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BIOLOGICAL CONTROL IN WESTERN AUSTRALIA.

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CONTENTS.

INTRODUCTION.

No method of combating pests has appealed so generally to the popular fancy as that usually known as biological control. This is readily understandable for it involves the use of one creature to subject another and reduces to a minimum all manual labour. Despite their general appeal, the principles

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of biological control are by no means generally understood, and the very popularity of the method sometimes leads to the appearance of the most extravagant claims or unreasonable criticisms.

Many of the most outstanding successes with biological control have been achieved under insular conditions. The Hawaiian Islands are probably the best examples followed by Fiji and New Zealand.

Where pests have become widely established on a continental land mass, the chances of successfully introducing parasites are seriously limited. The new environment presents such a complex of factors to be contended with, biotic, climatic and physiographic, that no single parasite or predator is likely to be of more than local significance. This does not mean that successes have not been achieved on large land masses such as America and Australia, but in these instances, the introductions have been made into areas which may be regarded as distinct ecological entities. South Western Australia is generally recognised as an ecological island and possessing a warm equable climate and a certain degree of physiographic isolation, it conforms with the main requirements necessary for the successful establishment of parasites.

The first definite experiment along the lines of biological control is reported to have been made in 1873 (Imms. 1937) when Planchon and Riley introduced an American predatory mite (*Tyroglyphus phylloxeræ* Riley) into France to try and combat the growing menace of *Phylloxera vitifoliæ* in French vineyards.

Parasite introduction received its first real stimulus from the subjugation of the Cottony-cushion scale (*Icerya purchasi*) following the mission of A. Koebele to Australia and the transference to the United States of the ladybird *Rodolia cardinalis*.

The appointment in 1901 of George Compere (Essig. 1931) to collect parasites and make investigations into problems of biological control on behalf of the Western Australian Government, marks the commencement of a period of very active local interest in this branch of insect control and one which has been keenly maintained up to the present day. In 1904 it was arranged for Compere to collect jointly for the Californian and West Australian Governments and his services were retained until 1910 when he returned to California.

Prior to Compere's appointment, however, several attempts had been made to acclimatise useful insects. As early as 1895 (Anon 1895) it was suggested that local parasites and predators be exchanged for insects to control woolly aphis, cabbage aphis and coccids and the first local introduction was the ladybird *Leis conformis* by Claude Fuller in 1896 (Anon 1901). Compere spent much of his time travelling and collecting, his specimens being forwarded to Newman at the West Australian Department of Agriculture for breeding and distribution. Surprising as it may seem the early exponents of biological control did not receive general commendation and in some instances were the subject of ill-conceived abuse. The late W. W. Froggatt (1909) rather bitterly attacked some of Compere's work and strongly refuted many of the claims made on behalf of biological control.

The ensuing pages comprise an account of the various attempts at parasite and predator introduction into Western Australia.

The information has been gleaned from all possible sources including many unpublished manuscripts. Where possible the information given in these early records has been checked by reference to subsequent literature and specimens in various collections. In many cases, however, the original meagre statements cannot in any way be amplified.

Unsatisfactory as such information may be from many points of view, it is felt that the following details may serve a useful purpose in the planning of future biological control programmes. A knowledge of what insects have already been tried and their subsequent fate must be of paramount importance in considering new projects and it is with this consideration in mind that the following data are presented.

LITERATURE.

Anon 1895 "Beneficial Insects," *Journ. Bur. Agric. W. Aust.*, Vol. 2, p. 499.

Anon 1901 *Journ. Dept. Agric. W. Aust.*, Vol. 3, p. 143.

Essig, E. O. 1931 "A history of Entomology," Macmillan (N.Y.), p. 375.

Froggatt, W. W. 1909 "Report on Parasitic and Injurious Insects," N.S.W. Dept. Agric. p. 56, *et seq.*

Lea, A. 1895 "Exchanging Useful Insects," *Journ. Bur. Agric. W. Aust.* Vol. 2, p. 564.

Imms, A. D. 1937 "Recent Advances in Entomology," J. and A. Churchill Ltd., London, p. 370.

Imms, A. D. 1937A, *ibid.* p. 395.

Newman, L. J. 1909 "Beneficial Parasites," *Journ. Dept. Agric. W. Aust.*, Vol XVIII., p. 380.

Olliff, S. A. 1895, "A New Western Australian Lady-bird," *Journ. Bur. Agric. W. Aust.*, Vol. 2, p. 313.

Order. COLLEMBOLA.

F. SMINTHURIDAE.

Sminthurus viridis Linn. (Clover Springtail or Lucerne Flea).

The Clover Springtail is believed to have reached Western Australia in 1910 (Newman 1910) per medium of baled fodder imported into the State from South Australia. Since that date it has spread rapidly through the South-West, its distribution being bounded roughly by the 15 isohyet, although the principal damage is done within the 19 in. rainfall line where the subterranean clover pastures are established.

On account of the large areas involved, artificial control measures never offered a practical solution to the problem, so cultural and biological methods seemed the most worthy of investigation. The biological aspect of Lucerne Flea control came into evidence in 1931 when the Bdellid Mite [*Biscirus lapidarius* (Kramer)] was discovered at Waroona (Newman and Womserley 1932).

Since then, colonies have been distributed to all parts of South Western Australia where the flea is troublesome, as well as to South Australia, Victoria, New South Wales, Tasmania, and New Zealand.

The mite established itself most readily in the higher rainfall areas and for some time it appeared doubtful as to whether it would gain a footing in the comparatively dry Avon Valley districts (Newman 1934). In recent years, however, it has increased greatly in these regions, with apparently beneficial results.

An account of the biology of the mite is given by Jenkins (1935) showing that the creature passes over the summer in the egg stage. Discussing the population density of *Sminthurus* and *Biscirus*, on a small area intensively studied over a period of 2 years, Norris (1938) states " The impression was gained in the field that *Sminthurus* diminished in numbers at the end of the season long before the meteorological conditions were sufficiently adverse to account for the fall whilst *Halotydeus*, though even more susceptible to conditions of drought and high temperatures was still present in large numbers. It seems possible that the Bdellid was at least partly responsible for this early decline."

LITERATURE.

Anon, 1930 *Journ. Coun. Sci. Ind. Res.*, (Aust.) iii, p. 189.
Currie, G. 1934. *Ibid.* vii, p. 9.
Davidson, J. 1934 *Coun. Sci. Ind. Res.* (Aust.) *Bull.* p. 79.
Holdaway, F. G. 1927, *Coun. Sci. Ind. Res. Aust. Pamphlet* 4.
Jenkins, C. F. H. 1935 *Journ. Dept. Agric. W. Aust.* 2nd ser. Vol. XII., p. 342.
Maclagen, D. S. 1932. *Bull Ent. Res.* Vol. XXIII., p. 182.
Newman L. J. 1910, *Ann. Rept. Dept. Agric. W. Aust.* p. 46.
Newman, L. J. 1927. *Journ. Dept. Agric. W. Aust.* 2nd ser. Vol. IV., p. 78. 449.
Newman, L. J. 1934. *Ibid.* Vol. XI., p. 100.
Newman, L. J. and Womersley, H. 1932, *Ibid.* 2nd ser. Vol. IX., p. 289.
Norris, K. R. 1938, *Coun. Sci. Ind. Res. Aust. Pamphlet* 84.
Womersley, H. 1933, *Journ. Coun. Sci. Ind. Res.* (Aust.) Vol. 6, No. 2, p. 83.

Order. HEMIPTERA.

F. PENTATOMIDAE.

Nezara viridula (Linn.) (Green Tomato Bug.)

This introduced bug was first reported within the State at Bunbury in 1920. Since then, it gradually spread throughout the lower South West to become a serious vegetable pest. Artificial control measures have never proved very satisfactory owing to the robust nature of the insect, and several experiments with parasite introductions have been made.

The first attempt at biological control was made in 1932 when Newman obtained from the Florida Agricultural Experimental Station, two consignments of a tachinid fly (*Trichopoda pennipes* F.). In both instances no living material survived the journey.

In 1933 from Dr. Priesner of Egypt, Newman obtained a few rafts of bug eggs parasitised by the Scelionid *Microphanurus basalis* Woll. and from the 30 wasps which emerged, a nucleus colony was formed (Newman 1934).

During 1934 about 1,000 wasps were distributed and parasitised material was regained in the field. The wasp carried over the winter as an adult in the laboratory and survived successfully in the field as parasitised material was obtained from several localities in the spring of 1935.

In 1935, 30,000 and in 1936, 20,000 parasites were distributed and the insect is now widely established. A marked decrease in the importance of the pest has been noted since the establishment of the Egyptian parasite.

Microphanurus has been reared from the eggs of *Oechalia consocialis* and the Pittosporum bug (*Apines geminata*) in Western Australia.

LITERATURE.

Newman, L. J. 1934, *Journ. Dept. Agric. W. Aust.* Ser. 2., Vol. XI., p. III.
Newman, L. J., *Ibid.* Vol. XI, p. 573.
Newman, L. J., *Ibid.* Vol. XI, p. 434.

F. JASSIDAE.

Typhlocyba froggatti Baker (Apple leafhopper).

The apple leafhopper is a native of Europe which has now become established in many apple growing countries of the world.

It was first recorded in Australia in 1918 but did not reach Western Australia until 1938 when it was reported at Bridgetown.

Artificial control measures employing nicotine sulphate and D.D.T. have proved very satisfactory but an attempt to establish a wasp parasite was considered justified. *Anagrus armatus* Ashm. was successfully introduced from New Zealand by Dr. J. Evans of the Tasmanian Department of Agriculture and parasitised overwintering eggs were obtained from this source in 1943.

The wasps were liberated at Bridgetown in October, 1943, but so far there is no evidence of their having become established. Arrangements are in hand for further introductons to be carried out.

LITERATURE.

Jenkins, C. F. H. 1943, *Journ. Dept. Agric. W. Aust.* ser. 2, Vol. XX., p. 194.

F. APHIDIDAE.

Brevicoryne brassicae Linn. (Cabbage Aphis).

Several attempts have been made to control cabbage aphis biologically and, although complete success has not been attained, the pest has been greatly reduced. The chief controlling factor is recorded as being a hymenopterous parasite obtained from Ceylon, twenty four having been originally introduced by George Compere in 1907 (Robinson 1908). Two Coccinellids and two hymenopterous parasites (one possibly being *Diaeretus rapæ* Curt.) were also introduced by Compere from Eastern Australia in 1902 (Compere 1902 and Anon 1906). *Orcus chalybeus* Bd. became established, but O. *lafertei* Mls. did not survive. Lea (1897) referred to the Cabbage Aphis as the " worst enemy that the cabbage has." Newman (1934) says " the position is greatly improved by the introduction of parasites from the Orient."

So far it has not been possible to check the identity of the hymenoptera involved.

LITERATURE.

Compere, G. 1902, " Introduction of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. VI., p. 238.

Despeissis, A. 1906, " Acting Director's Report," *Ibid.* Vol. XIV, p. 327.

Lea, A. M. 1895, *Journ. Bur. Agric. W. Aust.* Vol. 2, p. 551.

Newman, L. J. 1907, " Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aust.* Vol. XV., p. 918.

Newman, L. J. 1934, *Ibid.* 2nd ser. Vol. XI., p. 203.
Robinson, J. 1909, *Journ. Dept. Agric. W. Aust.* Vol. XVII., p. 683.
Smith, J. H. 1945, *Journ. Queensland Dept. Agric.* Vol. 62, p. 341.

Eriosoma lanigera. Hausm. (Woolly Aphis).

When this aphis reached Western Australia is not definitely known, but as early as 1895 (Lea 1895) it was recorded as "widely distributed throughout Western Australia and one of the most serious pests which the apple grower has to contend with." The suppression of the aphis by the wasp *Aphelinus mali* Hans. is one of the most outstanding local achievments in biological control. The parasite was introduced into the state in 1923 from New Zealand with the co-operation of Dr. Tillyard of the Cawthron Institute. The first experiments were carried out in an orchard at Guildford and subsequently the insect was distributed to orchardists throughout the South West. Before the introduction of *Aphelinus* several routine spray treatments failed to control the Woolly Aphis in the principal apple growing districts whereas now, artificial treatments for the pest are seldom necessary.

Lady-birds (*Leis conformis*) also plays a part in the control of this pest and the first colony was introduced into the State from Tasmania as early as 1896 by Claude Fuller (Breen 1906 and Despeissis 1901). Further introductions were made by Lea in 1901 (Anon 1901A) and Hooper in 1902.

LITERATURE.

Anon, 1901, "Scale Eating Lady-birds." *Journ. Dept. Agric. W. Aust.* Vol. III., p. 143.
Anon, 1901A, "Introduction of Lady-birds," *Ibid.* Vol. IV., p. 15.
Breen, D. 1906, "Lady-birds and Woolly Aphis," *Ibid.* Vol. XIII., p. 447.
Despeissis, A. 1906, "Acting Directors Report,"*Ibid.* Vol. VI., p. 327.
Lea, A. M. 1895, *Journ. Bur. Agric. W. Aust.* Vol. 2, p. 515.
Newman, L. J. 1924, *Journ. Dept. Agric. W. Aust.* Ser. 2., Vol. 1, pp. 41 et 481.
Newman, L. J. 1924, *Ann. Rept. Dept. Agric. W. Aust.* p. 21.
Newman, L. J. 1926, *Journ. Dept. Agric. W. Aust.* Ser. 2, Vol. III., p. 486.

Toxoptera aurantii. Fons. (Black Orange Aphis).

Although no economic control has been obtained, the Woolly Aphis parasite (*Aphelinus mali* Hans.) has been reared from *T. aurantii.*

Unspecified species of hymenoptera were introduced by Compere from Algeria in 1906 and from Ceylon in 1907 and 1909 against "Black aphis" presumably *T. aurantii.* The parasites failed to become established.

Macrosiphum rosae Reaum (Rose aphis.)

Compere forwarded some unspecified species of syrphids from the Philippine Islands in 1907 to combat this aphis, but the predators failed to establish.

Aphididae (unspecifi d.)

Compere, Lea, and Fuller introduced a number of aphis parasites and predators concerning which little accurate detail is available.

Table I shows what is known of these introductions:—

TABLE I.

Parasite or Predator.	Introduced From.	Introduced By.	Date Introduced.	Where Liberated.	Number Liberated.	Subsequent History.
Coccinellid	Marseilles	Compere	1904	Metropolitan Area	....	Established
Coccinella californica Man.	California	do.	1906	do.	328	Failed
Rhizobius sp.	Queensland and New South Wales	do.	1902	do.	....	?
Hippodamia convergens Guer.	California	do.	1906	do.	471	Failed
Coccinellid	Italy	do.	1906	do.	22	do.
Do.	India	do.	1906	do.	65	do.
Do. ...	Algeria	do.	1907	do.	8	do.
Verania lineola Fabr.	Eastern Australia	do.	1902	do.	...	do.
Scymnodes lividigaster Muls.	do. do.	do.	1902	do.	...	do.
Syrphid flies ...	Malaga (Spain)	do.	1902	do.	....	do.
Do.	do.	do.	1903	Guildford	2	?
Do. ...	Colombo	do.	1907	Metropolitan Area	10	?
Do. ...	Philippine Islands....	do.	1909	do.	50	?
Coccinella septempunctata L.	Mediterranean	do.	1903	do.	...	Failed
Hymenoptera	Algiers	do.	1906	do.	....	do.
Orcus bilunulatus ... (Anon 1901A)	Tasmania	Lea	1901	Swan	....	?
Haylzia mellyii (Anon 1901A)	do.	do.	1901	?	...	?
Coccinellid	Colombo	Compere	1907	Metropolitan Area	25	Failed
Do.	do.	do.	1907	do.	?	do.
Do.	India	do.	1907	do.	50	....
Do. 4 spp.	do.	do.	1907	Metropolitan Area and Goldfields (Kalgoorlie?) and Burracoppin	430	?
Unspecified (Despeissis, 1906)	Queensland	do.	1902	Metropolitan Area	5	?
Do. do.	N.S.W.	do.	1902	Perth and Bunbury	40	?
Do. do.	Seville	do.	1903	Metropolitan Area	4	?
Do. do.	do.	do.	1903	do.	56	?
Do. do.	Algiers	do.	1906	do.	2	?

LITERATURE.

Anon, 1901, "Scale-eating Lady-birds," *Journ. Dept. Agric. W. Aust.* Vol. III., p. 143.

Anon, 1901A, "Tasmanian Lady-birds," *ibid.* Vol. IV., p. 205.

Despeissis, A. 1901 "*Leis conformis* in Western Australia," *ibid.* Vol. IV., p. 348.

Despeissis, A., 1906, *ibid*, Vol. XIV, p. 325.

F. COCCIDAE.

Saissetia oleae (Bern.) (Olive Scale)

This almost cosmopolitan pest has been established in Western Australia for many years. In fact, Lea (1895) suggested that it was an indigenous species, although there appear to be no authentic grounds for this assumption.

For many years, Olive or Black Scale was one of the most serious pests of local orchards (Newman 1909), but successful parasite introductions have greatly reduced the toll taken by this insect.

Several species of parasites have been experimented with over the past 50 years but the three which have proved most successful are *Scutellista cyanea* Mot. *Metaphycus loundsburyi* How. and *Tomocera californica* How.

The results of the recent trials with *Metaphycus helvolus* Comp. must not be taken as conclusive as only a small colony was procured from the C.S.I.R. and satisfactory host material was not available in sufficient quantity to breed a second generation.

Table II indicates the various attempts at insect introduction which have been made in past years :—

TABLE II.

Parasite or Predator.	Introduced From.	Date of Intro-duction.	Number Intro-duced.	Number Liber-ated.	Where Liberated.	Intro-duced By.	Subse-quent History.
Red scutellista	China	1905	3	?	?	Compere	Failed
Do. do.	Timor	1905	....	3	Metropolitan Area	do.	do.
Scutellista cyanea Motsch	Brazil	1904	60	?	?	do.	do.
Do. do.	California	1904	19	19	Metropolitan Area	do.	Established
Do. do.	Capetown	1902	30	30	do.	T. Hooper	Failed
Do. do.	do.	1903	85	85	do.	do.	do.
Do. do.	do.	1902	?	11	Perth and Coolup	Compere	?
Do. do.	California	1903	?	90	Various	do.	Established
Metaphycus loundsburyi How.	Capetown	1902	?	?	Metropolitan Area	T. Hooper	do.
Microterys sp.	do.	1902	?	?	do.	do.	Failed
Do.	do.	1902	?	20	do.	Compere	do.
Tomocera californica How.	N.S.W.	1902	?	45	?	do.	Established
Quaylea whittieri (Girault) = *Hymencyrtus crawi* Ashm. (Essig., 1931A)	do.	1902	?	11	Metropolitan Area.	do.	Failed
**Myiocnema comperei* Ashm.	Queensland....	1902	?	938	51 colonies, various	do.	Established
Aristolochia sp.	Hong Kong....	1903	?	12	Metropolitan Area	do.	Failed
Rhizobius centralis Ericks	Eastern Australia	1902	?	?	do.	do.	Established
Metaphycus helvolus Comp.	Canberra (C.S.I.R.)	1943	No liberations made	?	....	Jenkins	....
Unnamed	Eastern Australia	1903	?	60	....	Compere	?
Do.	South Africa	1903	?	85	....	do.	?
Do. ..	Brazil	1904	?	60	....	do.	?
Do.	California	1904	?	19	..	do.	?
Do.	Canton	1903	?	10	Metropolitan Area	Compere	?
Do.	Hong Kong ...	1903	?	12	do.	do.	?
Do. ..	Capetown	1903	?	83	Various	do.	?
Do.	do.	1903	?	17	Metropolitan	do.	?

*Now considered to be a possible secondary parasite (Essig., 1931B).

LITERATURE.

Anon, 1903, " In Search of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. VII., p. 51.

Anon, 1906, " Saving California's Fruit Crops," *ibid.* Vol. XIII., p. 333.

Compere, G. 1902. " Introduction of Parasites," *ibid.* Vol. VI., p. 238.

Compere, G. 1904, " Black Scale Parasites," *ibid.* Vol. X., p. 94.

Despeissis, A. and Compere, G. 1903, *Dept. Agric. W. Aust., Bull* 4, p. 91.

Despeissis. 1904, " Black Scale and Fruit Fly Parasites," *Journ. Dept. Agric. W. Aust.* Vol. X., p. 172.

Essig, E. O. 1931A, " A History of Entomology," (N.Y. MacMillan), p. 359.

Essig, E. O. 1931B, *ibid*, p. 330.

Harper, 1906, " Introduction of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. XIV., p. 178.

Lea, A. 1895, "Scale Insects," *Journ. Bur. Agric. W. Aust.* Vol. 2. p. 564.

Newman, L. J. 1907, "Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aust.* Vol. XV., p. 914.

Newman, L. J. 1909, "Beneficial Parasites," *ibid.* Vol. XVIII., p. 381.

Aonidiella aurantii (Mask.) (Red Scale)

Red Scale was first reported on citrus in Western Australia from the Metropolitan Area by Lea in 1895. Since that date, it has gradually spread to most of the citrus growing districts of the State.

Various attempts to control this scale biologically have been made and a number of Coccinellids as well as wasp parasites have been introduced. The most successful introduction is the hymenopteron *Aphytis chrysomphali* Mercet, imported by Compere from China in 1905.

The most recent introductions have been made with the co-operation of the Entomological Division of the C.S.I.R., the wasp having been originally obtained from China by the Imperial Parasite Service, Canada.

Comperiella bifasciata How. has long been known as a parasite of the Yellow Scale [*A. citrina* (Coq.)] but it is only in recent years that a race has been detected capable of developing in *A. aurantii.*

In Table III details of the various attempted introductions are set out :—

TABLE III.

Parasite or Predator.	Introduced From.	Date of Intro-duction.	Number Intro-duced.	Number Liber-ated.	Where Liberated.	Intro-duced. By.	Subse-quent History
Coccinellid	China	1905	?	14	Metropolitan Area	Compere	Established
Do.	Jerusalem	1904	?	160	do.	do.	Failed?
Do.	Japan	1907	?	?	do.	do.	Failed
Do.	Ceylon	1907	?	?	do.	do.	do.
Do.	Spain	1907	?	?	do.	do.	do.
Aphytis chrysomphali (Mercet)	China	1905	?	?	do.	do.	Established
Unspecified parasite (Hymenoptera?)	Japan	1907	?	20	do.	do.	?
Do. do.	Colombo	1907	?	50	do.	do.	?
Do. do.	China	1907	?	20	do.	do.	?
7 spp.	do.	1907	?	?	?	do.	Failed
2 spp.	Ceylon	1907	?	?	?	do.	do.
6 spp.	Japan	1909	?	1120	?	do.	?
Comperiella bifasciata How.	Japan	1909	?	?	?	do.	Failed
Do. do.	Canberra (C.S.I.R.)	1943–44	400	1000	Harvey, Sawyers Valley, Gosnells, Metropolitan Area	Jenkins	?

