to depths of at least 200 feet in permeable sediments in the arid or seasonal rainfall areas of Western Australia. This is the case with the poorly sorted siltstones and sandstones of the Yarragadee Formation in the Allanooka water bores.

Samples of considerably different lithology were examined from surface and subsurface occurrences. These ranged from lignites and carbonaceous black shales through to siltstones and poorly sorted sandstones. It was found possible to recover plant microfossils from all of these sediment types except where weathering had produced excessive ferruginization. Surface silicified sandstones of the "grey billy" type yielded rare unoxidized spores and pollen grains despite the low content of organic material.

PROCEDURES

In general normal palynological preparation methods were used, namely the Schulze method for oxidation of carbonaceous material such as dark shale and coal as well as maceration methods for siliceous, clastic sediments. The procedures when applied uniformly often failed to produce results due to excessive oxidation of a very small content of palynomorphs.

Modifications of the usual steps taken in palynological preparation were found necessary for different kinds of surface sediments. In addition various methods were employed to separate the rare organic content of surface samples from a comparatively large volume of fine undissolved mineral particles. The principal procedures used in the palynological preparation of different types of sediments are given below.

PREPARATION OF CLASTIC SEDIMENTS

The preparation of fragmental rocks such as claystones, siltstones and sandstones mainly involves the removal of inorganic, mineral material with hydrofluoric acid. Many additional procedures are required in this method such as neutralization, oxidation, centrifugation and staining. The processes used by the Geological Survey are as follows:

Dark Shales and Siltstones

1. Crush approximately 6 gms of rock sample to fragments not exceeding 3 mm.

2. Apply dilute HCl to test for the presence of carbonates.

3. If effervescence takes place treat the material with 20% HCl for one hour or until reaction ceases. Wash several times with distilled water.

4. Transfer 4 gms of the decalcified or original non-calcareous sample to a platinum dish and add 30% HF to fill half the dish.

5. Stir with a glass rod and boil gently under a fume hood for about 10 minutes or until the original volume is reduced by about two-thirds. Then add 10% HCl to restore the original volume.

6. Agitate gently using tongs and transfer the contents to a plastic centrifuge tube.

7. Centrifuge once for 30 seconds at 2,500 r.p.m. and follow by washing with distilled water.

8. A small quantity of $KClO_4$ (½ gm or less) is added to the wet residue and mixed thoroughly with a glass rod.

9. Add concentrated HNO_3 to fill about ⅓ of the centrifuge tube. Stir the mixture carefully and allow to stand for 3 minutes. Proportionately less time is required with lighter, less carbonaceous samples.

10. Wash with distilled water, stir and centrifuge. Repeat this process 3 times.

11. Add dilute (5%) NaOH to fill about ⅓ of the tube, then stir, transfer to a small beaker and heat until simmering. Do not boil as the caustic solution ultimately removes spore and pollen exines.

12. Wash 3 times with distilled water immediately after alkali treatment until a clear solution is obtained.

13. Concentrated HNO_3 is then added to fill about 1/6th of the centrifuge tube, the solution is stirred and washed with water 3 times.

14. Add a similar small quantity of dilute NaOH, stir and quickly wash out with water several times.

Sandstones, light claystones and kaolinites

Light coloured or leached clastic sediments are generally oxidized in nature and have a very low content of spores and pollen. They require no further oxidation by treatment with boiling HF and alkalies. In the preparation of such samples it is necessary to modify the maceration procedure applied to carbonaceous sediments.

1. The outer portions of these surface samples must be scraped off or removed with a rock saw. If this is not done there is resultant misleading contamination by Recent spores and pollen grains.

2. A much larger sample of from 10 gm to 20 gm needs to be disintegrated to a maximum grain size of 3 mm. Extra care should be taken that all crushing implements, vessels and stirring rods are thoroughly cleaned with distilled water.