LITERATURE.

Compere, G. 1906, "Red Scale Parasites," *Journ. Dept. Agric. W. Aust.* Vol. XIV., p. 5.

Compere, H. 1936. *Bull. Ent. Res.* Vol. 27., p. 494.

Despeissis, A. 1906, "Acting Directors Report," *Journ. Dept. Agric. W. Aust.* Vol., XIV., p. 326.

Lea, A. 1985, *Journ. Bur. Agric. W. Aust.* Vol. 2. p. 564.

Newman, L. J. 1907, "Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aus'.* Vol. XV., p. 918.

Newman, L. J. 1909, "Beneficial Parasites," *Ibid.* Vol. XVIII., p. 381.

Jenkins, C. F. H. 1945, "The Citrus Red Scale," *Ibid.* Vol. XXII, (2nd Sen) p. 10.

Aonidiella perniciosus (Comst.) (San Jose Scale)

The above pest was first recorded in Western Australia in 1897 (Despeissis 1897 and Fuller 1897). Its presence was so much dreaded that very stringent control measures were at once adopted and infested trees were grubbed and burned.

Attempts at parasite establishment have been made, two introductions from Pennsylvania being reported (Newman 1915). Unfortunately no living material reached this State and the species concerned is not mentioned. Two attempts to introduce hymenoptera from California in 1907 also failed. An unnamed ladybird forwarded by Compere from Spain was liberated (Anon. 1903), but with no better results than the other attempts listed.

LITERATURE.

Anon, 1903, "In Search of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. VII., p. 432.

Despeissis, A. 1897, *Journ. Bur. Agric. W. Aust.* Vol. IV., p. 1290.

Fuller, C. 1897. *Ibid.* Vol. IV., p. 1293.

Newman, L. J. 1909, "Beneficial Parasites," *Journ. Dept. Agric. W. Aust.* Vol. XVIII., p. 380.

Newman, L. J. 1915, Ann. Rept. Dept. Agric. W. Aust. 1914–15, (unpublished).

Aspidiotus sp.

Compere in 1902 introduced a coccinellid *Chilocorus circumdatus* Shon. from Hong Kong. Releases were made in the metropolitan area but without success. In 1903 a batch of 350 coccinellids imported from Seville were also liberated in the Perth area, but were not known to become established.

Coccus hesperidum L. (Soft Brown Scale).

This scale first appeared in local literature in 1894 (Anon. 1894) although the actual date of its introduction into Western Australia is not known. Although not a major pest, it has a wide host range and causes orchardists some inconvenience. Attempts to control this scale biologically have not been successful, but the introductions attempted are itemised in Table IV.

TABLE IV.

Parasite or Predator.	Introduced From.	Date of Introduction.	Number Introduced.	Number Liberated.	Where Liberated.	Introduced By.	Subsequent History.
Scutellista sp.	Philippine Islands	1907	?	....	?	Compere	Failed
Do.	Colombo	1907	?	16	?	do.	do.
Coccophagus lycimnia Walk.	California	1907	?	1500	?	do.	do.
Unnamed parasites (? hymenoptera)	do.	1907	?	?	....	do.	Failed to breed out
Do. do.	N.S.W. and Queensland	1902	83	?	Metropolitan Area	do.	Failed
Do. do.	China	1905	81	?	?	do.	do.
Do. do.	Algiers	1906	....	....	....	do.	All died
Do. do.	China .	1905	....	....	....	do.	do.
Do. do.	Ceylon ...	1907	....	16	Metropolitan Area	do.	?
Scutellista, sp. ..	Ceylon ..	1908	....	....	do.	do.	?
?	Italy and Egypt	1908	....	....	....	....	?
Scutellista and others	China and India	1909	....	....	....	Compere	?

LITERATURE.

Anon, 1894, *Journ. Bur. Agric. W. Aust.* Vol. 1, p. 178.

Despeissis, A. 1906, "Acting Director's Report," *Journ. Dept. Agric. W. Aust.* Vol. XIV., p. 326.

Lea, A. 1895, " Scale Insects," *Journ. Bur. Agric. W. Aust.* Vol. 2, p. 564.

Newman, L. J. 1907, " Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aust.* Vol. XV., p. 918.

Newman, L. J. 1909, " Beneficial Parasites," *Ibid.* Vol. XVIII, p. 381.

Lecanium sp.

In 1909 Compere introduced a Red Scutellista from the Philippine Islands, but it failed to become acclimatised.

Lecanium persicae F. (Vine Scale)

This introduced coccid was first recorded from Perth in 1901. Several parasite introductions have been made and a considerable degree of biological control has been achieved.

The wasp *Aphycus timberlakei* Ishii was introduced from California by George Compere in 1907 and is now well established throughout the South-West.

Four other unidentified species, one from Italy (Anon. 1903), two from France (Despeissis 1906) and one from California were introduced, but without success.

Coccophagus lecani Walk. was also introduced in 1907 from California and 1,500 were released in the metropolitan area, but failed to become established.

Myiocnema comperei Ash. was introduced by Compere in 1902 and, although established, is of doubtful value (Essig, 1931).

LITERATURE.

Anon, 1903, " In Search of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. VII., p. 432.

Despeissis, A. 1906, " Acting Director's Report." *Ibid.* Vol. XIV., p. 326.

Essig, E. O. 1931, " A History of Entomology" (N.Y. MacMillan), p. 330.

Newman, L. J. 1907, " Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aust.* Vol. XV., p. 918.

O'Conner, B. A. 1933, *Ibid.* 2nd Ser., Vol. X., p. 228.

Pseudococcus Spp. (Mealy Bugs)

In 1902, Compere introduced colonies of *Cryptolaemus montrouzieri* Muls. from New South Wales and Queensland and some 1,300 were liberated in the Metropolitan Area. The ladybird is now firmly established and is an important factor in Mealy Bug control.

LITERATURE.

Compere, G. 1902, " Introdiucton of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. VI., p. 238.

Despeissis, A. 1906, " Acting Director's Report," *Ibid.* Vol. XIV., p. 327.

Newman, L. J. 1909, " Beneficial Parasites," *Ibid.* Vol. XVIII., p. 381.

Newman, L. J. 1934, " Entomological Problems," *Ibid* 2nd Ser. Vol. II., p. 203.

Order. COLEOPTERA

F. **BRUCHIDAE.**

Bruchus pisorum Linn. (Pea Weevil).

The pea weevil was first recorded in Western Australia in 1931 (Newman 1932). It is widely distributed in the major pea-growing districts of the South-

West and is a serious menace to the industry. The first attempted biological control was made in 1939 when, through the co-operation of the C.S.I.R., the wasp *Triaspis thoracicus* Curt. was introduced from France.

Approximately 1,000 parasites were reared and liberated at the following localities: Burges Siding, Seabrook, Wooroloo and Muresk. Field recoveries were made from peas harvested the same season at Wooroloo but although peas were planted on that site for two successive seasons no further recoveries were made either there or elsewhere.

In 1942 parasitised bean weevil eggs (*B. obtectus*) were obtained from the U.S.D.A. Bur. Ent. and Plant Quarantine, and further attempts were made to rear *Triaspis*. These were unsuccessful, however, and further introductions were prevented by war conditions.

LITERATURE.

Newman, L. J. 1932, *Journ. Dept. Agric. W. Aust.* 2nd. Ser. Vol. IX., p. 297.

Order. DIPTERA.

F. TRYPETIDAE.

Ceratitis capitata Wied. (Mediterranean Fruit Fly.)

The first record of Fruit fly in Western Australia came from Claremont in 1895. The following year it was found in Perth and by 1897 it had spread to Guildford. These appear to be the first records for the Commonwealth, as N.S.W. did not report the fly until 1898.

This insect is the most serious fruit pest established in Western Australia and strenuous efforts have been made to bring about its subjection by the introduction of parasites. Unfortunately, however, all attempts at biological control have met with absolute failure. The parasites from which the best results were expected were :—

Syntomosphyrum indicum Silv. and *Diachasma tryoni* Com. These wasps and also *Tetrastichus giffardianus* Silv. were reared in large numbers in cages and liberated in the field, but not in a single case was parasitised material obtained as a result of these liberations.

Table V summarises the attempts so far made to control fruit fly by biological means :—

TABLE V.

Parasite or Predator.	Introduced From.	Date of Introduction.	Number Introduced.	Number Liberated.	Where Liberated.	Introduced. By.	Subsequent History.
Staphylinid (*Haamerocera brasiliensis*) (Essig., 1931)	Brazil	1904	?	?	Metropolitan Area	Compere	Failed
Hymenoptera ...	do.	1904	?	?	do.	do.	do.
Syntomosphyrum indicum Silv.	India	1908	?	250,000	Guildford	do.	do.
Hymenoptera	do.	1908	?	?	Metropolitan Area	do.	do.
Diachasma tryoni Com.	Queensland....	1909	?	5,000	Guildford	do.	do.
Tetrastichus giffardianus Silv.	Fiji	1936	50 parasitised pupae	20,000	Metropolitan Area and Darling Range	Newman	do.

As seen from the table, the last parasite tested was *Tetrastichus giffardianus*, obtained from Fiji through the courtesy of H. W. Simmonds. Parasitised pupae were safely imported and a number of generations were reared in captivity, thin slices of orange being used to rear the host maggots. The laboratory colony was kept going until August, 1937, but the overwintering wasps, although apparently well developed, failed to emerge from the pupae and all breeding stock was lost.

LITERATURE.

Baker, C. 1908, "Fruit Fly Parasites," *Journ. Dept. Agric. W. Aust.* Vol. XVI., p. 27.

Compere, G. 1903, "In Search of Parasites." *ibid.* Vol. VIII., p. 518.

Compere, G. 1904, "The Introduction of the Fruit Fly Parasite," *ibid.* Vol. X., p. 68.

Compere, G. 1905, "Fruit Fly Parasite," *ibid.* Vol. XII, p. 6.

Despeissis, A. "Acting Director's Report," *ibid.* Vol. XIV., p. 328.

Essig, E. O. 1931, "A History of Entomology." (N.Y. MacMillan), p. 376.

Hooper, T. 1904, "Black Scale and Fruit Fly Parasites," *Journ. Dept. Agric. W. Aust.* Vol. X., p. 172.

Newman, L. J. 1908, "The Fruit Fly Parasite." *ibid.* Vol. XVII, p. 561.

Newman, L. J. 1909, "Beneficial Parasites," *ibid.* Vol. XVIII, p. 382.

Newman, L. J. 1910, *Dept. Agric. W. Aust. Bull.* p. 38.

Newman, L. J. 1916, *ibid. Bull*, p. 48.

Newman, L. J. 1924, *ibid. Bull.*, p. 122.

F. MUSCIDAE.

Musca domestica Linn. (House Fly)

The only record of any attempt at the biological control of houseflies appears in the Annual Report of the Department of Agriculture and Industries of Western Australia for 1911. (Newman 1911.) Sarcophagid parasites said to control houseflies and blowflies were introduced from Hawaii, where they had been received from Japan. No details are available as to the technique adopted in handling these flies but the insect failed to become established.

LITERATURE.

Newman, L. J. 1911, *Ann. Rept. Dept. Agric. and Ind. W. Aust.*, p. 29.

Siphona exigua (de Meij.) (Buffalo Fly)

The Buffalo fly is believed to have reached Australia about 1825 when the first buffaloes were introduced on to Melville Island. In 1838 they were taken to the mainland and with them, the fly. The possibilities of biological control were discussed by Handschin (1932) and a summary of the life history of *Spalangia* spp. was given.

The parasite thought to be most promising was *S. sundaica* Graham from Java. A special strain of this species was tested by the Council for Scientific and Industrial Research and in March, 1933, a consignment of parasitised pupae were forwarded from Brock's Creek to Twaddle, Government Veterinary Officer stationed at Derby. From 640 parasitised pupae received, a number of wasps were bred and 60 were liberated at Yeeda Station on cattle faeces in a permanent cattle camp. The remainder were kept to breed up further supplies for distribution. In May, further sendings (approximately 3,000 pupae) were received from Brock's Creek and further releases of flies were made. In June more releases were made and in July, Twaddle (unpublished report 1933) writes " approximately 1,900 wasps have been released in the Derby District—Meda Station 1,300 ; Yeeda, 600 to date. On 16th June I released 500 wasps on Roebuck Plains Station, Broome, on the cattle camp at Equire Well. Approximately 300 of this lot of parasites were bred at Derby, the remainder being obtained from Brock's Creek during the month of May."

In July, 1933, Twaddle writes :—

" Owing to the difficulty of breeding buffalo fly pupae at Derby for infection, the further release of these parasites is suspended for the time being."

No published information is available concerning the fate of *Spalangia* but Mr. Twaddle informed me that when he left the district in 1935 there was no sign of the wasp being active and that at no time had it given any signs of permanently establishing itself.

LITERATURE.

Handschin, E. 1932, *Coun. Sci. Ind. Res. Aust. Pamph.* 31.

F. CALLIPHORIDAE.

(Blowflies)

Three parasites have been tested in Western Australia for the purpose of controlling blowflies. In 1927 Newman obtained a consignment of 500 wasps (*Alysia manducator* Panz.) from Sir Guy Marshall, England, but none were reared for distribution.

In 1929 with the assistance of Dr. Miller of the Cawthron Institute an attempt was made to introduce specimens from New Zealand, but again without success. Experiments with a local wasp (*Stenoterys fulvoventralis* Dodd), were conducted for a number of years (Newman and Andrewartha 1930) but although many thousands were artificially reared and distributed, no success was obtained.

In 1915 *Mormoniella vitripennis* Wlk. = (*Nasonia brevicornis* Ashm.) was introduced from N.S.W. but without success (Newman 1915).

LITERATURE.

Newman, L. J. 1915, Ann. Report Dept. Agric. W. Aust. 1914–15, (unpublished).

Newman, L. J. 1928, " Sheep Maggot Fly Parasite," *Journ. Dept. Agric. W. Aust.* Ser. 2, Vol. V., p. 151.

Newman, L. J. and Andrewartha 1930, " Blowfly Parasite," *Journ. Dept. Agric. W. Aust.* Ser. 2, Vol. VII, p. 89.

Order. LEPIDOPTERA.

F. PLUTELLIDAE.

Plutella maculipennis Curtis. (Diamond-backed Cabbage Moth)

It is not known when this pest first gained a footing in Western Australia but it must have been amongst the first introductions as it appears in local literatures as far back as 1897 (Lea 1897). Unpublished records show that several attempts have been made to establish parasites and all available details are included in Table VI.

TABLE VI.

Parasite or Predator.	Introduced From.	Date of Introduction.	Number Introduced.	Number Liberated.	Where Liberated.	Introduced By.	Subsequent History.
Hymenopteron (*Hymenosbosmina rapi* (Cam.))?	Eastern Australia	1902	....	110	Metropolitan Area	Compere	Established
Do. do.	do. do.	1902	....	12	do.	do.	....
? Larval parasites	Malaga	1903	....	24	do.	do.	....
? Hymenopteron	Colombo	1907	....	35	do.	do.	....
Do.	India	1907	....	100	do.	do.	....
Do.	China	1909	....	110	do.	do.	....

It is now considered that the hymenopteron established in 1902 is referable to *Hymenosbosmina rapi* (Cameron). Although this parasite is often very active it does not entirely remove the necessity for artificial control measures.

Additional parasites reared from moth larvae in this state include an undetermined pteromalid and a chalcid believed to be *Chalcis victoriae* (Girault).

LITERATURE.

Compere, G. 1902, "Introduction of Parasites," *Journ. Dept. Agric. W. Aust.* Vol. IV. VI., p. 238.

Despeissis, A. 1906, "Acting Director's Report," *ibid.* Vol. XIV., p. 327.

Hardy, J. E. 1938, "*Plutella maculipennis* Curt., Its Natural and Biological Control in England" *Bull. Ent. Res.* Vol. 29, p. 343.

Lea, A. M. 1897, *Journ. Bur. Agric. W. Aust.* Vol. IV., p. 1419.

Newman, L. J. 1907, "Report of Assist. Entomologist," *Journ. Dept. Agric. W. Aust.* Vol. XV, p. 916.

F. PYRALIDAE.

Hellula undalis Fr. (Turnip Moth)

This moth, like the cabbage moth, was a very early introduction into the State as it was well established by 1897 (Lea 1897).

An unidentified species of braconid was introduced from India by Compere in 1907, but it failed to become established.

LITERATURE.

Lea, A. M. 1897, *Journ. Bur. Agric. W. Aust.* Vol. IV., p. 1419.

F. GELECHIDAE.

Gnorimoschema operculella (Zell.) (Potato Moth)

This world-wide pest first figures in local literature in 1895 (Lea 1895).

It is a major pest both of growing crops and stored tubers. One attempt only at biological control has been made in this State, the wasp *Bracon gelechiae* Ashm. having been obtained from the C.S.I.R. in March, 1944. Approximately 300 wasps were liberated on a potato crop at Harvey and no further work has yet been possible on this problem.

LITERATURE.

Lea, A. M. 1895, *Journ. Bur. Agric. W. Aust.* Vol. II., p. 533.

F. PIERIDAE.

Pieris rapae (Linn.) (Cabbage Butterfly)

The cabbage butterfly was first recorded in Western Australia in January, 1943, and its rapid spread soon indicated it serious potentialities as a vegetable pest.

In December, 1943, twelve butterfly pupae parasitised by the wasp *Pteromalus puparum* Lynn. were obtained from Dr. Evans of Tasmania, who had successfully introduced the insect from New Zealand. 14,000 of this European wasp were reared and liberated the first season, colonies being sent to country and metropolitan districts. The wasp was successfully carried over the winter and a further 40,000 wasps were liberated in the summer of 1944-45 and approximately a similar number in the 1945-46 season.

Although it is somewhat early to make a definite pronouncement on the success of the introduction, the fact that parasitised material has been collected from localities as far apart as Kalamunda and Albany shows that there is every prospect of *Pteromalus* becoming permanently established.

Native parasites found to be attacking this butterfly are *Chalcis ruskini ?* Girault ; *Tricholyga sorbillans ?* (Wiedemann).

LITERATURE.

Jenkins, C. F. H. 1943, " The Cabbage Butterfly " *Journ. Dept. Agric. W. Aust.* Vol. XX, 2nd Ser. p. 35.

THE INTRODUCTION OF VERTEBRATES FOR INSECT CONTROL.

Attempts to utilise various of the higher animals for insect control have been made from time to time and as early as 1897 Helms suggested the acclimatisation of the Mole (*Talpa europaea*). The Hedgehog (*Erinaceus europaeus*) ; the Shrew (*Sorex vulgaris*) and the Toad (*Bufo bufo*). Fortunately his suggestions were not acted upon and the only actual attempt to acclimatise any of the higher animals for the purpose of pest control was made in 1933 when specimens of the Asiatic Cattle Egret (*Bubulcus ibis coromandus*) were imported (Anon. 1933). Twenty of these birds were obtained from London, 18 were liberated in tick infested country and two were retained by the Perth Zoological Gardens. The site chosen for their release was the Leonard River at Kimberley Downs Station, but the birds survived scarcely more than a week, falling an easy prey to hawks and other enemies. Another bird whose introduction into the North has been suggested to combat the cattle tick is the Starling (*Sturnus vulgaris*), but no definite action has been taken and the bird is at present on the prohibited list under the Vermin Act.

LITERATURE.

Anon, 1933 *Journ. Coun. Sci. Ind. Res.* (Aust.), Vol. 6, p. 213.

Helms. R. 1897, " A Proposal for the Acclimatisation of a Few Insectivorous Animals " *Journ. Bur. Agric. W. Aust.* Vol. IV, P. 1129.

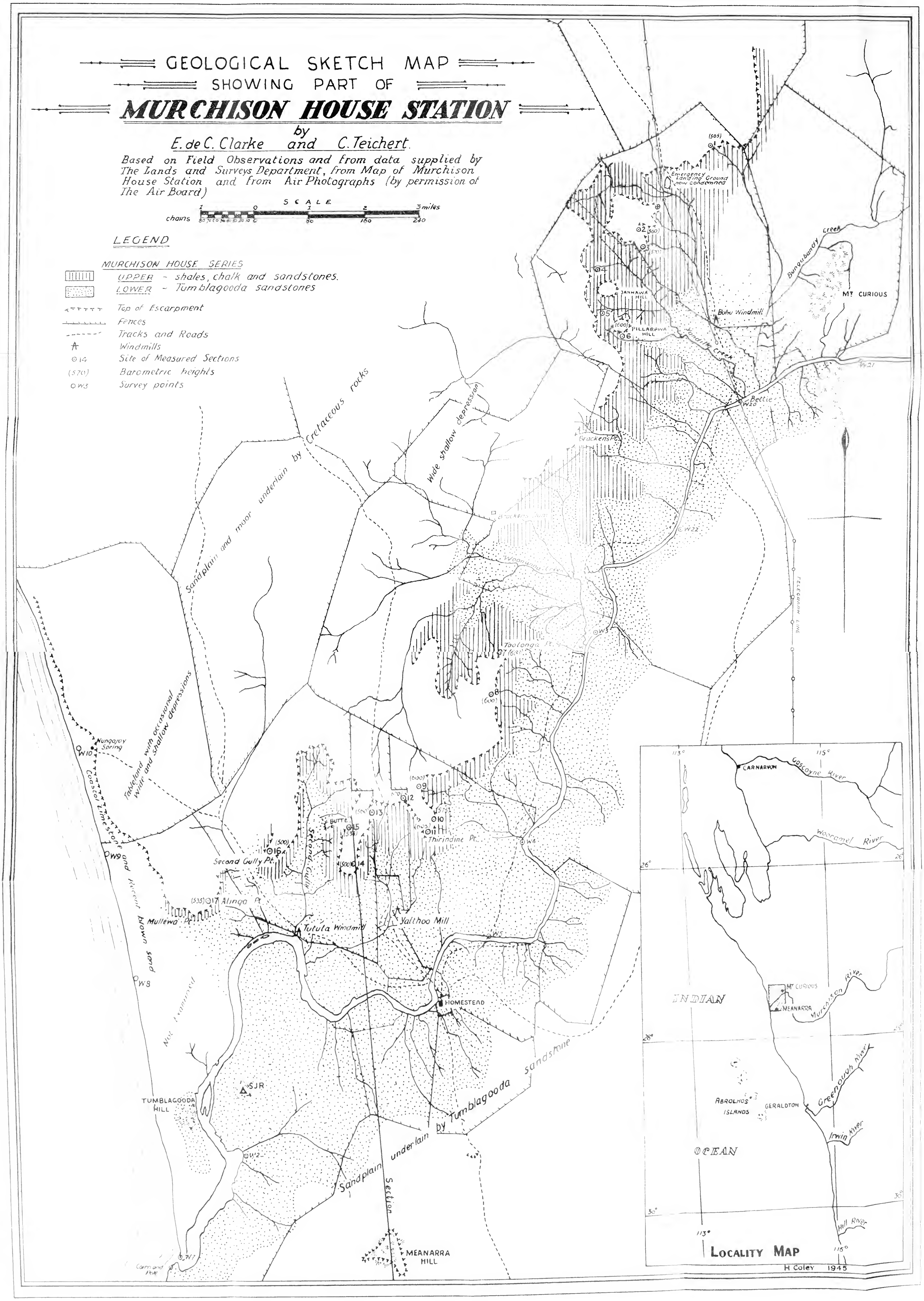
Jenkins, C. F. H. 1935 *Journ. Dept. Agric. W. Aust.* 2nd Ser. Vol. XII., p. 462.

Jenkins, C. F. H. 1936 *Ibid.* 2nd Ser. Vol. XII., pp. 195, 360, 520.

ACKNOWLEDGMENTS.

In the preparation of this paper, I am much indebted to the late Mr. L. J. Newman, whose long association with the entomology of the State rendered his ready suggestions and advice always of very great value.

To Messrs. Toop and Twaddle, Veterinary Officers of the Department of Agriculture, my thanks are due for helpful information concerning stock pests in the northern portions of the State and to Mr. T. G. Campbell of the C.S.I.R. for assistance in identifying specimens.



GEOLOGICAL SKETCH MAP
SHOWING PART OF
MURCHISON HOUSE STATION
by
E. de C. Clarke and C. Teichert.
Based on Field Observations and from data supplied by The Lands and Surveys Department, from Map of Murchison House Station and from Air Photographs (by permission of The Air Board)
SCALE
3 miles
chains
LEGEND
MURCHISON HOUSE SERIES
UPPER - shales, chalk and sandstones.
LOWER - Tumblagooda sandstones
Top of Escarpment
Fences
Tracks and Roads
Windmills
Site of Measured Sections
Barometric heights
Survey points
Emergency Landing Ground now condemned
JANNAWA HILL
PILLARAWA HILL
Buhu Windmill
MT CURIOUS
Bungubandy Creek
Bettie
Brackens Pt.
Sandplain and moor underlain by Cretaceous rocks
Wide shallow depression
Toolonga Pt.
TELEGRAPH LINE
Nungajay Spring
Tableland with occasional wide and shallow depressions
Coastal Limestone and Recent blown sand
Second Gully Pt.
Second Gully
Butte
Thirindine Pt.
Alinga Pt.
Mullewa Pt.
Tutula Windmill
Yalthoo Mill
HOMESTEAD
Not Examined
SJR
TUMBLAGOODA HILL
Sandplain underlain by Tumblagooda sandstone
Section
MEANARRA HILL
CARNARVON
Gascoyne River
Wooramel River
INDIAN
OCEAN
MT CURIOUS
MEANARRA
Murchison River
ABROLHOS ISLANDS
GERALDTON
Greenough River
Irwin River
Hill River
LOCALITY MAP
H Coley 1945

1.—CRETACEOUS STRATIGRAPHY OF LOWER MURCHISON RIVER AREA, WESTERN AUSTRALIA

By

E. DE C. CLARKE AND C. TEICHERT
(Department of Geology, University of Western Australia)

Read: 12th June, 1945.

CONTENTS.

I. INTRODUCTION.

The latest available geological map of Western Australia, published in 1933 by the Geological Survey of Western Australia, shows an area of Cretaceous rocks extending northward from the mouth of the Murchison River almost as far as Shark Bay, that is between 27°40′ and 26°30′ S. lat. As practically nothing was known about the succession, thickness, lithology, and fossils of the rocks in this area it had long been our desire to investigate the geology of the lower Murchison River where good outcrops in these little known strata were reported to exist. After a preliminary visit to parts of the area by the junior author in 1943, our wish was finally realized in August, 1944.

1. PREVIOUS WORK.

As early as 1907 the occurrence of sedimentary strata along the lower part of the Murchison River was noted by Maitland who described how, about 20 miles east of the sea coast the river enters a narrow gorge, flanked by vertical walls of sandstone and grit. "The junction between these sandstones and the older gneissic rocks (to the east), as can be seen by a section on the north bank of the river, is a fault dipping to the west. This sedimentary formation occupies the whole of the Murchison Valley as far as Gantheaume Bay." This fault had been discovered by Maitland on an earlier occasion. In 1898, he stated that in the vicinity of Hardabut Pool, on the Murchison River, sandstones and grits are exposed a few yards from gneissic and schistose rocks and that the junction between the two series is a fault dipping west. However, Maitland did not then realize the extent of the sedimentary area to the west of this fault.

Neither in 1898 nor in 1907 does Maitland give any indication of the possible age of the sandstone series, but in 1919 he referred to it briefly in connection with a description of the Jurassic rocks of Western Australia.

Jutson, in 1934, quoted Maitland's observations and was puzzled by the appearance of a deep gorge in this country. The reason for this, he said, is not apparent.

The first indication of the presence of fossiliferous rocks in the area was in November, 1929, when Mr. L. Glauert of the Perth Museum received some fossils, collected on Murchison House Station. These he found to be identical with species from the Gingin chalk. Nothing was published about this occurrence, except a brief notice in the local press.

In 1932, the country near the mouth of the Murchison River was visited separately by E. S. Simpson and F. G. Forman. Dr. Simpson, who had been attracted by a report of phosphatic rocks, spent a few days at Murchison House, five miles from the mouth of the river, and in 1934 published a note on apatite, barite, and glauconite from these beds. In this connection he stated that the Murchison River flows for about fifty miles through a deep gorge before reaching Gantheaume Bay. "The walls on the south side of this gorge are about 800 feet high and consist essentially of reddish sandstone (Jurassic?). The north side is somewhat higher, the sandstone being overlaid by glauconitic sands and shales, and finally capped by chalk, both of proved Cretaceous age." This latter piece of information was based on an examination by Mr. L. Glauert of some fossils collected by Dr. Simpson, but no fossils were mentioned by name in Simpson's paper.

Mr. Forman crossed the Murchison on camels, travelling from the south towards Shark Bay, but the full report of his trip has never been published. Reference was first made to it in a paper by Hobson in 1936 who says that Forman found Cretaceous sediments overlying a sandstone series, the whole sequence dipping 1° or 2° west. Forman himself briefly referred to his observations in a report in 1937, when he proposed a tentative correlation of the lower sandstones with the Permian Kennedy sandstones which had then become known from Raggatt's investigations (1936) in the Carnarvon Natural Region. He recognised the Cretaceous age of the beds overlying this sandstone series and noted the occurrence, in the vicinity of Mt. Curious, of fossiliferous chalk containing *Trigonosemus*, *Cidaris*, *Inoceramus*, *Ostrea*, and other fossils.

In subsequent years the junior author frequently crossed this same area by aeroplane; the senior author had already seen it from the air in 1927. From these observations it was clear that the lower sandstones which could be seen outcropping all along the bottom and the sides of the Murchison River valley were overlain by a series of whitish rocks which formed an escarpment a few miles north of the river and more or less parallel to it. These white cliffs extended inland at least as far as the telegraph line, more than 16 miles up-stream from the coast, and since Simpson's discovery of chalk in the vicinity of Murchison House Homestead the conviction grew that these cliffs in their entirety were more or less composed of the same kind of rock.

In March 1943 the British Phosphate Commissioners decided to investigate in somewhat greater detail the phosphate occurrences described by Simpson and the junior author was fortunate enough to be invited to accompany the Government Geologist of Western Australia, Mr. F. G. Forman, and the representative of the British Phosphate Commissioners, Mr. J. C. Dulfer, on an exploratory trip which took place in March of that year. The approach to the sedimentary area was made from the east, entering the country from the Northampton-Carnarvon road, but very bad conditions were encountered and it was only with difficulty that the party reached the telegraph line at a small, now abandoned, emergency aerodrome, four miles north of Bettie, where the telegraph line crosses the river. It was soon found that the country was virtually impassable for motor cars and since the party was not equipped for any other form of transport its radius of activity was small and the results of the trip limited. However, the country along the telegraph line was examined in some detail from the river bed as far as the white cliffs in the vicinity of the aerodrome, more than four miles from the river. The lower sandstones were found to be strongly cross-bedded and the cliff section was found to consist of glauconitic sands, glauconitic shales and siliceous shales, overlain by chalk which contained a typical Upper Cretaceous (Senonian) fauna, including *Uintacrinus* and *Marsupites*, identical with the well-known chalk fauna of Gingin, 280 miles to the south. In addition, several localities up to a distance of about 20 miles east of the telegraph line were examined, especially the vicinity of Weerinoogudda Dam, the upper part of Bungabandy Creek, and the country as far as Warranjababba Spring.

2. PRESENT INVESTIGATIONS.

In August, 1944, we were enabled to visit the Lower Murchison River Area and, in the sixteen days at our disposal, we tried to obtain a general picture of the geology of the main valley and its tributaries from the coast to a little beyond the Geraldton-Carnarvon telegraph line. We also saw something of the coastline from the mouth of the river to a point about ten miles farther north.

This work was made possible by an invitation from Messrs. Hubert Evans and A. J. Sims of Evans, Mawley and Sims who provided motor transport from Northampton to Murchison House homestead, a distance of seventy-two miles and, on the return journey, from the homestead to Geraldton, a distance of more than one hundred miles. On arrival at the homestead a native guide, and riding and pack horses were placed at our disposal for the entire duration of our stay. The first week was spent in camp at Bulu windmill with Mr. Tom Pepper and his family whose interest and local knowledge greatly expedited our work. It is our pleasant duty to record here our indebtedness to Messrs. Evans and Sims, to Mr. F. Blood, manager of Murchison House Station, and to Mrs. Blood for their hospitality, and to the others on Murchison House Station who were always eager to help us in our work.

Overlapping vertical aerial photographs, covering the entire area of our survey were made available to us by the Department of the Army. Unfortunately, we did not learn of their existence until after our return from the field. They were, however, invaluable in the final preparation of this report.

3. Geographical Notes.

The Murchison is one of the major rivers of Western Australia and is intermittent, as are all rivers in this State between 18° and 30° south latitude. It rarely floods more than once or twice in a year. It rises about 350 miles inland and after traversing the Pre-Cambrian shield for the first 275 miles of its course it enters an area of sedimentary rocks near Bompas Hill (about 115° 20′ east longitude). Here the river bends sharply and pursues a general south-west course. At Rocky Pool about 45 miles south west from Bompas Hill it enters Pre-Cambrian rocks which persist through Galena to Hardabut Pool, which is about 16 miles south-west of Rocky Pool. Near Hardabut Pool the river turns sharply north and traverses a series of sandstones which is an extension of the Tumblagooda Sandstone described in this paper.

Below Hardabut Pool the river enters a gorge which extends downstream almost as far as Mt. Curious where it turns south-west and flows to the Indian Ocean in a fairly wide valley. On the north-west side of this part of the river the country rises to a plateau about 600 feet above sea-level which breaks off towards the river in a steep scarp about 200 feet high formed of Upper Cretaceous shales, chalk, and sandstone (text figs. 13 and 14). The edge of the scarp is broken by broad valleys (Plate I). Its top is protected by "duricrust," on the average about 15 feet thick which is somewhat discontinuously covered by sand, making the plateau look like a sand plain, although the crust is close to the surface and crops out in many places.

The plateau on the south-east side of this part of the Murchison River is somewhat lower (text fig. 7) probably averaging about 450 feet above sea-level, but Meanarra Hill, an erosion remnant, rises to about 590 feet (text fig. 5). The surface of this plateau is sandy and we did not notice any outcrops of duricrust such as are frequent on the higher plateau. There is, however, a lateritic layer below the sandy surface; this is the laterized top of the Tumblagooda Sandstone which underlies the entire country south of the river mouth and west of the great bend of the river. Good exposures showing the gradual transition from the sandstones to the laterite can be seen in gravel pits close to the point where the road from Murchison Homestead to Ajana reaches the general plateau level. The laterite is overlain by several feet of sand which make very "heavy going" for motor vehicles.

The area which we investigated forms part of Murchison House Station. It can be reached by motor over a very sandy track from Ajana, the nearest railway station, 35 miles to the south. Apart from this track the country is impassable for motor vehicles of the ordinary type.

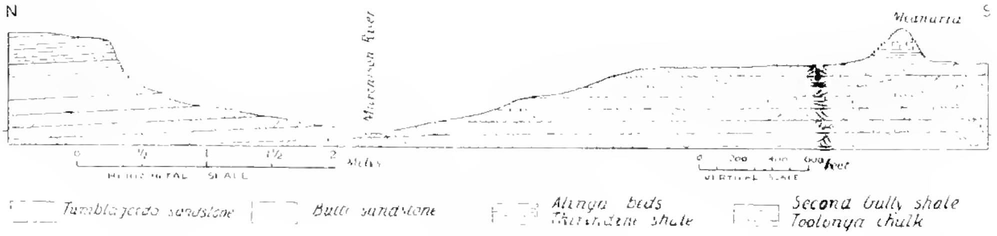
II. GENERAL GEOLOGY.

The Cretaceous rocks fall readily into two divisions; a lower of sandstone, mostly reddish and cross-bedded, and an upper of softer, more easily eroded rocks, such as loosely cemented sandstones, shales, and chalk. As already noted the Murchison River enters a deep sandstone gorge at the point where it leaves the Pre-Cambrian rocks north of Ajana. Some glimpses of this gorge can be obtained from the road leading from Ajana to Murchison House Station, particularly in the vicinity of Pine Thicket rain-shed, about 15 miles N.W. of Ajana and about the same distance S.E. of Meanarra Hill. The valley here is shallow and wide and the river occupies an over-deepened gorge of which only the upper part is visible from the rain-shed. This gorge apparently continues to a point south of Mt. Curious, but farther west the valley widens and erosion has cut more deeply into the lower sandstones all the way from Bettie Crossing to the sea shore.

On the north-western side of the river, in this last part of its course, the strata dip 2–3° to the N.W. Occasional dips of as much as 5° have been measured, but these are exceptional. No dips were measured on the south-eastern side of the river.

South-east of the river in this part the belt of exposed sandstone is not more than a mile wide, and in many places it is less, whereas north-west of the river it is rarely narrower than two miles, and, in many places is as much as four miles wide. This suggests a regional north-westerly dip.

One of the most noticeable features of the sandstone belt on both sides of the river is the jointing. We noticed the presence of many parallel vertical joints but did not have time to study this feature more closely. The influence of jointing on the topography becomes very clear on inspection of the aerial photographs.



Text Fig. 1.

Geological section the Murchison valley from Meanarra Hill to the vicinity of Second Gully (for location see Plate II.).

The strike of the joints is between 130° and 140°. Over wide areas differential erosion has taken place along them and consequently the outcrops are channelled by innumerable parallel furrows. On the photographs it can be seen that they are from about 200 to 400 feet apart. Often they can be followed from deeply eroded into less eroded country, where they may only be indicated as strips of slightly denser vegetation. On the ground we observed the presence of numerous open joints with their walls as much as four feet apart. In many places it seemed that they were due to tensional movements rather than to erosion.

From the air it can be seen that the characteristic N.W.-S.E. jointing becomes less conspicuous a short distance S.E. of Mt. Curious and still higher upstream is completely replaced by a system of prominent E.-W. joints which becomes more and more marked towards the boundary of the sandstone area near Hardabut Pool.

The overlying softer rocks are exposed along an escarpment about two to four miles north-west of the river. They underlie the plain to the north probably as far as Shark Bay. Along the escarpment, gullying is active almost everywhere, and on the whole the escarpment is probably receding at a fairly rapid rate. That this upper series once extended across the river towards the south is shown by the occurrence of these rocks at Meanarra Hill which forms an erosion remnant about four miles south of the river (text fig. 5).

The escarpment on the north side approaches the sea coast about five miles north of the mouth of the Murchison River, where it turns in a direction more or less parallel with the coast. The distance between the top of the escarpment and the shore is at first a mile or so, but diminishes gradually until, north of Nungajay Spring, it is not more than about 500 yards. Exposures along the coast are exceedingly poor owing to a covering of slipped duricrust on the slopes. There are chalk exposures in a few places, but the nature of the overlying and underlying beds can rarely be ascertained.

Text Fig. 2.

View across lower part of Second Gully from slope below Alinga Point. Lower shelf is Tumblagooda Sandstone partly covered with loose sand, probably disintegregrated Butte Sandstone. In the distance is the scarp of the upper part of the Murchison House Series (Alinga Beds to Second Gully Shale). (Traced from photographs.)

III. CRETACEOUS STRATIGRAPHY.

(Murchison House Series.)

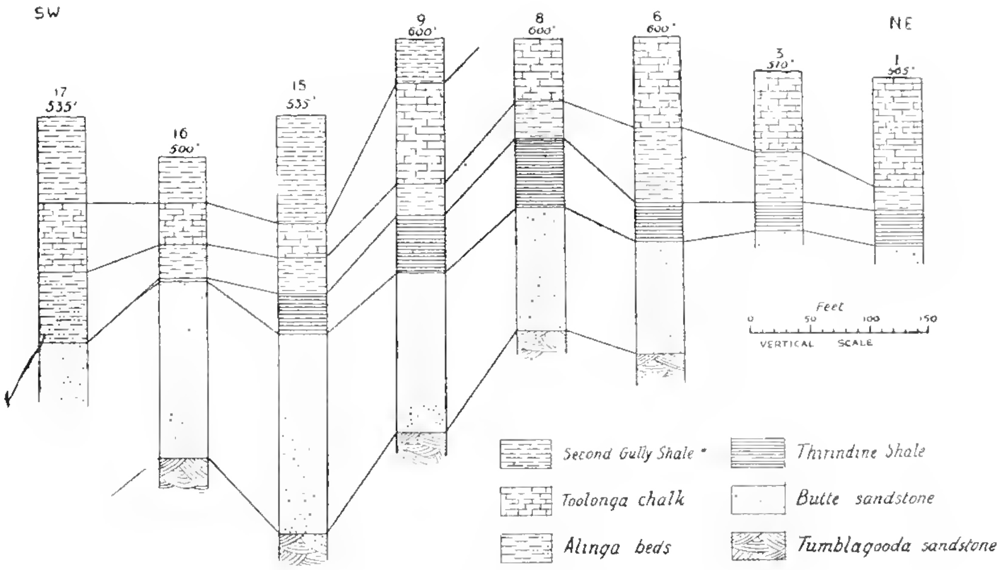
1. GENERAL.

The name Murchison House Series is here proposed for the succession of sedimentary rocks which occurs on both sides of the Murchison River from the coast of the Indian Ocean eastwards to at least a few miles east of the telegraph line i.e. for a distance of about 18 miles. The eastern boundary of the outcrop area of this series has not yet been determined. Southwards the sediments disappear a short distance from the river under a cover of loose sand, but outcrops exist along the coast at least as far as Bluff Point (text fig. 6) and very probably they continue still farther to the south. North of the river the sediments likewise are covered by sand, but, along the coast, outcrops were observed to a point ten miles north of the mouth of the river and they seem to extend considerably farther north.

All good outcrops of the series and all sections studied by us occur on Murchison House Station.

The following subdivisions of the Murchison House series are here proposed:—

Name.	Lithology.	Fossils.	Thickness in feet.
Second Gully Shale	Light green glauconitic shales	...	92+
Toolonga Chalk	Mostly pure chalk, sometimes glauconitic; in many places with a 6in. layer of phosphatic nodules at the base and usually rich in chert nodules in the upper part.	Foraminifera, *Cidaris*, *Marsupites*, *Uintacrinus*, *Gryphaea*, *Inoceramus*, brachiopods	35–120
Alinga Beds	Glauconitic shales, often sandy and with greensand pockets, grading into greensand	Belemnites	10–75
Thirindine Shale	Whitish to grey, siliceous shale, sometimes more massive and grading into siltstone	Very poor belemnite fragments, rare	0–63
Butte Sandstone	Predominantly unbedded pure quartz sandstone, mostly loosely cemented or incoherent ("running sand"); uppermost part usually ferruginous and glauconitic	Vertical and oblique burrows, fossil wood (rare)	75–170
Tumblagooda Sandstone	Predominantly reddish and purple sandstones, as a rule strongly cross-bedded, but grading into well-bedded sandstones above	Vertical burrows and invertebrate trails on bedding planes	400+



Text Fig. 3.

Selected columnar sections of the Murchison House Series above the Tumblagooda Sandstone. The positions of these and other measured sections are indicated on Plate II.

Thickness.—Owing to the fact that the base of the Tumblagooda Sandstone is not exposed and also because of the lateral variations in thickness of most of the higher stages of the series, it is somewhat difficult to give a reliable estimate of the total thickness of the Murchison House Series. Near the northern end of Second Gully 355 feet of sediments are exposed above the top of the Tumblagooda sandstone. However, some members of the series, particularly the Toolonga Chalk and the Alinga Beds, are thinner here than elsewhere, so that the total thickness of the beds in other sections might well be somewhat greater. To this must be added the minimum thickness of the Tumblagooda sandstone (400 feet). It may then be concluded that the minimum thickness of the Murchison House Series in the area surveyed by us is at least 750 feet.

2. TUMBLAGOODA SANDSTONE.

Derivation of name.—Tumblagooda Hill, on the coast two miles north of the mouth of the Murchison River, about 290 feet high, where a typical section is exposed.

Areal distribution and outcrops.—The Tumblagooda Sandstone crops out on both sides of the Murchison River (text fig. 4). On the south-east

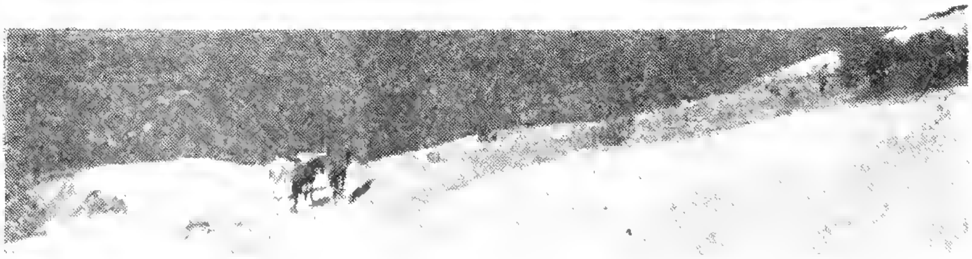
Text Fig. 4.
River flat near Tutula windmill showing hillocks of Tumblagooda Sandstone.

side the outcrops disappear at the edge of the sand plain at about 400 feet above sea level, in most places about a mile or so from the river bed. On the north-west side the belt of outcrops is wider, in places up to four miles wide, and towards the north the Tumblagooda Sandstone disappears under the Butte Sandstone and higher formations. The outcrops are generally good. The sandstone is strongly dissected by erosion and can be studied in numerous cliffs along the river, along hill slopes, and in the many tributaries.