3. Transfer the crushed sample to a large polycarbonate beaker, cover with twice its volume of cold 50-60% HF, stir and allow to stand for 12 to 24 hours.

4. Add twice as much distilled water as fluid in the beaker. The specific gravity is thus reduced allowing pollen to settle when centrifuged.

5. Decant and centrifuge the material in the beaker and wash several times in distilled water.

6. The residue is then washed into a small beaker with 50% HCl and warmed to remove undissolved fluorides formed at an earlier stage. Follow by rewashing with distilled water 3 times.

7. Treat the residue for 10 seconds or less with a very small amount of $KClO_4$ and HNO_3 and follow by several rinses with distilled water.

8. Add a small quantity of dilute NaOH (5%), stir with the residue and wash twice without allowing to stand. The residue is then ready for staining or further separation of spores and pollen using heavy liquids.

Some outcrop or shallow subsurface samples of a leached argillaceous nature yield a relatively large quantity of yellowish or whitish gel after treatment. This can be removed by agitation alternately with dilute HCl and NaOH for very short periods with intermittent washing and centrifuging.

PREPARATION OF COALS

The palynological preparation of surface coal samples is less complex as carbonaceous material predominates. Oxidation is necessary to remove a large amount of organic debris and to separate the acid insoluble spores and pollen. This is primarily achieved by use of Schulze solution, which consists of a rather explosive mixture of $KClO_4$ and concentrated HNO_3.

Preparation procedures used for coal samples are as follows:

1. Crush several grams of the rock to a grain size of 1 mm.

2. Place crushed material in a beaker with Schulze solution, consisting of one part of saturated aqueous $KClO_4$ solution to 2 or 3 parts of cold, concentrated nitric acid. About 3 times as much Schulze solution should be added as the volume of crushed material.

3. The oxidizing process should be allowed to proceed for at least 12 hours.

4. After oxidation the residue is washed several times by centrifuging and decanting with distilled water.

5. A solution of 30 cc of 5% KOH is then added to the residue, stirred and allowed to stand for a short period. If allowed to remain in alkali or Schulze solution for too long spore and pollen exines swell and may dissolve completely.

6. After treatment with a base the residue is washed 3 times in distilled water. It is then ready for staining and slide preparation. If mineral material is present in large quantities in the initial slide, treatment for 12 hours with 50-60% HF is necessary. Alternatively water soluble heavy liquid separation may be used to remove mineral particles.

HEAVY LIQUID SEPARATION

After the above maceration with HF, Schulze solution and other reagents, the majority of mineral material has been dissolved away. In many cases, however, an appreciable cloud of fine undissolved mineral remains and obscures the acid insoluble plant micro-fossils which have been retained. The most effective method of separating organic particles from inorganic material is by heavy liquid separation with controlled centrifuging. This method is the basis for success in recovering spores, pollen grains and microplankton from surface samples with a very depleted organic content.

There is substantial difference in the specific gravities of all varieties of undissolved mineral particles (e.g. fluorite 3.2, quartz 2.6 and calcite 2.7) and those of organic particles (between 1.3 and 1.7). This provides an ideal basis for separating palynomorphs from mineral material which often masks them completely in the final macerated residue. However, any separation scheme needs to avoid heavy liquids which are organic solvents and those which are non-water miscible. Solutions of $ZnCl_2$ or $ZnBr_2$ both fulfil these requirements and although the latter is less viscous and probably preferable it is an expensive reagent. In the Geological Survey we have found a saturated solution of $ZnCl_2$ of specific gravity 1.95 to be very adequate for separation of organic material. It is necessary to keep a periodic check on this specific gravity with a hydrometer and to see that there is a minimum of water with the macerated residue when the heavy liquid is added. If this is not observed the specific gravity falls below 1.95 and an effective separation of pollen and spores cannot be achieved.