The Tumblagooda Sandstone must have a wide distribution outside the area of our investigations. It seems to form the coastal cliffs as far south as one can see from Tumblagooda Hill and other elevations north of the Murchison River, that is for at least 12 miles as far as and beyond Bluff Point, but probably much farther (text figs. 5, 6, and 7). No outcrops of the sandstone can be seen along the coast north of Tumblagooda Hill, the lower parts of the coastal cliffs being here entirely covered with younger formations (sand and "coastal limestones"). In an easterly direction the Tumblagooda Sandstone certainly continues beyond Mt. Curious—we mentioned under "Previous Work" the deep gorge cut by the Murchison River, and the formation can be followed along Bungabandy Creek and still farther east. It was seen by the junior author in 1943 as far east as Warranjababba Spring, 19 miles E.S.E. of Mt. Curious. Maitland reports that west of Geraldine at Hardabut Pool, in the great southern bend, the sandstone is faulted down against pre-Cambrian rocks, and, though the geology along the Murchison River down-stream from Hardabut Pool to the area which we have mapped has

Text Fig. 5.
View from one of the low hills in Fig. 4 looking south across Murchison River to Meanarra Hill.

Text Fig. 6.
Looking south from sand hills west of Tumblagooda to Bluff Point which is probably Tumblagooda Sandstone.

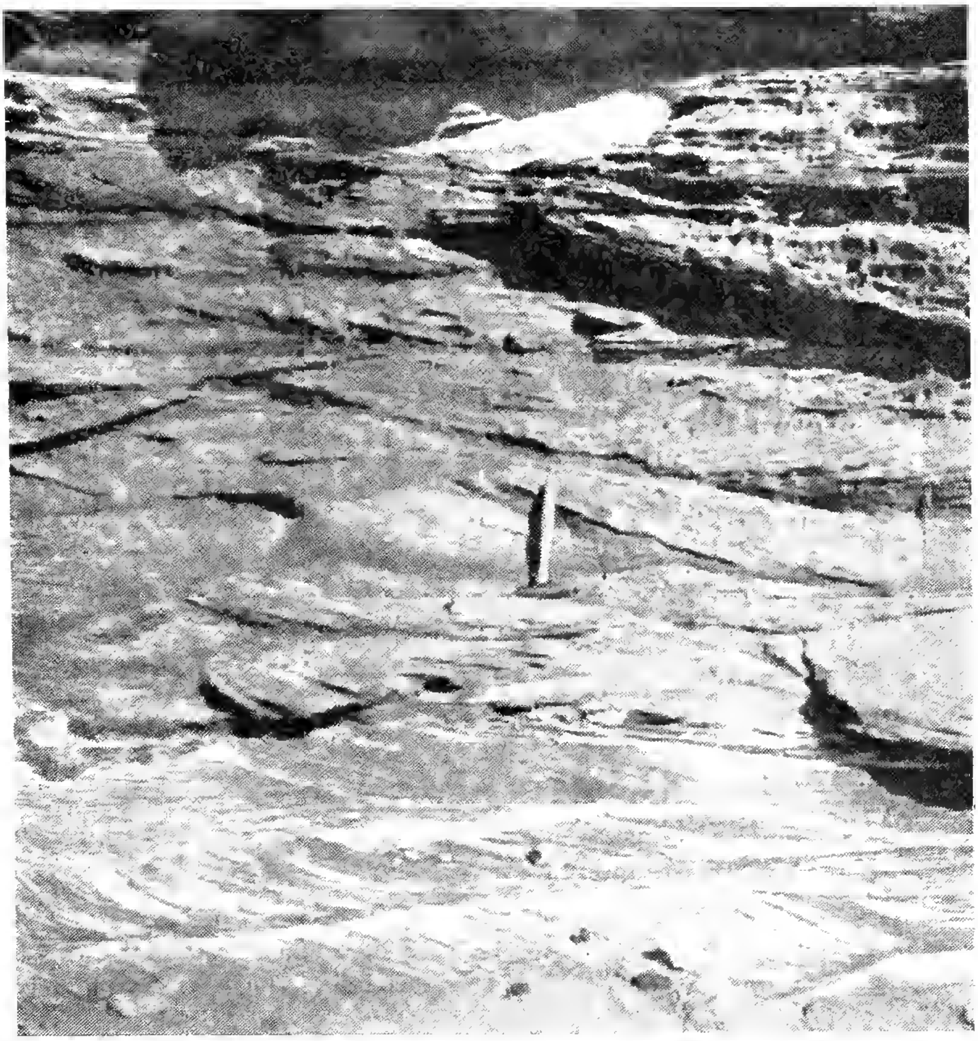


Text Fig. 7.
Looking south-east from the scarp just north of Thirindine over the Murchison valley to the sandplain which is underlain by Tumblagooda Sandstone.

not been studied, from the air it can be seen that outcrops of sandstone are continuous on both sides of the river as far as Mt. Curious.

Scope.—The base of the Tumblagooda Sandstone is not exposed anywhere within the map area. Its upper limit though not as a rule well exposed, is clearly defined by a succession of well-bedded reddish and white sandstones and the contact with the overlying unbedded, incoherent lower part of the Butte Sandstone is sharp and well marked.

Lithology.—Seen from a distance outcrops of the Tumblagooda Sandstone have the appearance of being very thick-bedded, with bedding planes ten or twenty or more feet apart, but closer inspection shows that nearly all these thick beds are very strongly and irregularly cross-bedded (text fig. 8). The bulk of the sandstone is reddish to purplish in colour, but in many places, where it is very finely laminated, white layers alternate with red. On the whole the sandstone is medium-grained



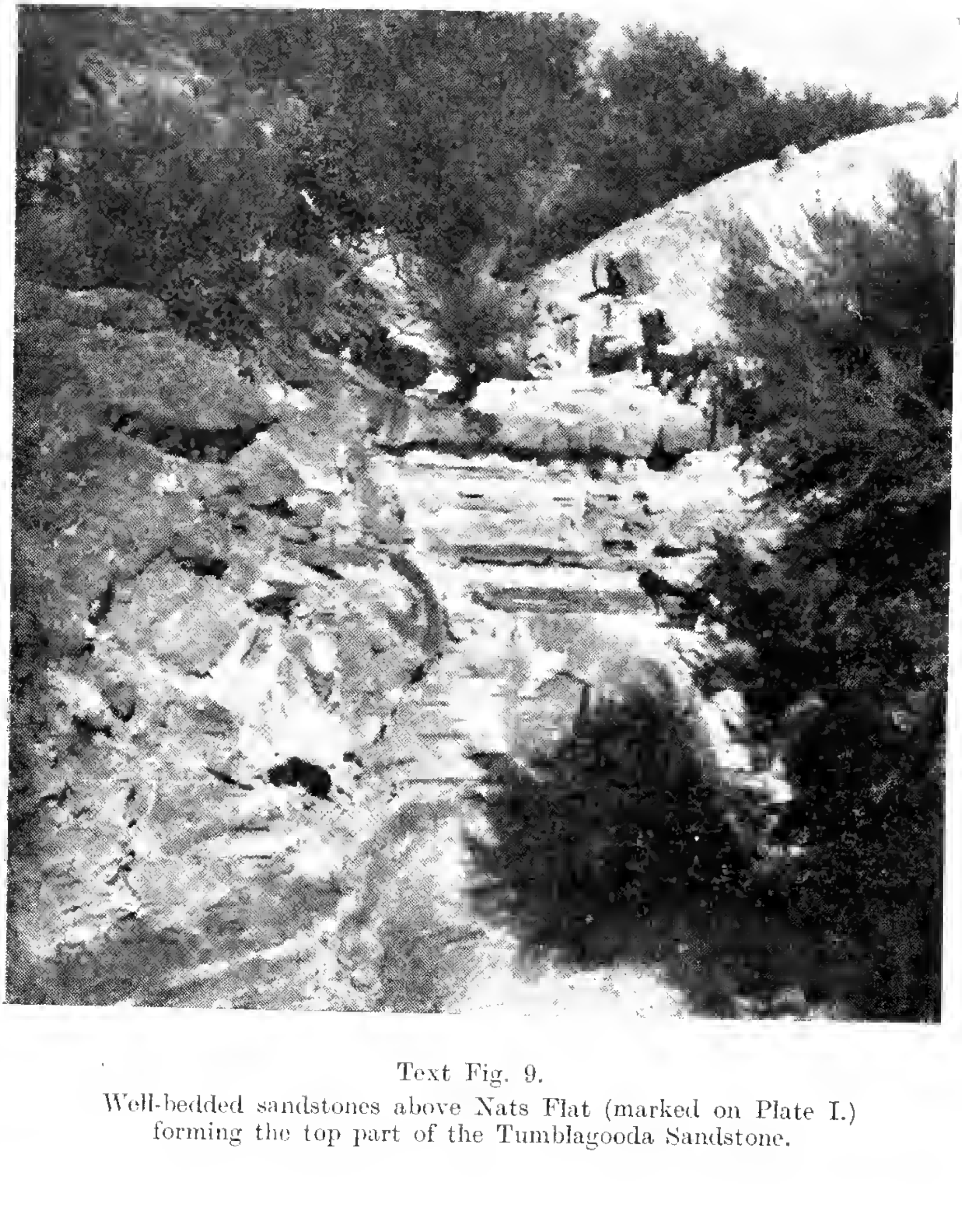
Text Fig. 8.

Typical Tumblagooda Sandstone near foot of east side of Tumblagooda showing cross-bedding and (above and to right of pick) worm burrows. Honeycomb structure in upper right corner is due to weathering, not to worm burrows.

with grains up to 1 or 2 mm. diameter. The components are predominantly quartz grains. Bands of pebbles of varying sizes, up to 1 or 2 cm. diameter are not uncommon, but larger pebbles of several centimetres in diameter are rare. Many of these large pebbles are surrounded by bleached zones as much as 10 cm. wide. Bleached spherical spots of anything up to 2 or 3 cm. diameter may also appear anywhere in the reddish sandstone.

As regards the cross-bedding, the impression was in general that the prevailing dip was in a westerly direction. We had not time to get sufficient data for a thorough statistical analysis, but about 50 measurements in the vicinity of Murchison House Homestead suggest that the source of the sediments, at least in this locality was approximately from the E.S.E. The dip of the cross-bedding rarely exceeds about 20°

Towards the top the cross-bedded sandstones change gradually into well bedded, more shaly sandstones (text fig. 9.) The transition is very gradual: At first a few horizontally bedded sandstone layers are intercalated between strongly cross-bedded strata; then the horizontally bedded layers become thicker and more numerous and frequently shaly, and cross-bedding becomes subordinate; also the red colour becomes less prominent, the horizontally



Text Fig. 9.
Well-bedded sandstones above Nats Flat (marked on Plate I.) forming the top part of the Tumblagooda Sandstone.

bedded layers being either whitish or brown. This transition zone was only seen well in a few places, e.g. in the Pillarawa section and at Second Gully Point, where it is approximately 20 feet thick. In many places detritus derived from the rather incoherent overlying Butte Sandstone conceals the higher part of the Tumblagooda Sandstone. At Tumblagooda Hill itself the upper part of the sandstones is well exposed and here includes a 20-foot band of rather massive brownish, strongly cross-bedded sandstone which is intercalated in the well-bedded series, and makes the transition zone at least 60 feet thick in this place.

The sandstones exposed east of Mt. Curious, in the upper reaches of Bungabandy Creek and in the vicinity of Warranjabahba Spring are fine-grained and thin bedded and cross-bedding is not much in evidence. It is at present impossible to say whether these are exposures of the normal facies of the top section of the Tumblagooda Sandstone, or whether a change in the character of the whole formation takes place in an eastward direction.

Fossils.—The only fossils in this sandstone are invertebrate tracks and vertical burrows. The latter are particularly prominent and occur at many horizons throughout the entire sequence. They were observed in more detail in the vicinity of "Stone Wall" at the foot of Toolonga Point, in the outcrops below the cliffs between Thirindine and Toolonga, in Second Gully, and in the Tumblagooda Hill section where several horizons with many burrows were seen. The burrows now form cylinders which are either filled with sandstone of a different colour from that of the surrounding rock, (for example they may consist of red sandstone penetrating laminated red and white rock), or are merely made evident on cliff sides by differential weathering. They are always vertical and generally have a diameter of one half to one inch, although diameters up to two inches have been observed. They may be up to eight inches long, but are mostly shorter. They are generally restricted to sandstone layers which are two to four feet thick, and there is usually a considerable thickness, rarely less than 20 feet, between successive burrow horizons.

The burrows are frequently rather crowded: in one horizon in the Tumblagooda Hill section 100 burrows were counted on a surface measuring 50 x 50 cm. On the bedding planes the place of a burrow is indicated by a little mound.

Invertebrate tracks along bedding planes have been observed only in one locality, a low hill east of Tutula windmill where the inclined bedding planes of the cross-bedded sandstone are densely covered with meandering trails which are six to eight mm. wide and stand out in low relief above the bedding plane; they are characterized by a sharp furrow in the middle and may have been made by gastropods.

Thickness.—Since the base of this sandstone has not been discovered its true thickness cannot be stated. The plateau level on the south-east side of the river is about 400 feet above the sea and this may be taken as the approximate maximum exposed thickness in the area of our investigations. This, however, must be taken as a minimum figure, for by extending the survey towards the south-east a somewhat greater thickness would probably be obtained.

3. Butte Sandstone.

Derivation of name.—Small prominent conical hill (butte) on south side of Second Gully (text fig. 10), where the greatest thickness (170 feet) of this sandstone was measured.

Text Fig. 10.

Second Gully seen from the north. In the centre is the butte with capping of Thirindine Shale, underlain by Butte Sandstone which extends nearly to the valley floor. The scarp on the other side of the valley consists of Toolonga Chalk and Second Gully Shale. In the foreground is the hardened surface (duricrust) of the latter.

Areal distribution and outcrops.—The Butte Sandstone forms the base of the scarp everywhere north of the Murchison River and can be traced all the way from the telegraph line to Mullewa Point, a mile or so from the coast. From the foot of the scarp there extends a strongly dissected shelf of varying width which is covered with loose sand, consisting, at least in part, of disintegrated Butte Sandstone (text fig 2). Although part of this loose sand may be derived from the top layers of the Tumblagooda Sandstone, the whole of this shelf area has been included on our map in the upper part of the Cretaceous series which begins with the Butte Sandstone. The Butte Sandstone is not exposed along the coast, where it is probably buried under younger deposits of sand and "coastal limestone." There is reason to suppose that it forms the base of Meanarra Hill, south of the Murchison River, but no exposures have been seen.

Scope.—The base of the Butte Sandstone is rarely well exposed, though it is sharply defined by the sudden change from the thin-bedded uppermost layers of the Tumblagooda Sandstone. The upper boundary with the Thirindine Shales is mostly sharp (text fig. 11), though occasionally a more gradual transition can be detected on closer inspection. The

Text Fig. 11.
Butte Sandstone and Thirindine Shale in scarp just west of emergency landing-ground. The boundary between the two formations is marked by X. The top layer of the Butte Sandstone is here somewhat ferruginous and, therefore, harder.

Butte Sandstone thus includes all the strata between the uppermost layer of the well-bedded upper part of the Tumblagooda Sandstone and the base of the grey, siliceous, and mostly whitish-weathering Thirindine Shales.

Lithology.—Lithologically the Butte Sandstone is rather uniform throughout, being generally a whitish, unbedded, and incoherent deposit of quartz grains—in most places, indeed, a "running sand." The quartz grains have diameters of up to 3 mm. In the Toolonga section traces of cross-bedding can be seen, as well as occasional pebble bands with little pebbles not more than about 6 mm. across. In the Thirindine Point section the base of the Butte Sandstone is a deposit of three feet of massive, well cemented, mottled sandstone, with ferruginous patches and large quartz grains. In view of the fact that the base of the Butte Sandstone is in general not well exposed, being buried under loose material slid down from above, it is not known whether this mottled sandstone zone has a very wide distribution.

In the uppermost 10 feet or so the loose quartz sand changes into glauconitic and ferruginous loosely cemented sandstone.

South-west of Toolonga Point, at Thirindine, and in the gully north of Yalthoo windmill there is a somewhat gradual transition to the overlying Thirindine Shales; the quartz sand first becomes glauconitic, and the size of the quartz grains gradually diminishes until the deposit becomes a glauconitic clay; then the glauconite disappears and the transition to the overlying shales is complete. Farther south-west, at Second Gully Point, the boundary with the overlying shales is better marked, the top of the Butte Sandstone being a brown loose sand with ferruginous concretions.

Fossils.—Fossil wood was found in a few places in the uppermost two feet of the Butte Sandstone, notably to the south-west of Toolonga Point and at Thirindine Point. Some of the wood fragments are riddled with cylindrical burrows, probably made by a *Teredo*-like mollusc. Their presence suggests that the wood must have drifted for some time before it became embedded in the sand. Very poor silicified belemnite fragments were found in the cliffs west of the emergency aerodrome four miles north of Bettie. Definitely recognizable tracks and burrows were only seen in one place in the hard quartz sandstone layers near the top of the Butte Sandstone in the Pillarawa section. Vertical and oblique burrows, up to one inch wide, penetrate this sandstone bed to a depth of one to 10 inches. On the bedding plane the entrance to these burrows is surrounded by circular walls which are two to three mm. high. In addition, the bedding plane is covered by a network of shallow, sometimes winding, but more often straight furrows, obviously the trails of some crawling invertebrates. Most of these trails seem to bypass the openings of the vertical burrows, but some issue from them, so that it is reasonable to assume that both burrows and trails have been made by the same kind of animal, most probably a worm.

In the running sand of the Toolonga section long tube-like structures were observed which are about five mm. wide and up to 10 and 15 cm. long and are either vertical or inclined up to an angle of 60°. They are formed of sand grains which are very loosely cemented and are occasionally brought out by weathering, the surrounding matrix being quite incoherent. It is believed that these structures are also due to the activities of some burrowing animals.

Thickness.—The thickness of the Butte Sandstone varies rather considerably. In the Pillarawa section it is about 100 feet, farther east the sandstone is not sufficiently well exposed for measurements of thickness to be taken. Farther west in the Toolonga Hills the thickness increases from 75 to 105 feet in a westerly direction. From there it increases probably rather regularly until it reaches 170 feet at the butte in Second Gully, the maximum thickness measured, and 152 feet at Second Gully Point. At Meanarra there must be about 50 feet of Butte Sandstone.

4. THIRINDINE SHALE.

Derivation of name.—Thirindine is the name of a prominent point in the scarps north-west of the Murchison River, due north of Yalthoo Windmill.

Areal distribution and outcrops.—The Thirindine Shale crops out all along the scarps north-west of the Murchison River. It can be traced almost without interruption from Second Gully Point in the south-west to a point about one and a half miles east of the telegraph line where the outcrops disappear under the vegetation cover and have not been traced farther east. In 1943, however, the junior author located an extensive outcrop area of these shales in the vicinity of Weerinoogudda Dam, about eight to nine miles farther N.N.E., whence it continues for a distance of about six miles to the south-east along the track to Warranjababba Spring as far as a point about six miles north-east of Mt. Curious and about four miles north of Bungabandy Creek, near the eastern boundary of Murchison House Station. From the air it can be seen that good outcrops of the shale extend N.E. and E.N.E. of Weerinoogudda Dam for a distance of three to four miles. In the west, the Thirindine Shale is absent west of Second Gully Point and in the interior of Second Gully, but south of the Murchison River small patches were found on the north side of Meanarra Hill.

Scope.—The Thirindine Shale is always easily recogonizable because it weathers with a whitish surface. Its lower boundary is mostly fairly well defined, although in certain places there is a transition zone, one or two feet thick, from the underlying Butte Sandstone. The upper boundary against the glauconitic Alinga Beds is mostly quite sharp.

Lithology.—The Thirindine Shale is a very fine-grained deposit, usually of greyish colour. In places it consists of alternating softer and harder layers, the latter usually being whiter. However, the softer, greyish layers also harden on exposure and form a whitish surface. This surface-hardening causes the Thirindine Shale to be less easily eroded than the softer sediments above and below, so that it forms a characteristic terrace in the profile of the slopes along which it crops out.

In some places, the shale contains some glauconite. This is particularly marked in the scarp on the north-east side of Second Gully where its glauconite content increases gradually upwards so that there is a transition to the overlying glauconitic Alinga Beds. Glauconite was also observed elsewhere in the Thirindine Shale, for example in the Toolonga Hill section, but it is usually subordinate.

Fossils.—Remains of fossils were found only in the lower part of the shale at Toolonga Hills, where hard bands contain cavities left by belemnite guards which have been dissolved by circulating waters. In places where the shale is glauconitic a peculiar vermicular structure of the sediment was observed which is believed to be due to the action of mud-burrowing organisms, probably worms.

Thickness.—The thickness of the Thirindine Shale varies greatly. In the east, east of the telegraph line, it is 18 feet thick, and just west of the line, near the emergency landing ground, it decreases to five-and-a-half feet, but farther west it increases again until it reaches a maximum of 60-63 feet at Toolonga Hills. At Thirindine it is still 52 feet thick, but from there westward the thickness decreases somewhat irregularly. In the Butte section in Second Gully it is still 35 feet, but at Second Gully Point it has dwindled to three feet and at Alinga has disappeared. At Meanarra this shale is about 15 feet thick.

5. Alinga Beds.

Derivation of name.—Alinga, four-and-a-half miles N.W. of Murchison Homestead, is a prominent point in the chalk scarps, a little more than a mile north of Mullewa Point.

Areal distribution and outcrops.—The Alinga Beds could be followed from Mullewa Point in the west to the eastern termination of our survey area, one-and-a-half miles east of the telegraph line. They form an easily recognizable zone of dark rock between the whitish Thirindine Shales below and the chalk above, but actual outcrops are poor, owing to the softness of the rock. There is much slipping so that it is often difficult to get a correct picture of the lithology of the beds. Gully erosion and subsurface erosion are cutting strongly into this zone and removing large quantities of it. About nine miles to the north-east of the area mapped the junior author found the Alinga Beds overlying the Thirindine Shales at Weerinoogudda Dam where they form the top of the escarpment north of the dam. The Alinga Beds are also probably present at Meanarra Hill south of the Murchison River; no good outcrops have been seen but they most probably occur in a zone with no outcrops between the top of the Thirindine Shale and the base of the chalk.

Lithology.—The Alinga Beds consist of dark green, always strongly glauconitic clays, shales, and sands. In general it seems that sandy components predominate to the north-east and that towards the south-west the beds become increasingly clayey and shaly. At Weerinoogudda Dam, nine miles north-east of our survey area and 21 miles east of the coast, the Thirindine Shale is overlain by greensand which forms an escarpment immediately north of the dam. No higher strata are exposed in this vicinity. Immediately west of the telegraph line, in the vicinity of the emergency landing ground, the Alinga Beds are predominantly shaly, but farther west in the Pillarawa section they are sandy throughout the lower 15 feet, changing into shales above which contain a number of gypseous layers. Still farther west at Bracken's Point the top of the Alinga Beds is formed by reddish weathering clay which changes downward into clayey greensand. In the Toolonga Hill section and to the west thereof the Alinga Beds change into almost pure glauconitic clay which here and there may contain beds or pockets of glauconitic sand such as are well exposed near the butte in Second Gully. At Alinga Point (text fig. 12) the predominating sediment seems to be a very fine sandy clay or shale of very uniform lithology.

Fossils.—The only fossils seen in these beds are belemnites, probably of the genus *Dimitobelus*, which occur in great quantity at Alinga Point, but also at Thirindine Point and in the south-western part of the Toolonga

Text Fig. 12.
Alinga Point. The darker greensands of the Alinga Beds forming the lower part of the slope are overlain by light-coloured Toolonga Chalk.

Hills. The preservation of these fossils is as a rule very poor, the guards weathering easily on exposure.

Thickness.—The thickness is small in the east. East of the telegraph line it is only 18 feet, increasing gradually to about 75 feet in the Pillarawa section. West of this there is again a decrease in thickness to 10 feet near the west end of Toolonga Hills followed by a rapid increase in the cliffs north of Yalthoo windmill to 60 feet. On the east side of Second Gully the thickness has decreased to 25-30 feet and near Alinga it increases again to 55 feet. At Meanarra there are about 22 feet of Alinga Beds.

6. TOOLONGA CHALK.

Derivation of name.—Toolonga Hills is the name of the highest part (about 600 feet above sea level) of the scarp north-west of the Murchison River. This scarp of white rocks is visible from the plateau south of the river many miles away.

Areal distribution and outcrops.—The Toolonga Chalk is widely distributed over the area. It forms the top of the coastal cliffs north of the Murchison River at least as far as several miles to the north of Nungajay Spring, but probably much farther. Outcrops along the coast are not good, because the slopes are everywhere covered with a crust of hard secondary travertine ("duricrust") and the chalk can only be seen in a few places where this hard crust has been removed. North-west of the Murchison River the chalk can be followed along the whole length of the scarps from Mullewa Point in the west to a place about one-and-a-half miles east of the telegraph line and the outcrops are generally very good (Plate I). There is much slumping in the chalk, mainly owing to the slippery nature of the underlying Alinga Beds. The result is that in places the entire slope of the escarpment down almost to the top of the Tumblagooda Sandstone is covered with slumped chalk (text fig. 13). The eastern limit of the Toolonga Chalk has not

Text Fig. 13.
Looking south at the scarp of the upper part of the Murchison House Series from the site of section 3 near north end of Plate II., with Jannawa and Pillarawa Hills in the middle of the picture.

yet been determined. As seen from the air a conspicuous belt of thick scrub which characterizes the top of the chalk scarp, bends sharply to the north-east east of the telegraph line; it is most likely that this marks the edge of the chalk outcrops. Farther east remnants of the chalk may occur in places as, for example, in the duricrust which covers the Alinga Beds on top of the escarpment just north of Weerinoogudda Dam, about nine miles N.N.E. of the eastern end of the area of our survey. South of the Murchison River small outcrops of the Toolonga Chalk occur on the north side of Meanarra Hill.

Scope.—The Toolonga Chalk forms an exceedingly well defined zone. Its lower boundary is rarely well exposed, but when seen (as in text fig. 12), seems to be sharp, though sometimes somewhat undulating. In the eastern half of the area mapped the chalk forms the top of the scarp north-west of the Murchison River, but in the west it is overlain by shales (Second Gully Shales). The boundary is rarely exposed, but in general the transition from the chalk to the shales seems to be rather sudden.

Lithology.—Lithologically the Toolonga Chalk is rather uniform throughout the entire area. It is a yellowish-white, massive, usually rather coherent rock which, however, weathers easily on the surface. At its base it contains in many places a layer of phosphatic nodules, usually not more than six inches thick. The nodules themselves are of irregular shape and are often geode-like, with characteristically cracked surfaces. The lower part of the chalk above the phosphate layer is as a rule very pure and where fossils occur they are usually more numerous in this lower part. In many places the upper part of the chalk is rich in chert nodules which may reach large sizes, measuring six inches and more across. Concentration of chert nodules in the upper half of the chalk was observed especially at Toolonga Hills, but farther west at Alinga Point the chalk is cherty throughout and chert nodules are numerous in the first few feet above the basal phosphatic layer which is here well developed.

Fossils.—On the whole the Toolonga chalk is rather fossiliferous although the distribution of fossils is very patchy and irregular. Fragments of *Inoceramus* shells are ubiquitous, but entire shells are quite rare. As a rule the lower half of the chalk is more fossiliferous than the upper, but this does not hold everywhere because in some sections, such as west of the emergency landing ground, fossils are quite plentiful in the upper half of the chalk. In addition to *Inoceramus* the only common pelecypod is *Gryphaea* ("*Pycnodonta*") *gingineusis* (Etheridge) which occurs in great quantities at Pillarawa and elsewhere. Other common fossils are the brachiopods *Trigonosemus acanthodes* Etheridge and *Magadina cretacea* (Etheridge), and echinoid spines, probably belonging to *Cidaris comptoni* Glauert, of which a few interambulacral plates were also found. Very important members of the chalk fauna are *Marsupites* and *Uintacrinus* whose detached plates are locally very numerous. Of the former genus there are two distinct types of calicular plates: one resembles the common *Marsupites testudinarius* (Schloth.) of the Northern Hemisphere, both the smooth and the ribbed variety being present; the second type of plate is considerably larger and indicates a calyx about twice the size of that of mature specimens of *M. testudinarius*. These plates are always smooth. They might well represent a new species of this interesting genus. Foraminifera are abundant but have not yet been studied.

Following is a list of the non-foraminiferal fauna (preliminary determinations only):

Cidaris comptoni Glauert, *Marsupites testudinarius* (Schlotheim), *Marsupites* nov. sp., *Uintacrinus* sp., *Serpula gregaria* (Etheridge), *Trigonosemus acanthodes* (Etheridge), *Magadina cretacea* (Etheridge), *Gryphaea gingineusis* (Etheridge), *Inoceramus* sp., *Ostrea* sp., *Spondylus* sp., belemnite fragments, *Scillalepas gingineusis* (Etheridge).

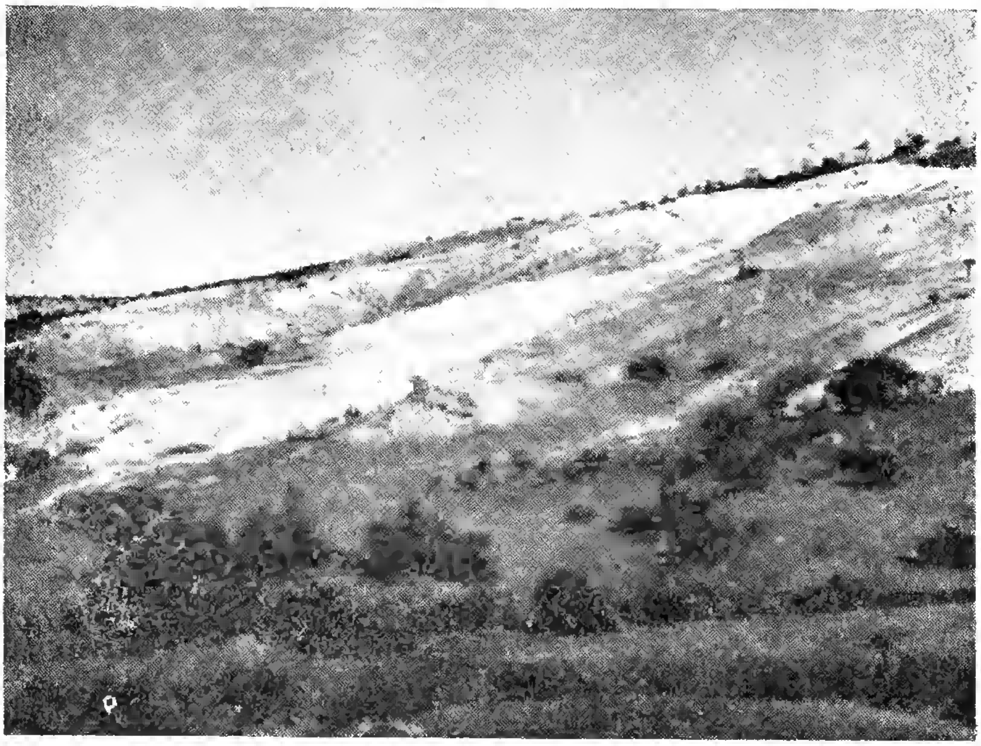
Thickness.—The greatest thickness of chalk, 120 feet, was measured just west of Jaunawa, a small residual hill north of Pillarawa (text fig. 13); of this thickness 20 feet is duricrust and we do not feel quite certain that part of this might not consist of altered Second Gully Shale. However, even in that case the thickness of the chalk cannot be less than 100 feet. East of the telegraph line the thickness of the chalk is slightly more than 90 feet, but west of Pillarawa it decreases to little more than 35 feet at Toolonga Hills. Farther west it increases again to 55 and 65 feet at and near Thirindine. In Second Gully the thickness is again less (25-35 feet), but at Alinga it has increased to 55-60 feet. At Meanara there are about 70 feet of chalk.

7. Second Gully Shale.

Derivation of name.—Second Gully is the name of the valley of one of the northern tributaries of the Murchison River about three miles from the sea coast and due north of Tutula windmill. The shale is well exposed all along the sides of this valley.

Areal distribution and outcrops.—The Second Gully Shale is of somewhat limited distribution. It is absent from the north-eastern half of the area where it has been removed by erosion. Owing to the general westerly dip of the entire sedimentary series it begins to appear above the chalk in the Toolonga Hills section. The outcrops are here very poor, because the thin cover of shales is almost entirely indurated and penetrated by travertine. The appearance of the duricrust is here that of a travertine (or "caliche") in which fragments of porcellanized green shales are embedded. West of Toolonga Hills the thickness of the shales increases, owing to the general north-westerly dip, and they are well exposed in Second Gully, in the valley between Second Gully and the coast, at Second Gully Point, and at Alinga. They probably form the top of the coastal cliffs north of the Murchison River, but the duricrust layer is here very thick and no outcrops of the shale were observed. South of the Murchison River the Second Gully Shale occurs at Meanarra Hill, where it forms the top of the series, but is poorly exposed owing to heavy duricrust formation.

Scope.—The Second Gully Shale forms the highest beds of the Murchison House Series, in the mapped area. Its contact with the Toolonga Chalk is never well exposed, owing partly to induration of the beds near the top of the scarps, partly to heavy slumping of the fine-grained rocks along the slopes (fig. 14).



Text Fig. 14.
Chalk slips in the scarp west of Toolonga. The chalk is *in situ* only near the top of the scarp.

Lithology.—As far as could be ascertained the lithology of this shale is very uniform throughout the area of its occurrence. It is a very fine glauconitic shale which seems to be devoid of any admixtures of other rock types.

Fossils.—No fossils were found in this shale series.

Thickness.—The greatest thicknesses of the Second Gully Shale were measured at Alinga (75 feet), along the east side of Second Gully near the Butte (92 feet) and north of Thirindine (80 feet). From here the thickness decreases eastward owing to the general rise of the strata in this direction. It was not observed anywhere east of Toolonga Hills. At Meanarra Hill, south of the Murchison River, about 45 feet of the Second Gully Shale are preserved.

8. AGE AND CORRELATION OF THE MURCHISON HOUSE SERIES.

The only part of the Murchison House Series which can be accurately dated by means of fossils is the Toolonga Chalk. The occurrence of *Marsupites* and *Uintacrinus* characterizes it definitely as an equivalent of the Santonian stage of the Upper Cretaceous.

As to the remainder of the sequence, more particularly the various sandstone and shale series below the chalk, no definite conclusion can be drawn. From general considerations of the nature of these sediments it seems, however, unlikely that strata of an earlier age than Cretaceous are present. The whole sequence of rocks is conformable and there are no major breaks in the sedimentation processes. On the whole there is a gradual change from coarse-grained near-shore to fine-grained off-shore sediments. The total exposed thickness of beds below the chalk is less than 700 feet to which must be added an unknown thickness of rocks below the lowest exposed beds of the Tumblagooda Sandstone. However, these lower sandstones must have been deposited fairly rapidly and the time represented by them cannot be very long.

From such general considerations it might be concluded that sedimentation in the area began probably not before the beginning of Upper Cretaceous time and certainly not earlier than some time in the Lower Cretaceous.

Contemporaneous deposits are widespread in Western Australia in a coastal belt between about 22° and 31½° S. lat., seldom extending more than fifty miles inland from the shores of the Indian Ocean. The Toolonga Chalk can easily be correlated with lithologically similar deposits at Gingin and at Dandarragan, 60 and 100 miles north of Perth. Chalk deposits occur in these places with a maximum thickness of about 70 feet, carrying a fauna identical with that of the Toolonga Chalk. However in both places the thickness of the Cretaceous beds is smaller and the whole sequence apparently much less complete. Both at Dandarragan and at Gingin the chalk is sandwiched between greensands: a Lower Greensand which is 20 feet thick at Gingin and up to 70 feet at Dandarragan, and an Upper Greensand of which 140 feet are exposed at Gingin and less at Dandarragan (see Clarke, Teichert, and Prider, 1944, p. 274, and Teichert and Matheson, 1944, p. 168). The Lower Greensand is most probably contemporaneous with the strongly glauconitic Alinga Beds of the Murchison House Series, but farther down in the section the parallelism ceases. The greensand-chalk series at Gingin rests on sandstones whose age has recently been determined as Jurassic (Walkom 1944). Below the Lower Greensand at Dandarragan is a series of sandstones (probably several hundred feet) of unknown age, tentatively assigned to the Jurassic by Forman (1935). In both sections there is an abrupt change in sedimentation from these lower sandstones to the greensands underlying the chalk. It would thus seem that these sandstones are not to be correlated with the lower sandstone series (Tumblagooda Sandstone and Butte Sandstone) of the Murchison House Series, but are older, and that no equivalents of the strata below the Alinga Beds are found in the south.

Sandstone which is lithologically similar to the Tumblagooda Sandstone occurs in many places between Geraldton and Northampton, particularly in the vicinity of Oakabella, on the railway line 20 miles north of Geraldton, but no survey of this sandstone area has been made.

Another area of fairly well known Cretaceous stratigraphy, discovered by Raggatt (1936), is situated more than 300 miles north of the Murchison River in the Cardabia Range, south of Exmouth Gulf. Stratigraphical and palaeontological information regarding this district is still fragmentary, but from published accounts (Raggatt 1936, Crespin 1938) it seems evident that there is a considerable thickness (up to 800 feet and perhaps more) of chalk, chalky clays, and marls which underlie a greensand deposit with ammonites of Maestrichtian age (Spath 1940). It would thus seem that much of the chalky deposit is of Senonian age (Campanian and older) and, judging from foraminiferal evidence (Crespin 1938), might also include Turonian equivalents.

From the Cardabia Range the Cretaceous extends southward as far as the Gascoyne River where chalk and other rocks have been recognized in bores. Nothing is at present known about the possible continuation of this Cretaceous belt along the east side of Shark Bay, but in the vicinity of the southern end of Shark Bay there are numerous outcrops of white shale which undoubtedly represent some part of the Cretaceous. That most of the sand plain between Shark Bay and the Murchison River may be underlain by Cretaceous sediments will be pointed out below. It is thus possible that a more or less continuous belt of Cretaceous sediments extends from somewhere south of the Murchison River northward as far as Exmouth Gulf.

IV. GEOLOGICAL HISTORY OF THE AREA.

At some time during the Lower or early Upper Cretaceous an area of some relief must have existed east of the area under review, the coast running somewhere east of 114½° E. long. A large river flowing to the west or west-north-west entered the sea, approximately where the present lower course of the Murchison is situated, and built up a large delta which was gradually pushed westward. The size of this delta was at least 1,000 square miles, though it may have been much bigger. Only some parts of the western half of this delta have been investigated and from the uniformity and smallness of the sand grains one may conclude that, when this part was being built, the river furnishing the sediment drained a wide plain surrounded by hilly country. During this time the sedimentation area must have been subsiding, but so slowly that subsidence lagged behind sedimentation and the delta was gradually pushed out to sea.

As denudation continued, relief was diminished and the supply of sediments decreased. Sinking of the sea-floor continued, deltaic cross-bedding disappeared and fine-grained bedded sandstones were deposited. Further deepening of the area of sedimentation led to the deposition over the entire area of a uniform deposit of medium-grained unbedded quartz sand, up to 170 feet thick, which must have been laid down with great rapidity. Cross-bedding is practically absent from this deposit so presumably it was formed in moderately deep water at least below the zone of wave action and surface currents. Continued deepening of the sea is indicated by the appearance of glauconite in the upper part of the Butte Sandstone which can hardly have formed at depths of less than about 25 fathoms.

The deposition of the following Thirindine Shale indicates further reduction of the relief of the adjoining land or deepening of the sea and retreat of the coastline in an easterly direction. There may have been a combination of both events.

Throughout all this time, since the beginning of the formation of the delta, conditions must have been generally unfavourable for most types of life. Certain types of sand and mud burrowers constituted practically the entire fauna. Occasionally, especially during the closing stages of the deposition of the Butte Sandstone, logs of wood drifted out to sea and were buried in the sand. Some pieces are riddled by wood-borers (*Teredo?*) and must have drifted a long time before they settled down on the sea-floor. Remains of belemnites in the Thirindine Shale are so rare that it seems that they must have drifted there from some more favourable environment.

The sediments which were deposited after the Thirindine Shale indicate clearly a slow, probably more or less continuous deepening of the area of sedimentation. The glauconitic Alinga Beds may have been formed at depths anywhere between 25 fathoms and 100 fathoms, while the overlying chalk seems to indicate a further deepening of the sea below the 100 fathom line. During the time of the deposition of the Alinga Beds the nearness of the coast in the east still affected the nature of the sediments for there seems to be a change from greensands in the east to glauconitic clays and shales in the western part. Belemnites were abundant at this time.

The chalk forms a uniform sheet of sediment and indicates the existence in this area of a moderately deep sea, probably of the order of 100 or 200 fathoms, where a fairly rich neritic life flourished. *Inoceramus* was common, and also other pelecypods, brachiopods, stalkless crinoids, and other forms of life. The transition from the glauconitic Alinga Beds to the chalk is marked by a bed of phosphatic nodules. The chalk was formed during Middle Senonian (Santonian) time. This period was followed by a time of deposition of glauconitic shale which may indicate a slight rising of the sea-floor and a westward advance of the coastline.

The post-Cretaceous history of the area will not be discussed in this paper.

V. EXTENSION OF CRETACEOUS NORTH OF MURCHISON RIVER.

Forman is the only geologist who has traversed the country between the Murchison River and Shark Bay west of the Carnarvon road and he remarks on the almost entire absence of outcrops (Forman 1937), as indeed observations from the air would suggest. Some idea of the geological structure of this area could perhaps be obtained by following the coast north from the mouth of the Murchison River, where coastal cliffs 800 feet high are reported to exist. The nearest known outcrop of supposedly Cretaceous beds farther inland is about 38 miles north of Mt. Curious in the southern part of Cobourn Station where Forman (1937) observed green-sand in a dry soak.

Another 35 to 40 miles farther north there are outcrops of white to yellowish shaly rocks with brown chert bands which form low hills, 40 to 50 feet high, along the road leading to Carnarvon and about seven to 10 miles east of Hamelin Pool. We traversed this area in 1941, but had no time to stop for any detailed examination. The rock seemed to resemble the Thirindine Shale, but lithologically very similar rocks are also known from the Lower Cretaceous Winning Series of the Cardabia Range, 250 miles farther north.

There are many limestone outcrops in the country south of Hamelin Pool, but these are probably Recent travertines. The country has the character of a slightly undulating karst landscape, with weathered limestone ridges about three-quarters of a mile to a mile apart, and red soil accumulating in the depressions.

Our only knowledge of subsurface geology comes from a few scattered sub-artesian bores of which only drillers' logs and no samples are available. Moreover, for most of the bores the heights of the bore sites above sea level are not known.

Of particular interest is a group of bores (Nos. 6, 7, 8 and 10) in the vicinity of Gee Gie Outcamp, on Murchison House Station, about 17 miles north of Nungajay Spring, and about 15 miles N.W. of Mt. Curious. Typical of these is No. 10.

Driller's Log.	Stratigraphic Interpretation.
0– 4 feet yellow sand ... ... 4– 12 feet red sandy clay	Surface deposits, 12 feet
12– 40 feet green clay ... ... 0– 85 feet yellow clay	Second Gully Shale, 73 feet
85–286 feet chalk	Toolonga Chalk, 201 feet
286–334 feet dark shale	Alinga Beds, 48 feet
334–341 feet, sand ... ... 341–343 feet black sandstone	Butte Sandstone, 9 feet

It is not possible from the driller's log to differentiate clearly between the Second Gully Shale and the Toolonga Chalk and it may be that part or all of the "yellow clay" between 40 and 85 feet should rather be included in the Toolonga Chalk. It is of some interest that there is no indication of the occurrence of the Thirindine Shale in these bores. Gee Gie Outcamp is about 15 miles west of Weerinoogudda Dam where considerable outcrops of Thirindine Shale are known to occur, and the disappearance of the shale in a westerly direction is in complete agreement with conditions found along the Murchison River where it peters out in Second Gully as described already in this paper.