The heavy liquid separation method adopted in our laboratory is similar to that outlined by Funkhouser and Evitt (1959). It consists of the following steps:

1. Approximately 8 cc of saturated $ZnCl_2$ solution of specific gravity 1.95 are mixed thoroughly with the residue and transferred to a 28 cm length of plastic tube of about 15 mm diameter.

2. The flexible tube and its contents are then agitated with fingers over both outlets.

3. Double the plastic tubing and place it in a centrifuge tube. Centrifuge at 1,500 r.p.m. for at least 15 minutes. This is generally sufficient to sink all mineral particles, but if the final slide still retains fine inorganic material the process may be repeated at slightly higher speeds—2,000 r.p.m. for as long as 30 minutes.

4. After centrifuging with heavy liquid a black layer of organic particles appears at the top of the liquid in each arm of the doubled tube. Pliers are used to tightly close off the plastic tubing just below this organic layer. In some sediments where there is a minute amount of organic material no layer can be seen after separation, but many particles are observable on the surface in indirect light. The surface layer in each half of the folded tube may be sucked off with an eyedropper in such cases and then washed and centrifuged.

5. The uppermost heavy liquid containing organic material is then placed in a conical based centrifuge tube together with a few drops of 10% HCl. This acidification prevents the formation of insoluble $Zn(OH)_2$.

6. After filling with distilled water the polycarbonate centrifuge tube is given a short centrifuging for a few minutes at 3,500 r.p.m. The liquid is carefully decanted except for a minimum amount containing the organic residue.

7. In staining the small organic fraction recovered from surface samples only 1 or 2 drops of Safranin Y are added. The stained residue is washed and centrifuged again. It is then ready for examination on a slide in a glycerine jelly mounting medium, suitably cover slipped and sealed.

Certain types of clastic sediments particularly glauconites or glauconitic sandstones yield a final residue which aggregates in large clumps of indistinguishable spores and pollen grains. By adding a few drops of detergent and shaking as much as possible by hand some of these clusters break up. A more effective method of disaggregating organic residues of this type is to subject them to 5 to 10 seconds ultrasonic treatment in a narrow phial with ⅛-inch diameter probe vibrating at 20 kilocycles per second.