No further bore records are available until Cobourn and Boolagoorda Stations are reached, 30 to 40 miles farther north, and it is perhaps inadvisable at this stage to attempt any detailed correlation of the driller's logs in places so far removed from the type section of the Murchison House Series. It is, however, worth recording that all bores here, after penetrating a few hundred feet of soft strata, usually marked as "clay" or "shale," reach sandy layers. In bores on Cobourn Station the first sandy beds were struck at depths below the surface varying from 170 to 373 feet and on Boolagoorda Station at depths between 403 and 450 feet. These sandy beds are mostly described either as "sand" or as "soft sandstone" and it would seem that they are most likely the northern continuation of the Butte Sandstone of the Murchison House Series. In the Shark Bay region the surface of these sandstones seems to dip towards the north-west, for in the centre of Peron Peninsula a bore was put down to a depth of 1780 feet without reaching any sandy rocks at all.

VI. BIBLIOGRAPHY.

Clarke, E. de C., Prider, R. T., and Teichert, C., 1944. Elements of Geology for Western Australian Students. Perth xii + 301 pp.

Crespin, I., 1938. Upper Cretaceous Foraminifera from the North-West Basin, Western Australia. *Journ. Paleont.*, Vol. 12, pp. 391-5.

Forman, F. G., 1935. The Geology and Petroleum Prospects of Part of O.P. 253H, near Dandaragan. *Ann. Progr. Rep. Geol. Surv. W.A. for 1934*, pp. 7-11.

Forman, F. G., 1937. Artesian and Sub-Artesian Water Possibilities, Woodleigh Station, Murchison District. *Ibid. for 1936*, pp. 9-11.

Hobson, R. A., 1936. Summary of Petroleum Exploration in Western Australia to January, 1935. *Ibid. for 1935*, pp. 22-34.

Jutson, J. T., 1934. The Physiography (Geomorphology) of Western Australia *Geol. Surv. W.A., Bull.* No. 95, xvi + 366 pp.

Maitland, A. Gibb, 1898. The Country between Northampton and Peak Hill. *Ann. Progr. Rep. Geol. Surv. W.A. for 1897*, pp. 14-19.

Maitland, A. Gibb, 1907. Possibility of the Occurrence of Artesian Water in the Northampton and Geraldine Districts. *Geol. Surv. W.A., Bull.* No. 26, pp. 7-9.

Maitland, A. Gibb, 1919. A Summary of the Geology of Western Australia. *Mining Handbook, Geol. Surv. W.A., Mem.* No. 1, pp. 1-55.

Raggatt, H. G., 1936. Geology of North-West Basin, Western Australia, with particular reference to the stratigraphy of the Permo-Carboniferous. *Journ. Roy. Soc. N.S.W.*, Vol. 70, pp. 100-74.

Simpson, E. S., 1934. Contributions to the Mineralogy of Western Australia. Series VIII. *Journ. Roy. Soc. W. Aust.*, Vol. XX (1933-4), pp. 47-61.

Spath, L. F., 1940. On Upper Cretaceous (Maestrichtian) Ammonoidea from Western Australia. *Journ. Roy. Soc. W. Aust.*, Vol. XXVI (1939-40), pp. 41-57.

Teichert, C., and Matheson, R. S., 1944. Upper Cretaceous Ichthyosaurian and Plesiosaurian Remains from Western Australia. *Aust. Journ. Sc.*, Vol. VI, pp. 167-70.

Walkom, A. B., 1944. Fossil Plants from Gingin, W.A. *Journ. Roy. Soc. W. Aust.*, Vol. 30 (1943-1944), pp. 201-7.

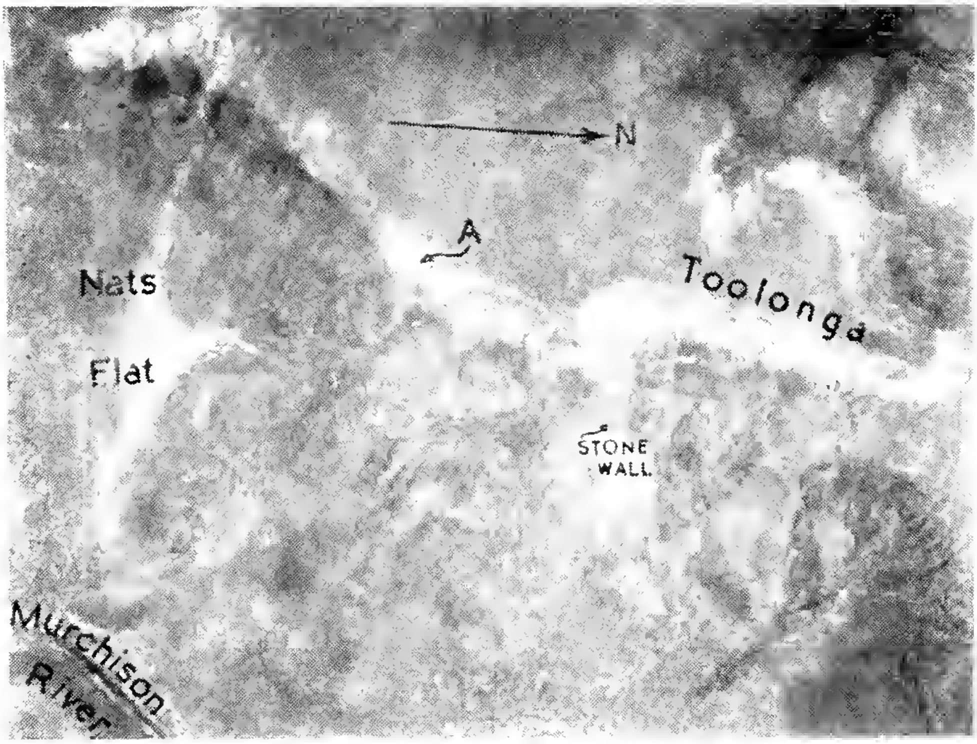
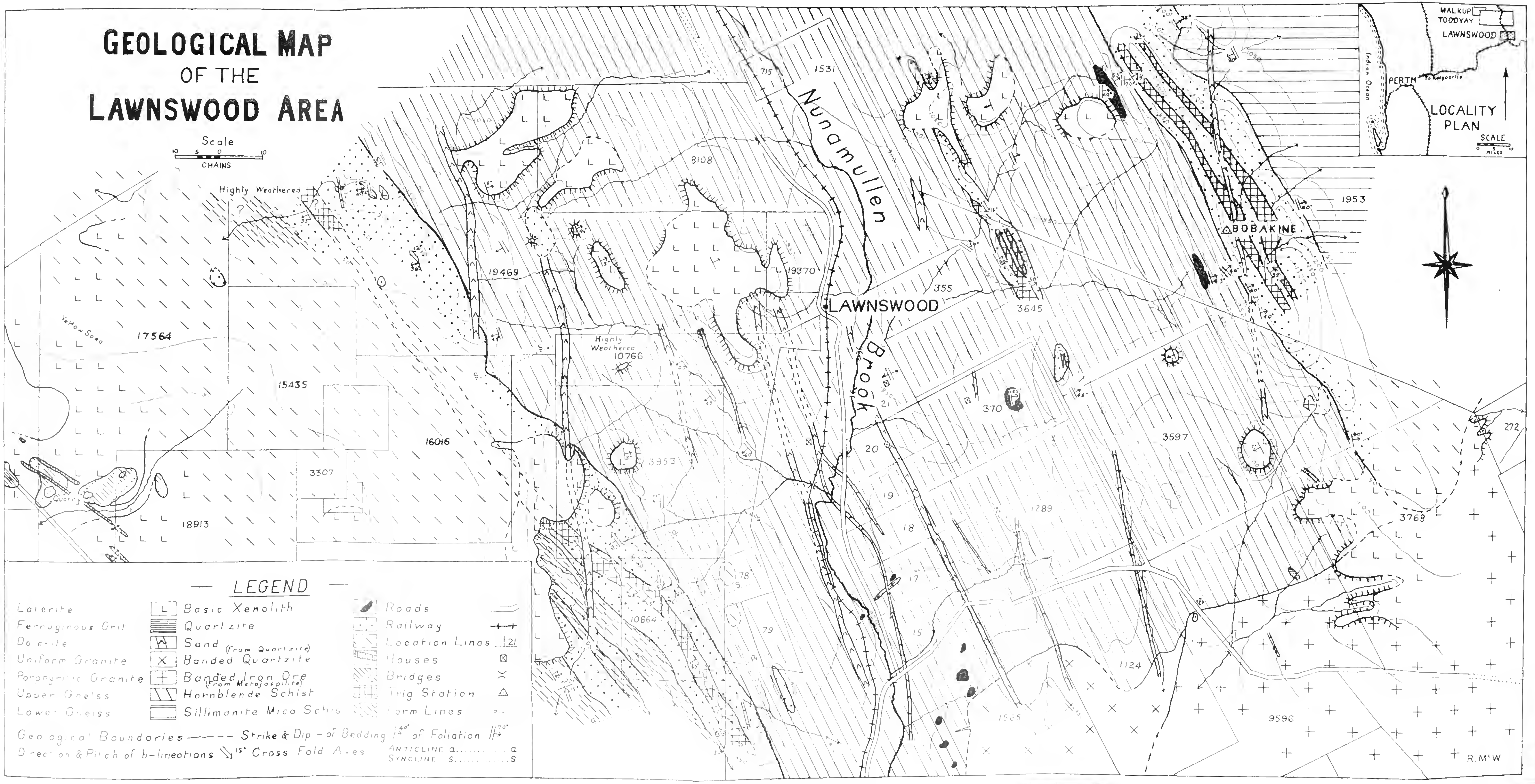


PLATE I.

Vertical aerial view of part of the country north-west of Murchison River, showing the scarp at Toolonga Hills. In front of it is the flat shelf covered with loose sand, here interpreted as Butte Sandstone. The conspicuously jointed rock is Tumblagooda Sandstone. At *A* is the part of the scarp shown in fig. 14 (*R.A.A.F. photo., Published by permission*).


GEOLOGICAL MAP
OF THE
LAWNSWOOD AREA
Scale
CHAINS
LOCALITY PLAN
MALKUP
TOODYAY
LAWNSWOOD
PERTH
Indian Ocean
SCALE
MILES
Nunamullen
Brook
LAWNSWOOD
BOBAKINE
Highly Weathered
Yellow Sand
Quarry
715
1531
8108
1953
19469
19370
355
3645
17564
10766
15435
16016
3307
3953
18913
370
3597
272
1289
3768
10864
1124
9596
1565
LEGEND
Laterite
Ferruginous Grit
Dolerite
Uniform Granite
Porphyritic Granite
Upper Gneiss
Lower Gneiss
Basic Xenolith
Quartzite
Sand (From Quartzite)
Banded Quartzite
Banded Iron Ore (From Metajaspilite)
Hornblende Schist
Sillimanite Mica Schist
Roads
Railway
Location Lines
Houses
Bridges
Trig Station
Form Lines
Geological Boundaries
Strike & Dip - of Bedding of Foliation
Direction & Pitch of b-lineations
Cross Fold Axes
ANTICLINE a
SYNCLINE s
R. McW.

2.—THE GEOLOGY AND PHYSIOGRAPHY OF THE LAWNSWOOD AREA

By

J. R. H. McWHAE, B.Sc. (Hons.).

Read: 12th March, 1946.

CONTENTS.

I. INTRODUCTION.

Lawnswood is situated on the Clackline-Miling railway, three miles north of Clackline and approximately 50 miles in an east-north-east direction from Perth (see locality plan on Plate I.). The Lawnswood Area, which occupies about 10 square miles with the southern boundary less than one mile north of Clackline, is largely composed of early Pre-Cambrian rocks of the Jimperding Series (6, p. 167). This series is composed of pelitic and psammitic metasediments with intercalated layers of acid and basic igneous rocks all of which have suffered sillimanite zone regional metamorphism (26, p. 11; 23, p. 84; 9, p. 168). It extends from York (15 miles south of Clackline) to at least as far north as the Irwin River District (23, p. 84). Forman (12, p. XXV) regards this series as equivalent in age to the Whitestone and Mosquito Creek Series, which, as indicated by recent work at Southern Cross (10, p. 13), are younger than the Older Greenstones of the Kalgoorlie Series (considered to be the oldest group of rocks in Western Australia (24).

The other rocks of more limited distribution are Late Archaeozoic Younger Granite (12, p. XXV), Late Proterozoic or Lower Cambrian quartz dolerite dykes (24) and a superficial deposit of Tertiary laterite. This

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laterite, unlike most of the laterite of Australia which is horizontal (31, p. 32), is formed on a surface sloping at 4° to 8° away from the resistant metasedimentary ridges.

Two parties of senior students of the University of Western Australia carried out the field work, under the guidance of Dr. R. T. Prider, during the first vacation of 1939 and 1945. Chain and compass traverses tied to a framework of Lands and Survey Department subdivisions were employed in the mapping.

II. PHYSIOGRAPHY.

The Great Plateau of Western Australia (15, p. 3) is generally mature, especially in the inland part of the plateau. There are, however, occasional laterite-capped mesas and buttes, the summits of which mark the level of a former peneplain, and rare monadnocks rising above the general plateau level (8, p. 11), which become more numerous towards the edge of the elevated peneplain producing an immature topography.

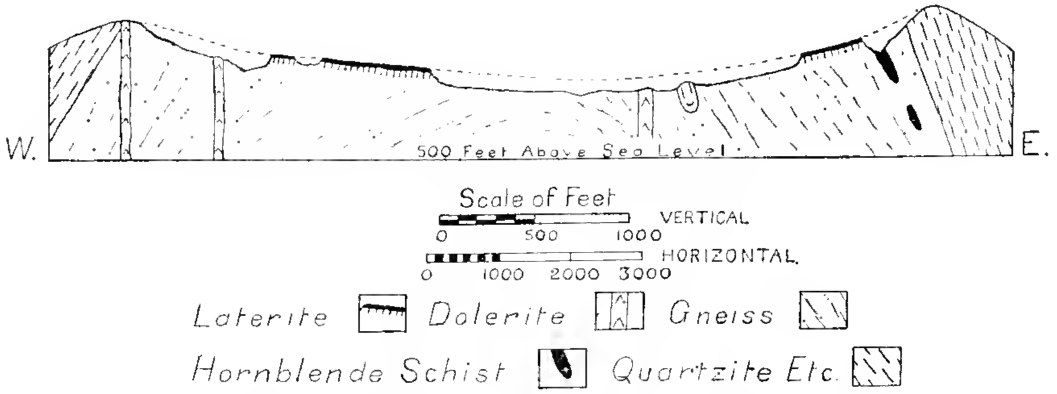
In the Lawnswood Area differential erosion and weathering, both in the present and past cycle of erosion, have been responsible for the main topographic features. As the quartzites are resistant to both weathering and erosion they form two monadnocks elongated parallel to the regional strike. The broad, mature valley running through the centre of the area corresponds to the less resistant granitic gneiss and possibly was formed by an ancient river which flowed in a south-east direction before it was captured by more vigorous west-flowing streams (14, pp. 155-156). Dolerite dykes are intermediate in resistance forming valleys in the quartzites and low ridges in the granitic gneiss (text fig. 1).

Text Fig. 1.

Three dolerite dykes in the upper granite gneiss, 20 chains south of Clackline. The dolerite dykes, being more resistant to erosion than the gneiss, form ridges. Note the parallelism of the dykes.

Differential erosion has been greatly aided by deep and long continued weathering which took place towards the end of the previous cycle of erosion. Granite and basic rocks alike were reduced to a whitish clay down to the base of the kaolinised zone, 50 to 100 feet below the laterite which was forming at that time. This extreme weathering is very unusual in Western Australia and is possibly due to moderate to heavy rainfall during the time of laterite formation forming unusually acid ground waters which altered all the rocks, with the exception of quartzite, into the residual clay deposit.

In the present cycle of erosion, differential erosion of these deeply weathered rocks has produced a dissected peneplain with laterite-capped mesas and buttes, overlying soft kaolinised rock, rising steeply above the unweathered rock to a height of 50 to 100 feet. The laterite mesas and buttes invariably slope at 4° to 8° towards the centre of the valley (see text fig. 2) and small streams consequent on this slope, which flow into a larger stream in the centre of the mature valley, have, in most places stripped off the kaolinised rock leaving the unweathered rock exposed. Very immature subsequent streams are dissecting narrow gorges in the soft hornblende and mica-schist bands in between the quartzite ridges.



Text Fig. 2.

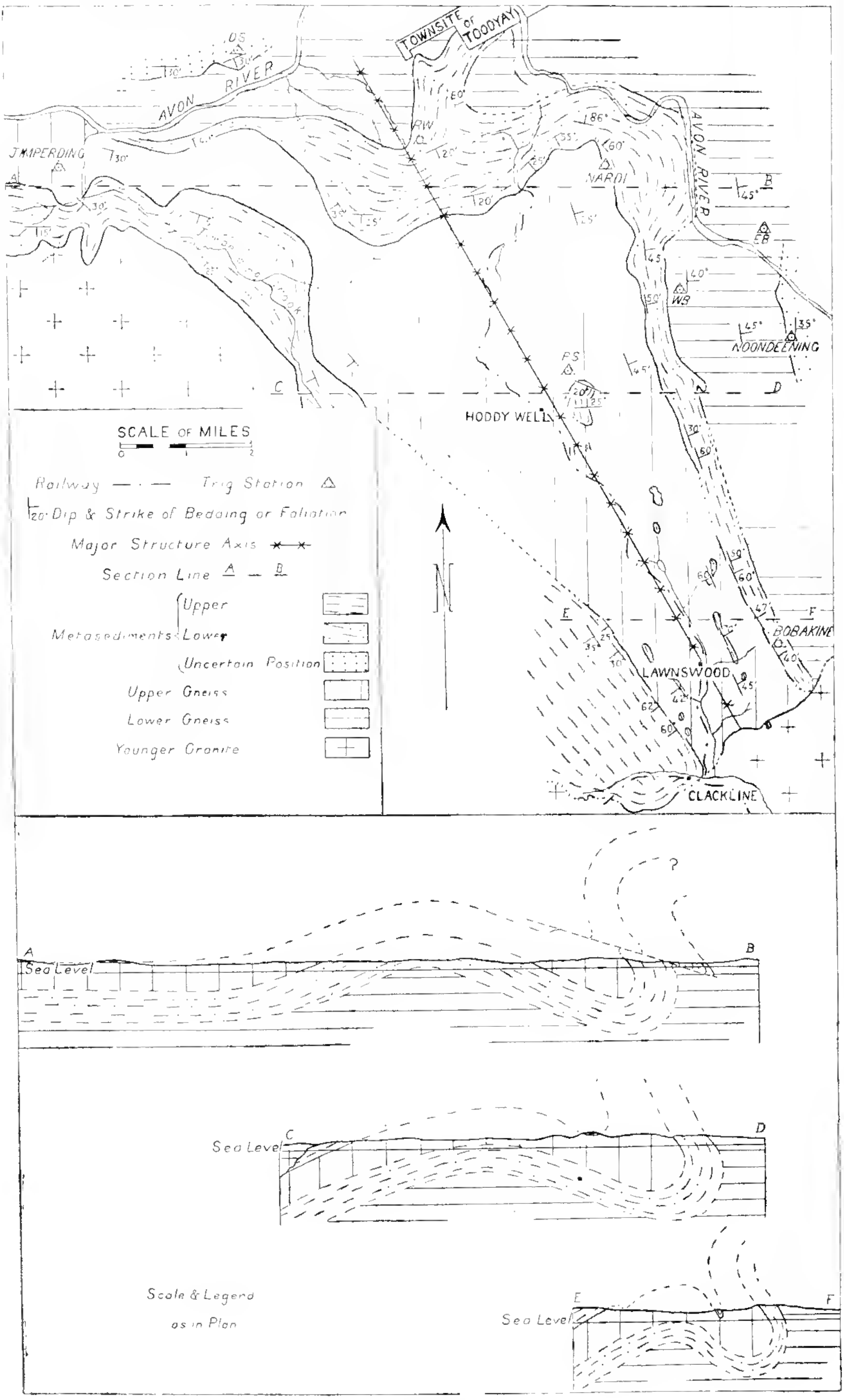
Cross section of the Lawnswood Area along a line bearing 73° at 23 chains north of Lawnswood siding, showing the laterite capped mesas which slope down towards the central valley. The old profile upon which the laterite was formed, is shown by broken lines.

III. GEOLOGY.

A. OCCURRENCE OF THE ROCKS.

1. Metasediments and Hornblende Schists.

There are two broad bands of metasediments in the area both with the characteristic north-north-west strike. The western band which dips west at 25° to 35° in the northern part, and west at 50° to 65° in the southern part of the area, is correlated with the upper metasediment of the Toodyay Area (23, p. 88) because it is on the same line of strike (see text fig. 3) and petrologically the quartzites are identical, both containing idioblastic pale-green chrome-muscovite oriented parallel to the bedding and poikiloblastically included in the quartz grains. The eastern metasediments, which have been connected in the field to the lower quartzites of the Toodyay Area (see text fig. 3), have dips varying from 40° to 50° to the east.



Text Fig. 3.

Geological sketch plan and sections to illustrate the structure of the country between Toodyay and Clackline. Data regarding the northern half of this area after Prider (23, p. 86).

A narrow strip of metasediments (mica schist and quartzite) outcrops in the upper granite gneiss, at a distance varying from five to 12 chains from the upper quartzite. Owing to the very highly weathered nature of its component rocks it is not certain whether this band is continuous, whether it is a series of elongated lenticular xenoliths of the Jimperding Series, or whether it is an infold of the upper metasediments in the gneiss. Another narrow and discontinuous band, situated approximately 40 chains east of Nunamullen Brook, dips 70° to the east in the south, 60° to the west about a mile and a half north of Lawnswood, while in the vicinity of P.S. Trig station there is an anomalous western strike and a low dip to the south.

As the sediments have been very highly metamorphosed causing complete recrystallisation, original features, such as graded bedding and ripple marks, have been almost completely obliterated. Prider (23, p. 87), mentions that, in the Toodyay Area there are some obscure current bedding structures but no certain interpretation of these was possible. Drag folding was not observed in this area, but Prider (23, p. 87) has found drag folds in the lower quartzites of the Toodyay Area, approximately one mile south of W.B. Trig station, which indicate overturning in that locality. Minor cross folds are indicated by the variable pitch of well developed *b*- lineations in the quartzites.

2. Granitic Gneiss.

A thick, concordant, granitic gneiss body occupies most of the central portion of the Area corresponding with a mature valley about three miles wide (see Plate 1). This is correlated with the Upper Gneiss of the Toodyay Area. In the north-east corner of the Area, a second concordant granitic gneiss occurs, which corresponds to the Lower Gneiss of Toodyay.

Although ptygmatic folding is occasionally developed in the gneiss, as is well seen in the outcrops in the bed of Spencer's Brook at Clackline, generally the platy parallelism of the gneiss conforms closely in dip and strike with the associated metasediments. No work was done on linear parallelism of the gneiss.

3. Intrusive Granite.

Granite invades the Jimperding Series in the south-east corner of the Area and continues immediately south and west of Clackline. Probably the boundary of this Younger Granite and the Jimperding Series turns north within a mile west of Clackline and thence runs north to the south-west corner of the Toodyay Area (see text fig. 3).

The intrusive granite appears massive in the field except near the contact with the metasediments south and west of Clackline, where the gneiss-like banding of the rock is due possibly to platy flow structures developing near the contact with the country rocks.

There are two varieties of granite, a porphyritic and an equigranular. The porphyritic is confined to the south-east part of the Area, and passes in a distance of a chain or two into the equigranular variety. The equigranular granite occupies the south-central portion of the Area and extends at least a mile west of Clackline. The porphyritic granite passes into the granitic gneiss very abruptly, but the transition from equigranular granite into granitic gneiss is very gradual.

4. Quartz Dolerite.

Quartz dolerite dykes, from half to two chains wide, are intrusive into all the above rocks. They have a general north-north-west trend and are most numerous in the centre of the Area. In some places there are closely spaced fractures resembling fracture cleavage in the dykes giving them a platy structure. Slight shearing of their edges indicates movement subsequent to intrusion.

5. Laterite.

Laterite-capped mesas and buttes are more common near the metasedimentary ridges and slope away from them at 4° to 8°. This sloping laterite is attributed to its formation on a gently inclined surface in the end stages of the previous cycle of erosion rather than to warping in late Kainozoic times, as in the case of an occurrence of dipping laterite in South Australia (31, pp. 32-33).

B. STRUCTURAL INTERPRETATION OF THE JIMPERDING SERIES.

Text fig. 3 is a simplified diagram of the broader geological and structural features of the Toodyay and Lawnswood Areas. The northern part of the map, the two sections A-B and C-D and the interpretation of the structure are taken from Prider's paper on the Toodyay Area (23, p. 87).

Whereas from the Lawnswood Area to the southern part of the Toodyay Area the strike is north-north-west, in the north of the Toodyay Area the strike is west and the dip is to the south at a fairly low angle. Again the quartzite near P.S. Trig has a westerly strike and a low dip to the south. This unusual westerly strike, the drag fold evidence of inversion of the lower metasediments and the discontinuous quartzite band running from near P.S. Trig to the intrusive granite at the south-east of the Lawnswood Area, can be explained if we imagine the Toodyay and Lawnswood Areas to be in the main a major anticline pitching to the south-south-east, having a recumbent syncline with an axial plane dipping to the east on the eastern limb of this major anticline.

The discontinuous quartzite band from near P.S. Trig is considered to be an infolded recumbent syncline of the Upper Quartzites regardless of its petrological resemblance to the lower quartzites. Dr. Prider predicted the presence of this infolded band of upper metasediments at P.S. Trig, as a result of his structural interpretation of the Toodyay Area and he suggests that the discontinuous nature of this band is due to the presence of minor cross folds. The cross folds superimposed on the major north-west trending structure have produced a series of minor transverse synclines and anticlines. Erosion has cut down so far that only the transverse synclines remain as lenticular outcrops while the transverse anticlines have been removed.

It is seen (Table 1.) that, while the lowest portion of the Toodyay sequence is not represented in the Lawnswood Area, there is a considerably greater thickness of upper metasediments in the west of the area which probably correspond to the metasediments in the south-east of the Malkup Area (9, Table 1. p. 146). Probably of some importance in regard to the origin of the hornblende schists is the change of "Horizon 6" from sillimanite schist in the Toodyay Area to hornblende schist in the Lawnswood Area.

TABLE 1.

COMPARISON OF STRATIGRAPHICAL SUCCESSION AND THICKNESS OF THE JIMPERDING SERIES IN THE LAWNSWOOD AND TOODYAY AREAS.

Lawnswood Area.			Toodyay Area.	
No.	Horizon.	Thickness	Horizon.	Thickness.
	Lower metasediments and hornblende schists.		*Lower metasediments and hornblende schists.*	
1	Not represented		Quartzite	unknown
2	Not represented		Hornblende schist	35ft.
3	Not represented		Quartzite	650ft.
4	Lower granitic gneiss	unknown	Lower granitic gneiss	5,400ft.
5	Quartzite	300ft.	Quartzite	375ft.
6	Hornblende schist	50ft.	Sillimanite schist	100ft.
7	Quartzite	150ft.	Quartzite	570ft.
8	Hornblende schist	70ft.	Hornblende schist	40ft.
9	Quartzite	180ft.	Quartzite	110ft.
	Upper metasediments.		*Upper metasediments.*	
10	Upper granitic gneiss	approx. 2,000ft.	Upper granitic gneiss	1,900ft.
11	Quartzite with some subordinate quartzose mica schists	250–600ft.	Quartzite	500ft.
12	Hornblende schist	180ft.	Indication of hornblende schist	
13	Quartzite	60–200ft.	Not represented	
14	Mica schist and quartzite	1,850ft.	Andalusite—muscovite schist	250ft.
15	Quartzite and mica schist	5 000ft. + ? (Thickness may be due to incompetent folding)	Not represented	
16	Metajaspilites and banded iron-ore			

IV. PETROLOGY.

The rocks are divided into two groups:—

A. The Jimperding Series.
B. The younger igneous intrusives.

A. THE JIMPERDING SERIES.

1. Metasediments.

(a) *Quartzites.*

These are coarse-grained almost pure quartz rocks with well defined bedding on which corrugations or *b*- lineations (19, p. 591) are developed. The Lawnswood quartzites are identical with those described by Prider at Toodyay (23, pp. 88-94).

(i) The Upper Quartzites are characterised by the presence of small ($<$ 0.1 mm.) pale green chrome-muscovite idioblasts enclosed in the quartz grains and oriented parallel to the bedding. Felspar is not found in the main band of upper quartzites in the west of the Lawnswood Area but is common in the infolded quartzite which is correlated with the upper quartzites on structural grounds.

(ii) The Lower Quartzites are identical with those of the Toodyay Area and have been connected in the field. The chrome-muscovite grains are larger than those in the Upper Quartzite being 0.3 to 0.5 mm. in diameter and lie between the grains of the quartz mosaic, while there are poikiloblastic inclusions of rutile, magnetite, sillimanite (?), felspar, and zircon in the quartz grains.

(iii) The Infolded Quartzites lithologically resemble the Lower Quartzites, being a felspathic variety free from oriented, poikiloblastic inclusions of idioblastic chrome-muscovite in the quartz grains. The felspar is slightly kaolinised microcline with frequent microperthite which generally occurs in xenoblasts up to one mm. in diameter in the quartz mosaic and may form five to six per cent. of the rock. The inclusions in the quartz grains are zircon, red-brown biotite and a green pyroxene, forming two to three per cent. of one rock (22742)*.

Origin of the quartzites.—The quartzites appear to have been derived from remarkably pure quartz sands which have recrystallized in the sillimanite zone resulting in the obliteration of the clastic structure (23, pp. 92 and 94).

(b) *Mica Schist.*

The mica schists occur in the western metasedimentary band and are light yellow-brown to grey brown, generally highly schistose, medium-grained, micaceous rocks which are frequently contorted. The characteristic features of these rocks are the constant presence of bands and lenses of sillimanite in very fine aggregates of acicular crystals which are frequently altered to sericite (26, p. 13) and the marked schistosity—the quartz grains having an index of elongation of four to five.

(i) The Muscovite-quartz-sillimanite schist (22569) has the following minerals visible in hand specimen:—golden plates of muscovite two to three mm. in length; colourless, strongly elongated quartz grains three to five mm. long; and bands up to two cm. wide and more than 10 cm. long containing an aggregate of fine white acicular sillimanite and sericite. There are rare inclusions of sericite and minute sillimanite prisms in the quartz and very corroded biotite is sometimes observed. The complete absence of undulose extinction in the elongated quartz grains indicates that complete recrystallisation took place during metamorphism.

The approximate mineralogical composition is muscovite 40 per cent. quartz 30 per cent. sericite 30 per cent. with biotite, sillimanite and iron ores accessory.

The sericite-sillimanite bands become most common in the south of the area in the vicinity of the Clackline fire-clay deposits, which are highly kaolinised sillimanite-mica schists composed largely of white kaolin with up to 10 per cent. of lenticular bands of very acicular sillimanite (26, p. 12). Quartz and kaolinised muscovite are visible in hand specimens. This sillimanite clay lies close to the Younger Granite and several pegmatite veins, genetically related to this granite, occur in the west of the deposit.

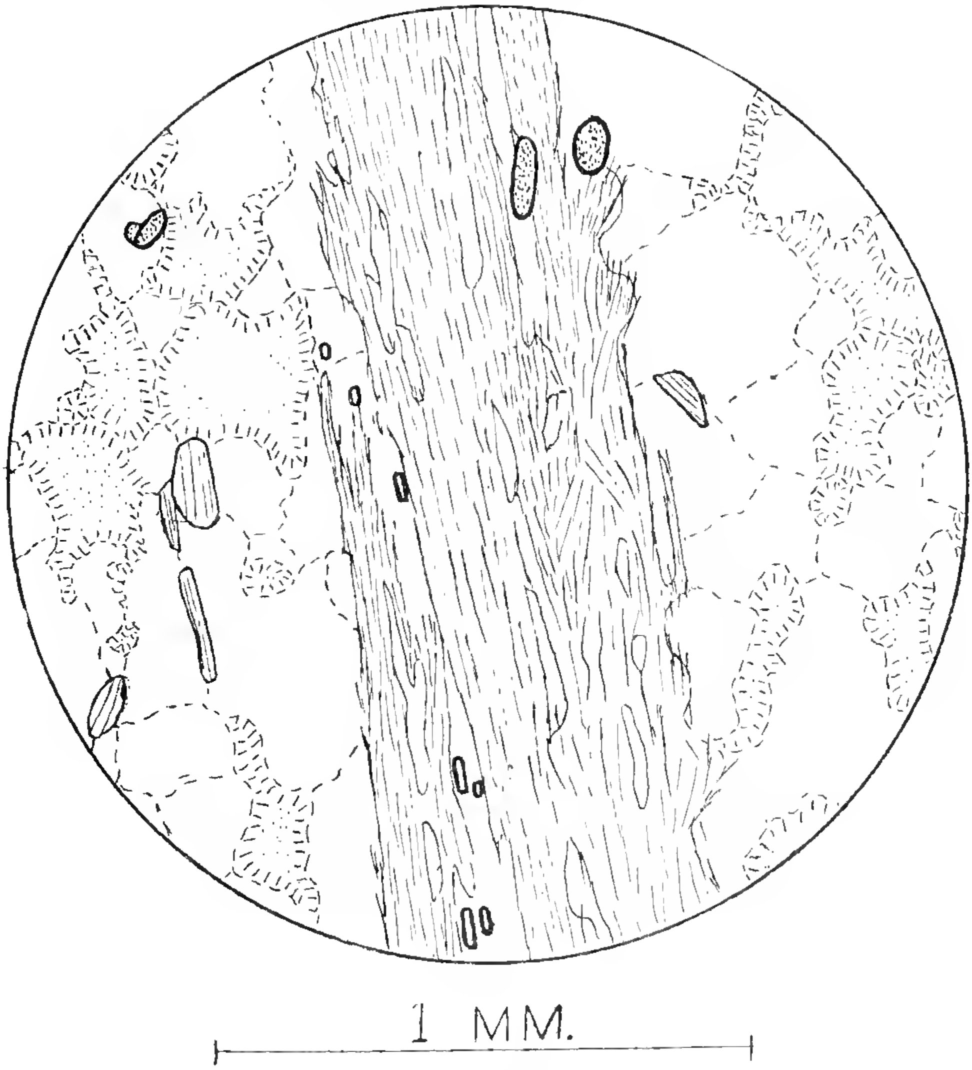
Mr. H. Bowley "picked up a loose crystal of kyanite a little to the north of the brickpit" (26, p. 11), but no kyanite has been found in the present investigation.

A lateritised form of the muscovite-quartz sillimanite schist (22568, 22569, 22570) occurs in a band in the upper granitic gneiss about 10 chains

*Numbers refer to the catalogue of the collection of the Department of Geology of the University of W.A.

east of the upper metasediments. This is petrologically indentical with unlateritised specimens (22539) from the base of the upper metasediments and is correlated with horizon 11 (Table 1.).

(ii) The Biotite-cordierite-quartz-sericite-sillimanite schist (19190) is frequently darker in colour and more gneissic than group (i). The biotite occurs in markedly elongated, strongly pleochroic plates — Y and Z = brown, X = very light brown to colourless, absorption X < Y = Z, c X = 0°, (-)2V very small. Pleochroic haloes around zircon grains are frequent. The quartz is very elongated and contains gas-liquid inclusions and minute inclusions of sericite, rutile, rounded zircon and rare sillimanite. Cordierite was observed in an irregular intergrowth with quartz in one slide (19953) but equidimensional sericite aggregates are possibly pinite pseudomorphic after cordierite. The sericite aggregates are evidently derived some from bands of sillimanite and some from an equidimensional mineral —probably cordierite or even felspar (see text fig. 4). The sillimanite is



Text Fig. 4.

Biotite-corderite-quartz-sericite-sillimanite schist (19190), showing a band of sericite pseudomorphic after sillimanite (small prisms with high relief) and equidimensional grains consisting of sericite after corderite (or felspar). Four rounded grains of rutile are seen in this field.

the variety fibrolite occurring in very fine prisms associated with elongated magnetite grains. It appears to be developing at the expense of biotite (23, p. 98). Muscovite, iron ores, zircon, sillimanite, and felspars, the latter occurring only in specimens from near the intrusive granite, are accessory minerals.

The average composition is quartz 40 per cent., biotite 15 per cent., cordierite and pinite 15 per cent., sericite 15 to 20 per cent., fibrolite is sometimes as high as 10 per cent.

(iii) Garnet schist.—A highly weathered whitish to brownish schist with numerous equidimensional, dark brown limonitic grains pseudomorphic after garnet (the original crystalline form being retained) has been noted only in the fire-clay quarry at Clackline. The rock has a maculose texture with about 40 per cent. of limonite pseudomorphs after garnet three to five mm. in diameter, the remainder of the rock being fine-grained quartz and mica.

Origin of the mica schists.—These mica schists are thought to be the result of extreme regional metamorphism of sandy argillaceous sediments or possibly glauconitic shales (26, p. 13).

Sillimanite-quartz-cordierite-biotite schists were probably formed at this stage of high regional metamorphism, with a tendency of the biotite to change to fibrolite and magnetite. Probably the original composition of the sediment determined whether the schist formed therefrom was high in sillimanite, mica, or garnet.

The sillimanite clay quarried at Clackline is thought to be a highly kaolinised variety of sillimanite-rich mica schist from the kaolinised zone below the laterite, i.e., the result of weathering, and not the result of hydrothermal metasomatism at the time of the intrusion of the Younger Granite, as are the sillimanitic clay deposits at Williamstown, South Australia (1, p. 10).

Considerable retrograde metamorphism probably took place as a result of the intrusion of the Younger Granite. "Hot alkaline potash solutions" (26, p. 13) metasomatised the sillimanite and cordierite producing sericite after sillimanite and pinite after cordierite and some of the biotite was altered to muscovite.

(c) *Metajaspilites.*

(i) Banded quartz-magnetite-garnet-amphibole rocks have been described by Miles (17, pp. 325-328). Megascopically they are heavy, dark green, medium to coarse-grained, granular, coarsely banded rocks. The banding is considered to be a relict structure of the original bedding. In (19956) there are three types of bands: (1) Quartz-rich with subordinate pale green amphibole (grain size of both two to three mm.); (2) a layer in which pale green amphibole predominates and which has subordinate dark amphibole and garnet and rare magnetite; (3) a layer of red garnet (1 mm. diam.), dark amphibole (two to three mm. diam.) and magnetite (half to one mm. diam.) with subordinate pale green amphibole.

The rock has a coarse granoblastic structure. The quartz forms a coarse mosaic and has gas-liquid inclusions and sometimes slight undulose extinction. Xenoblastic inclusions of amphibole sometimes occur in the quartz.

The amphiboles are of two varieties, both with a high relief, containing pleochroic haloes around zircon grains and tending to be idioblastic in form (17, pp. 327 to 328). One variety is a pale green amphibole with weak pleochroism, X = colourless, Y = b = pale yellow green to brown, Z = pale green-blue; absorption $X < Y = Z$; $Z \wedge c = 13°$; (-) 2V near 90°. Polysynthetic twinning is common on 100. The mineral is a grunerite with a composition near cummingtonite probably containing over 75 per cent $FeSiO_3$ (17, p. 327). The other variety is a dark amphibole with very strong pleochroism X = light green, Y = dark olive green, Z = intense blue-green. Absorption is strong and masks the interference colours, Z slightly $> Y > X$, $Z \wedge c = 22°$, Y = b, optical character biaxial -ve with large 2V (about 80°), twinning not seen. The mineral is probably an actinolitic hornblende. The garnet xenoblasts have an irregular form and a poikiloblastic character. They contain numerous inclusions of a highly birefringent mineral forming up to 60 per cent. of their volume. This garnet is a pink, probably iron-rich variety. Magnetite forms very irregular patches. The crystalloblastic order is: amphiboles, garnet, quartz and magnetite. Average composition—quartz 40 per cent., grunerite 30 per cent., dark green amphibole 15 per cent., garnet 15 per cent., magnetite accessory.

(ii) Banded quartz-iron ore rocks (19954) are bluish grey, strongly banded, fine to medium-grained, with a granular texture, and are reddish brown where weathered.

The bands are quartz, four cm. wide (grain-size about two mm.), quartz and iron ore, one cm. wide (grain-size 0.25 - 0.5 mm.), and narrow iron ore bands up to one mm. wide (grain-size 0.25 mm.). Bands of amphibole occur rarely.

A granoblastic structure is seen in the quartz and quartz-iron ore bands. The quartz has an irregular mosaic structure and is practically free from inclusions except next to the iron ore where it is crowded with fine, colourless, needle-shaped crystals. These are indeterminable but are perhaps incipient grunerite resulting from reaction between quartz and the iron ores. The iron ore is almost entirely hematite but a minor amount of magnetite is present and quite a number of octahedral crystals were observed, some of which may be hematite pseudomorphic after magnetite.

(iii) Lateritised banded quartz-iron ore rock (19961) is a brownish coloured rock which outcrops in the south-west corner of the area. It consists of alternating bands of quartzite and limonite, from one cm. to three cm. or more in width. The quartz (grain-size two to three mm.) has a mosaic structure. Sometimes the rock is almost pure, very fine-grained limonite which is dark brown and has a metallic lustre, other specimens are composed of dull limonite and strikingly resemble the rocks of group (ii).

Drag-folded and very contorted quartzites, called "banded quartzite" by Mr. R. A. Hobson of the Geological Survey of Western Australia who mapped the area in 1941, are very commonly associated with the banded iron ores. The data concerning the banded quartzite and banded iron ore in the south-west corner of the geological map of this area are taken from Hobson's map.

Origin of the metajaspilites.—Extreme metamorphism in the sillimanite zone of iron-rich siliceous sediments has produced these banded iron and silica-rich rocks. Probably the original rocks were finely bedded quartz sands and magnetite sands, similar to those of Yampi Sound (5, pp. 67-75), with some bands of impure iron-rich sediments containing greenalite or siderite (17, p. 369).

As banded hematite-quartz rocks with little or no amphibole (ii) occur, it appears that pure iron ores and quartz do not react to any extent, so it is considered that group (ii) is derived from finely laminated quartz-magnetite sediments, while group (i), in which iron-rich amphiboles and garnet are present, is the result of intense metamorphism of banded quartz and impure iron-rich sediments (greenalite or ferrous carbonate).

Group (iii) is considered to be the result of lateritisation of the metajaspilites especially the very iron-rich forms. This is a case of extreme retrograde metamorphism (katamorphism) as a result of weathering of high grade metamorphic rocks. The original bedded structure is in most cases clearly visible, the iron-rich minerals apparently have been metasomatically replaced by limonite so the rock may be considered to be a lateritoid (a term proposed by Fermor (11, pp. 381-3) for rocks similar to laterite but formed by metasomatism).

2. Meta-igneous Rocks.

(a) *Hornblende schist and its variants.*

These are fine to medium-grained, uniform-textured, schistose rocks dark greenish grey in colour and identical with those of the Toodyay Area (23, p. 104-107). A granoblastic microstructure and the absence of any distinct crystalloblastic order is characteristic of the group.

(i) Quartz-plagioclase amphibolite (22733) is the most common type as it is in the Toodyay Area (23, p. 104-105). The optical properties of the hornblende at Lawnswood are X = yellow, b = Y = olive green, Z = blue-green, absorption X > Z > Y, (-) 2V large, c $\wedge$ Z = 20°, β = 1.679. Its approximate composition is hornblende 65 per cent., oligoclase (Ab_8 An_2) 25 per cent., quartz five per cent., accessories (microcline, radio-active titanite and green diopside) five per cent.

(ii) Quartz-plagioclase-pyroxene granulite (22732) is a variant of the plagioclase amphibolite. It is a granular type in which green diopside is greatly developed while hornblende is rare or absent. The diopside is a bright green very feebly pleochroic variety, Z and X appearing to be green and b = Y = yellow green, optically positive, c $\wedge$ Z = 40° with simple twinning developed. The approximate composition of this is diopside 50 per cent., oligoclase 45 per cent., quartz four per cent., titanite one per cent.

(iii) Quartz-zoisite-hornblende schist (22583)—The hornblende schist layer intercalated in the western metasediments differs from those described above in the predominance of quartz and the absence of felspar. The presence of an aggregate of zoisite and sericite is probably the result of retrograde metamorphism (felspar $\Rightarrow$ sericite + zoisite). Accessories are apatite, iron ores, purple zircon, and rutile. Titanite is absent. The approximate composition is quartz 55 per cent., hornblende 30 per cent., zoisite and sericite 15 per cent.

Origin of the hornblende schists.—Types (i) and (ii) are thought to be the result of extreme regional metamorphism of basic igneous flows or sills, as, according to Wiseman (30, p.394), hornblende with a refractive index of β = 1.679 is indicative of an epidiorite formed in the sillimanite zone of metamorphism. Prider (23, p. 107) concluded, from the high refractive index of the hornblende, the occurrence of the rocks in beds intercalated with the metasediments and their chemical composition, that similar hornblende schists in the Toodyay Area are highly metamorphosed basic igneous rocks.