APPLICATIONS

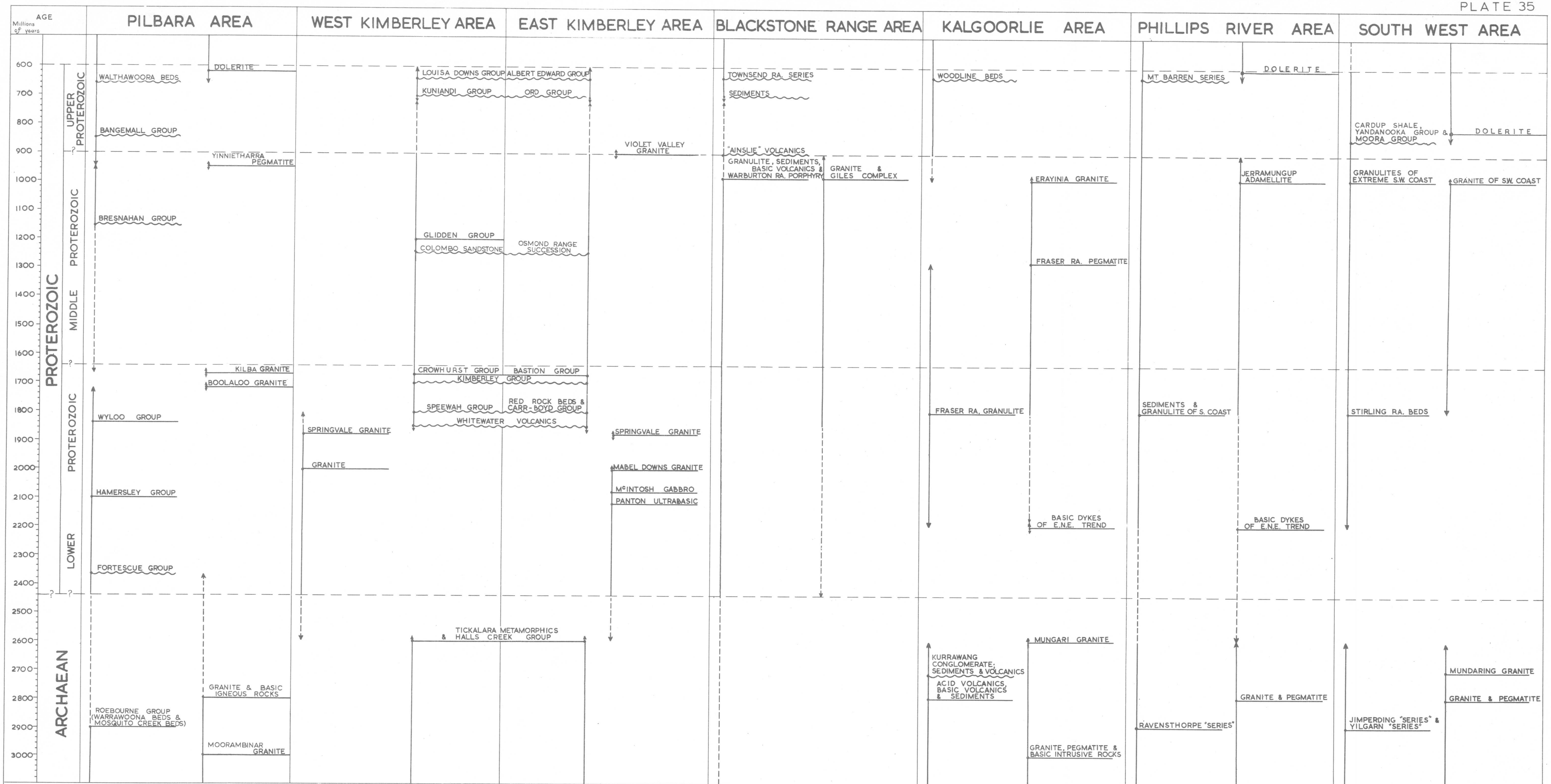
The recovery of spores and pollen grains from outcrop samples is most useful in general geological work. Although these rocks are usually much leached, weathered and improverished in organic content, it is essential for the geologist mapping an area to know their geological age and the formation to which they may be assigned. Knowledge of this type can otherwise only be obtained from the rare occurrences of larger fossils or by extensive drilling. Even then shallow subsurface material may be leached to a depth of several hundred feet. Construction of a geological map showing time-rock units depends largely on the palaeontological dating of surface outcrops. Age determinations and recognition of surface formations cannot always be made as diagnostic megafossils and larger microfossils are often absent. Most sediments contain plant microfossils no matter whether they are of marine or continental origin. Palynology thus provides an important key to stratigraphic interpretation of surface outcrops and especially to their mapping and correlation.

In conjunction with geological mapping in the southern Perth Basin the age of many outcrop samples has been determined palynologically. Well preserved Upper Jurassic and Lower Cretaceous microfloral assemblages have been recognised as well as a large number of Quaternary outcrops with the typical *Myrtaceidites eucalyptoides* microflora.

Surface samples collected by geologists of the Geological Survey from the Wilkinson Range Beds at localities in the Officer Basin have also been dated as Lower Cretaceous on the basis of spores and pollen. These beds cover a very large area north of the Eucla Basin and had previously been assigned to the Permian System.

Investigations for water in the Kalamunda area have been assisted by the dating of leached white kaolinitic material from just below the valley-filling laterites at depths of 20 to 30 feet. The age of these laterites has now been determined as post-Pliocene on palynological evidence.

Regional mapping of the Mt. Ramsay, Roebourne and Yanrey 1 : 250,000 Sheets has also been assisted by the recovery of spores and pollen grains from surface sediments enabling the dating of Pliocene and Quaternary outcrops.



AGE OF UNIT

PROPOSED ————

PROPOSED (UNIT RESTS WITH A BASAL UNCONFORMITY) ~~~~

PROBABLE RANGE WITHIN WHICH THE UNIT MAY FIT

POSSIBLE RANGE WITHIN WHICH THE UNIT MAY FIT

TENTATIVE POSITION OF TIME BOUNDARY —?— — —

PROVISIONAL SUBDIVISIONS OF THE PRECAMBRIAN IN WESTERN AUSTRALIA

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA 1964

8562

CONCLUSIONS

Through the modification and improvement of normal palynological techniques more sensitive methods of preparation have been developed. These have enabled the writer to recover spores and pollen from numerous outcrop samples which are generally weathered and oxidized. Leached clastic surface samples may now yield plant microfossils diagnostic of their age. A notable exception is that of strongly ferruginized sediments. Even in this case, however, a ferruginous outer zone may sometimes be removed from the outcrop sample giving a silicified or unoxidized inner part suitable for palynology.

These techniques require the removal of the exposed surfaces of samples which may contain contaminating recent palynomorphs. According to the type of lithology, it is necessary to adjust the amount of material prepared as well as the quantity and duration of Schulze and alkali treatment.

The main reason for successful recovery of identifiable spores, pollen and microplankton from samples of impoverished organic content is controlled heavy liquid separation. It is possible to separate all mineral particles from the lighter organic fraction of the sediments.

The ability to recognize the age of outcrops by the recovery of spores and pollen, is obviously valuable to geological mapping. The techniques described are those which have provided the most favourable results in the preparation of material for various palynological investigations. They are outlined here in the hope that they may prove useful to other workers in the field of palynology.

REFERENCES

Brenner, G. J., 1963, The spores and pollen of the Potomac Group of Maryland: Maryland Dept. Geology Mines and Water Resources Bull. 27, 215p.

Brown, C. A., 1960, Palynological techniques: Louisiana State University, 188p.

Dettmann, M. E., 1963, Upper Mesozoic microfloras from south-eastern Australia: Royal Soc. Victoria Proc., v. 77, pt. 1, 148p.

Funkhouser, I. W. and Evitt, W. R., 1959, Preparation techniques for acid-insoluble microfossils: Micropaleontology, v. 5, no. 3, p. 369-375.

PROVISIONAL SUBDIVISIONS OF THE PRECAMBRIAN IN WESTERN AUSTRALIA

The accompanying chart (Plate 35) sets out the present state of knowledge of Precambrian geochronology in Western Australia.

Rocks older than the Palaeozoic occupy more than half the area of Western Australia. These rocks have a complex history and have been formed during a large span of time. Geological mapping has brought to light many relationships of the various rock units within the Precambrian, whilst radiometric age determinations, carried out recently by workers at the Department of Geophysics, Australian National University, have added new data on the absolute ages of some rock units. This work is being continued and will no doubt cause considerable alterations to the chart.

At our present state of knowledge, the division of the Precambrian into Archaean and Proterozoic fits a very significant break in Western Australia. The Proterozoic has been divided into three major subdivisions—Lower, Middle and Upper—and the Geological Survey has tentatively adopted the time boundaries as used by the Geological Survey of Canada (Leech and others, 1963).

On the chart, where possible, the different units are referred to by rock unit names, and they are grouped in seven geographic areas.

The proposed age of any unit has been selected either on the results of an age determination or because of a correlation with a dated rock in another area. A probable range of time is shown; this does not indicate only the range during which the unit was formed but also the range within which the unit can be fitted to satisfy correlations with other areas. The possible range has also been indicated.

REFERENCE

Leech, G. B., Lowdon, J. A., Stockwell, C. H., and Wanless, R. K., 1963, Age determinations and geological studies: Canada Geol. Survey, Paper 63-17.

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