Previously when dealing with the correlation of the Toodyay and Lawnswood Areas it was pointed out that Horizon 6 (see Table 1.) is a hornblende schist in the Lawnswood Area and a sillimanite schist in the Toodyay Area. The presence of hornblende schist in the same horizon as sillimanite schist suggests that this hornblende schist was a basic (dolerite) sill that was injected in some places into a softer argillaceous stratum between two arenaceous bands prior to regional folding.

The quartz-rich hornblende schist (iii) is thought to be the result of extreme metamorphism of a basic sediment (greywacke) or basic tuff.

(b) *Cordierite-anthophyllite rock.*

About 50 chains west of Clackline an outcrop of a light greyish-green, medium to coarse-grained, uniform-textured cordierite-anthophyllite rock occurs. It has been described by Simpson (27, p. 115). It outcrops at the contact between the Jimperding Series metasediments, which are peltic in this exposure, and a rock which is thought to be the Younger Granite although it is gneissic.

The minerals are greyish-green cordierite, devoid of cleavage and up to three mm. in length, and grey prisms of anthophyllite up to two mm. in length. The microstructure is granoblastic gneissic. Cordierite occurs in colourless xenoblasts frequently altered along irregular cracks to pinite, and the anthophyllite is generally idioblastic. Red-brown biotite, rutile, and chromite are accessory. The approximate composition is cordierite (and pinite) 55 per cent., anthophyllite 45 per cent.

Simpson (27, p. 116) suggests that this rock originated by the "absorption of some slate or similar aluminous rock" into a basic hypersthene-rich rock. Similar cordierite-anthophyllite rocks occur as xenoliths in the granitic gneiss of the Toodyay Area, and these have been shown to be genetically related to an ultrabasic spinel-olivine-hypersthene rock. Prider concluded that a "hypersthenite magma which had been contaminated by assimilation of aluminous material" had been altered to cordierite anthophyllite rock "by the simple addition of silica (probably from the granite)" (21, p. 381).

The presence of mica schist adjacent to the cordierite-anthophyllite rock in the Clackline occurrence suggests that a hypersthenite invaded a pelitic band of the metasediments and assimilated aluminous material, as Simpson suggests. The cordierite was formed either during the highest stages of regional metamorphism or more probably as a result of the contact metamorphism (with silica addition) by the Younger Granite.

3. Granitic Gneiss and associated xenoliths.

The granitic gneiss is in two thick sills continuous with the Toodyay Area. The lower granitic gneiss outcrops in the north-east of the Lawnswood Area while the upper granitic gneiss covers its centre and has been studied in some detail.

(a) *Upper granitic gneiss.*

This gneiss is almost identical with the one described by Prider at Toodyay (23, pp. 107-111) except for the absence of augen structure.

There appear to be two main types:—(i) Granitic Gneiss A (chloritic) which is a medium- to coarse-grained, greyish gneiss, with widely spaced microcline phenocrysts (two cm. diam.) and is characterised by the presence of chlorite and epidote; (ii) Granitic Gneiss B (biotitic), which occupies the edge of the sill near the metasediments, being characterised by a finer grain, a more strongly developed gneissic structure and the presence of biotite.

(i) Granitic Gneiss A (chloritic) (22479)—The type rock has a coarsely gneissic structure sometimes with slight cataclasis and the following minerals:—slightly saussuritised oligoclase, clear microcline, quartz, chlorite, epidote (often in veinlets), and accessory apatite, magnetite, and zircon. The chlorite occurs in well developed plates frequently with purple zircon inclusions surrounded by strong pleochroic haloes. It is thought to be pseudomorphic after biotite because of its form and the purple zircon inclusions which are common to both. Its optical properties are:—pleochroism X = very pale yellow-green, Y and Z = green, absorption $X < Y = Z$, birefringence very low, anomalous blue colours frequent, elongation positive, optically negative, $\beta = 1.625$. These data indicate the variety as aphrosiderite which has a composition similar to biotite.

Approximate composition is oligoclase 35 per cent., quartz 30 per cent., microcline 25 per cent., chlorite five per cent., epidote five per cent.

(ii) Granitic Gneiss B (biotitic) (22574) is characterised by biotite in very elongated plates rather than chlorite and epidote pseudomorphic after biotite as in (i). The biotite plates are crowded with sagenitic rutile inclusions and have strong pleochroism X = yellow, Y = dark brownish green, Z = very dark brown, absorption $X < Y < Z$. Microcline phenocrysts are absent but some larger grains (two to three mm.) slightly kaolinised and with myrmekite frequently developed in associated oligoclase, probably represent early-formed microcline, while smaller (0.5 mm.) clear grains, strongly cross-hatched and containing microperthite are probably a later generation. The quartz generally occurs in rounded grains poikiloblastically enclosed in all the other minerals.

The approximate composition is microcline 35 per cent., quartz 35 per cent., oligoclase 15 per cent., biotite 15 per cent.

(b) *Xenoliths in the granitic gneiss.*

These are of amphibolites, except for one of sillimanite-mica schist and some of chlorite-epidote rock. Generally they are large, up to two or three chains in major diameter, and irregular, and are elongated parallel to the regional strike.

(i) The amphibolites are dark, grey-green medium- to coarse-grained, melanocratic rocks containing hornblende, plagioclase and diopside with accessory biotite, apatite, quartz, and sphene and are almost identical mineralogically with the hornblende schists of the metasediments. There are both granulose and schistose varieties.

Granulose quartz-plagioclase amphibolites (22524) are dark grey, uniform textured rocks with a medium to coarse grain and a granoblastic microstructure. The minerals present are intensely pleochroic blue-green hornblende ($c \wedge Z = 21°$, $\beta = 1.672$), basic oligoclase (saussuritised and with normal gradational zoning occasionally developed), strongly pleochroic greenish-brown biotite, quartz, and accessory apatite, radioactive titanite, actinolite and diopside.

The approximate composition is hornblende 65 per cent., oligoclase 25 per cent., biotite five per cent., quartz three per cent., titanite two per cent.

The schistose quartz-diopside-plagioclase amphibolites (19188) differ from the above in their schistose structure and greenish-grey colour due to the presence of green diopside which sometimes forms more than 10 per cent. of the rock. The hornblende is similar to that in the granulose amphibolites ($c \wedge Z = 24°$, $\beta = 1.675$); andesine ($Ab_4 An_6$) is the plagioclase present; and the diopside is a green variety with very feeble pleochroism. (+) 2V large, $c \wedge Z = 41°$.

(ii) The quartz-plagioclase-epidote-chlorite rock (22487) is greenish-grey with a uniform texture and fine grain. Occasional veinlets of pale yellow-green epidote are seen in the rock. The minerals are a very dark green platy chlorite, average grain size 0.5 mm., veinlets and aggregates of pale yellow green epidote, equidimensional white grains of felspar 0.5 - 1.0 mm. in diameter. There is a slight banding caused by the parallelism of the chlorite plates.

A chemical analysis of 22487 (Table 2, I) shows that except for higher SiO_2 and Al_2O_3 and the proportional lowering of the other constituents the rock chemically resembles a hornblende schist xenolith (Table 2, II) in the gneiss from Toodyay (23, p. 105).

The rock is a rare type as shown by the quantitative classification (II, 4, 5), only one comparable rock, a gabbro, being listed in Washington's "Chemical Analyses of Igneous Rocks" (28, p. 419).

The composition except for the high SiO_2 is somewhat similar to that of quartz dolerite so that the rock might be the result of the granitization of a basic igneous rock.

The rock (22487) has a granoblastic microstructure with a tendency to be finely gneissic. The quartz is generally clear with an irregular form. Inclusions of chlorite are rare and an intergrowth of quartz and untwinned plagioclase is sometimes observed. Chlorite is green, practically isotropic with occasional grey blue anomalous interference colours and weak pleochroism from green to light yellow green. It appears to be pseudomorphic after an amphibole as it occurs in forms similar to the typical amphibole basal section and occasional bands of epidote cross the chlorite at angles of about 60° which may be replacements along the amphibole cleavages. Epidote forms irregular aggregates (average diameter 0.5 mm.) which may in part replace felspars. Some epidote was introduced at a later stage along cracks. The felspar is untwinned oligoclase which is difficult to distinguish from quartz. Accessory minerals are apatite, titanite, iron ore, and zircon.

The approximate mineralogical composition is quartz 32 per cent., chlorite 30 per cent., epidote 25 per cent., plagioclase 10 per cent., and titanite and other accessories three per cent. Another specimen of this group (22488) is almost black in colour and contains 80 per cent. chlorite.

Table 2.

	I. %	II. %
SiO_2	59·23	50·20
Al_2O_3	16·18	15·00
Fe_2O_3	1·48	3·83
FeO	5·63	8·93
MgO	4·24	6·04
CaO	9·58	10·65
K_2O	0·10	0·07
Na_2O	0·65	1·90
H_2O+	1·71	1·62
H_2O-	0·20	0·07
TiO_2	0·61	1·06
MnO	0·13	0·16
P_2O_5	0·19	0·12
BaO	Nil	...
ZrO_2	Nil	...
S	0·03	...
	99·96	99·65
Norms.		
Q	25·86	6·18
Or	0·56	0·56
Ab	5·76	16·24
An	40·87	31·97
di	4·86	16·41
hy	11·50	19·18
mg	2·09	5·57
il	1·22	2·13
ap	0·34	0·34
py	0·10	...

C.I.P.W. classification II, 4, 5.

I. Quartz-plagioclase-epidote-chlorite rock (22487), xenolith in upper granitic gneiss, Lawnswood, W.A. (*Anal.* J. R. H. McWhae).

II. Schistose plagioclase amphibolite (1241) xenolith in upper granitic gneiss, Toodyay, W.A. (23, p. 105).

(iii) Sillimanite-mica schist (19193) is a slightly contorted, lustrous, grey schist, composed largely of platy mica, two to four mm. long, some of which is black biotite. Xenoliths of this type are of rare occurrence.

The main constituent is muscovite which has 2V approximately 40°. It contains poikiloblastic inclusions of sericite and chloritised biotite.

Biotite is highly corroded and brownish in colour where associated with sericite and its pleochroism is weak, X = light brown, Y and Z = brown. Where associated with muscovite the biotite is invariably altered to green chlorite. Sillimanite, variety fibrolite, occurs in bands of fine acicular aggregates and is largely altered to sericite. Magnetite and sillimanite are accessory. Primary minerals appear to have been muscovite, biotite, and sillimanite; secondary minerals sericite, chlorite, and magnetite.

The approximate composition is muscovite 36 per cent., sericite 30 per cent., biotite 20 per cent., chlorite seven per cent., sillimanite five per cent., magnetite two per cent.

(iv) Hybridised granitic gneiss.—There are several small occurrences of intermediate to basic rocks formed by the partial granitization of the basic xenoliths. They vary from basic hornblende pegmatites, with hornblende, quartz, and felspar grains two or three cm. in diameter, through coarsely banded diopside-plagioclase amphibolites with small scale "lit-par-lit" injections of quartz and microcline from the granite, to strongly gneissic acid to intermediate rocks injected by numerous quartz veins (22529). The latter type is light grey in colour and consists of an aggregate of fine-grained, blue-green hornblende, quartz, felspar and diopside in bands one to three mm. wide alternating with sill-like bands of quartz from one to four mm. wide. A similar gneiss has been described from Toodyay (23, pp. 122-123).

Origin of the granitic gneiss and associated xenoliths. This granitic gneiss is either a concordant acid intrusion or results from the granitization of sediments. If the gneiss resulted from the granitization of an acid sediment (arkose) then such granitization would be expected to transgress the stratigraphic horizons of the metasediments and other metasediments such as mica schists should also show the effects of granitization. As this is not the case and as the granitic gneiss contains different kinds of xenoliths it is considered to have been introduced as a highly viscous magma during the period of diastrophism. Ptygmatic folding, protoclastic structures, and the absence of preferred orientation in the quartz grains of these gneisses suggests that the magma was a viscous fluid, crowded with early formed phenocrysts and xenoliths during the folding, the quartz crystallising when the tectonic activity had ceased (23, p. 109).

The magma is considered to have been introduced at a considerable depth on the basis of the following generalizations of Bucher and Balk: "large concordant acid intrusives in folded sediments are wide spread only in early pre-Cambrian terranes" (1, p. 281); and "deep levels in the earth..........and slow consolidation of the mass during continuous movement are probably amongst the factors which seem to result in thick foliated shells" (2, p. 81). The more pronounced platy parallelism of the gneiss near its contact with the metasediments is probably due to movement of the quasi-solid granitic magma against the relatively stationary metasediments.

The typical granitic gneiss A has an abundance of hydrothermal minerals—epidote, chlorite, and "saussurite"—which were probably formed during the end stages of consolidation. Pegmatite and quartz veins are frequent, some possibly derived from the Younger Granite.

Granitic gneiss B, which has no hydrothermal minerals and contains greenish brown biotite, is considered to be a less altered form of A formed in the border zone of the cooling magma by more rapid cooling and greater frictional forces.

A cataclastic form of the granitic gneiss, greenish in colour, with strained and cracked plagioclase grains, undulose extinction in the quartz and with much introduced epidote, is frequently found near epidote-filled veinlets genetically related to the much younger dolerite dykes.

The great bulk of the xenoliths are amphibolites which suggest, by their chemical and mineralogical composition (23, p. 105) that they are derived from the hornblende schists with little or no addition of material from the gneisses. The presence of quartz in these basic rocks is probably due to the conversion of pyroxenes to hornblende liberating silica (13, p. 311). The high refractive indices of the hornblende ($\beta = 1.672$ and $\beta = 1.675$) is indicative of recrystallisation of a basic igneous rock in the sillimanite zone (30, p. 107). According to Harker (13, p. 281), at the highest grade of regional metamorphism of basic igneous rocks, in bands "richer in lime, the place of hornblende is partly or wholly taken by colourless diopside" and the felspar is commonly a medium andesine. These features were noted in the petrological examination of the amphibolites.

The hybridised granitic gneiss (iv) is considered to be the result of partial assimilation and granitization of these xenoliths by the granitic gneiss magma, and small scale lit-par-lit injection of acid material into the xenoliths from the magma.

The basic epidote chlorite xenolith (ii) is considered to be a xenolith of basic igneous rock similar to the hornblende schists xenoliths in the gneiss at Toodyay except that it has been extensively chloritized.

The sillimanite-mica schist xenolith (iii) is a fragment from the mica schists of the metasediments.

B. THE YOUNGER IGNEOUS INTRUSIVES.

1. Younger Granites.

Porphyritic granite occurs in the south-east corner of the area and in a small intrusion into the granitic gneiss, about an acre in area, near the eastern metasediments. In the south-central portion of the area a uniform-grained granite takes the place of the porphyritic type. About 30 chains north of this a small dyke of gneissic granite outcrops.

(a) *Porphyritic granite and xenoliths.*

A characteristic feature of this rock wherever seen in the field, is the presence of xenoliths up to four feet in diameter of finer-grained slightly darker-coloured material (text fig. 5).

The granite itself is a coarse-grained, porphyritic rock light grey in colour with frequent small, rounded grey xenoliths up to four feet in diameter. The "phenocrysts" are euhedral microclines averaging an inch in length which are dotted with random orientation throughout the granite and also in the xenoliths (text fig. 5). The groundmass is composed of

Text Fig. 5.

Porphyritic Younger Granite with adamellite xenoliths. Note the " phenocrysts " of microcline which have developed both in the xenoliths (compare rapakivi ovoids) and in the granite itself. Note also the absence of any preferred orientation of the microcline " phenocrysts " of the granite.

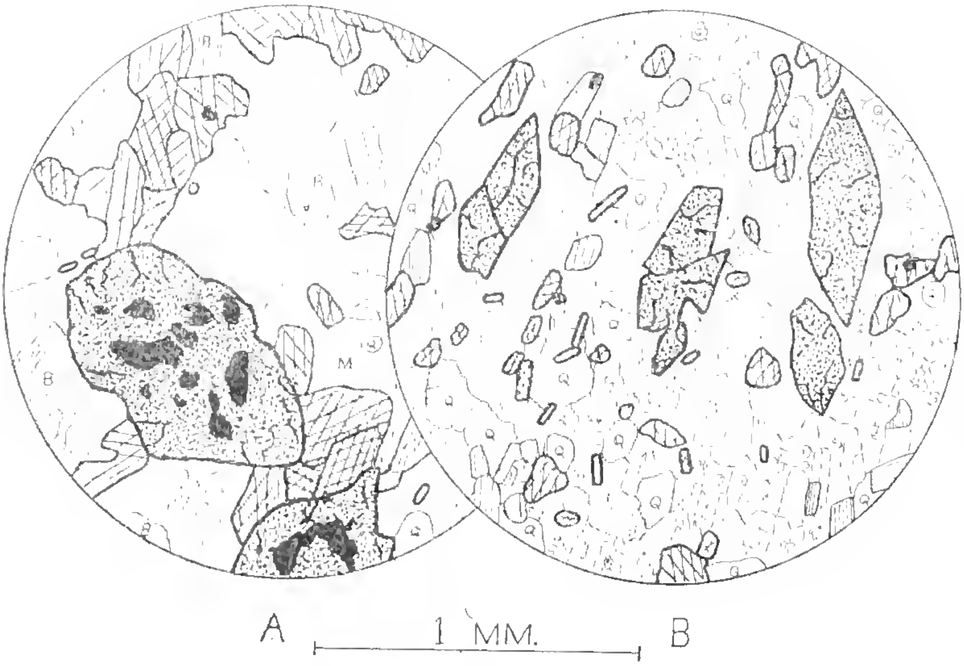
colourless glassy quartz about five mm. in diameter, pale green oligoclase, three to five mm. in diameter, pink microcline average diameter five mm. and black biotite and hornblende average grain size four mm.

The microcline " phenocrysts" are euhedral with many poikiloblastic inclusions of felspar, quartz, biotite, and hornblende. Smaller euhedral microcline grains, sometimes very slightly kaolinised, occur in the groundmass. Microperthite is frequently developed in the microcline. Oligoclase forms euhedral grains which are either extremely saussuritised, the "saussurite" being much coarser than in the granitic gneisses, or clear and slightly zoned with well developed lamellar twinning. The saussuritised oligoclase is thought to be a relic from the granitic gneiss. Coarse myrmekite structures are common. Quartz occurs in clear very irregular grains, free from inclusions, and appears to have crystallised last in interstices between earlier formed oligoclase, biotite, hornblende, and microcline. The biotite is a strongly pleochroic brown variety with subhedral form, usually occurring in aggregates with the other ferromagnesian minerals surrounding the colourless felspar and quartz grains. It has (-) 2V very small, pleochroism strong Y and Z = dark brown, X light brown, absorption Y = Z, b > X, $< c\ X = 0°$. There are pleochroic haloes around purple zircon inclusions and other inclusions of apatite and epidote. The hornblende is a strongly pleochroic type X = yellow, Y = b = dark grey green, Z = bluish green, absorption $X < Y < Z$, $c \wedge Z = 24°$, optically negative. Accessory minerals are titanite, magnetite, apatite and epidote.

Order of crystallisation:—Magnetite, titanite, apatite, hornblende, biotite, oligoclase, microcline, and quartz. The average composition is quartz 35 per cent., microcline 30 per cent., oligoclase 20 per cent., biotite 7 per cent., hornblende 5 per cent., titanite and magnetite 3 per cent.

The xenoliths in this granite are grey, coarse-textured rocks containing the same minerals as the granite but with a much higher percentage of ferromagnesians. Occasional microcline "phenocrysts" up to one inch long occur in the xenoliths (see text fig. 5). Some of the xenoliths are slightly gneissic (text fig. 6B).

The rock forming these xenoliths appears to be fairly constant in character. It has a granitic micro-structure. The minerals have the same optical properties as those in the granite, and are biotite with sagenitic rutile webbing, (grain-size up to two mm.), greenish-blue hornblende, (grain-size two to four mm.), saussuritised oligoclase with inclusions of magnetite and chlorite, (grain-size four to six mm.). Quartz and microcline are clear and very irregular in form and occur in variable quantities from two per cent. to 30 per cent. Grain-size two to five mm. except for rare microcline "phenocrysts" crowded with inclusions of all the other minerals which have an average size of 2 cm. Large (one mm.) euhedral titanite grains, probably the result of the alteration of original ilmenite, have inclusions of magnetite (see text fig. 6A). Apatite, epidote, and magnetite are accessories. Apatite, magnetite, titanite, hornblende, biotite, and the microcline "phenocrysts" are all euhedral.



Text Fig. 6.

Adamellite xenoliths in the porphyritic younger granite.

A. Granoblastic textured, showing association of titanite and magnetite (22517). Minerals are hornblende, biotite (B), plagioclase (slightly turbid), microcline (M), quartz (Q), titanite and magnetite.

B. Gneissic structured xenolith showing the development of titanite idioblasts (22581). Section from specimen taken from the edge of a xenolith near the contact between the granite and the xenolith.

Micrometric analysis of a more acid type of xenolith (22517) shows the following composition: Oligoclase 31 per cent., quartz 28 per cent., microcline 16.1 per cent., hornblende 11.1 per cent., biotite 8.3 per cent., epidote 2.7 per cent., titanite 1.6 per cent., magnetite 1 per cent., and apatite 0.2 per cent.

These xenoliths are best described as adamellites and are similar in many respects to the xenoliths in the granite at Victor Harbour, South Australia described by Kleeman (15a).

(b) *Uniform-grained granite.*

This differs from the porphyritic granite in being a uniform, medium-grained type with no xenoliths and no "phenocrysts," but very frequent aplite and pegmatite veins. The minerals are the same as in the porphyritic granite. Microcline forms clear irregular grains two to five mm. in size, which poikiloblastically enclose relics of quartz, oligoclase, and biotite. Microperthite is frequently developed. In one fresh looking specimen (22597) the microcline was extremely kaolinised. Oligoclase (Ab_8 An_2) occurs in extremely saussuritised grains (two to four mm.) considered to be relics from the granite gneiss and also in clear grains. Quartz and green chloritised biotite inclusions occur in the saussuritised form. The quartz occurs in two habits (i) small (0.1 to 0.3mm.) rounded inclusions in some of the microcline and oligoclase which may be relics from the granite gneiss, and (ii) larger, irregular, clear grains with an average size of three mm. Biotite is invariably associated with epidote and often with magnetite. It is a greenish-brown variety, X = light brown, Y and Z = dark green-brown to brown. This biotite may be developing from the epidote and magnetite. A pale green anhedral, moderately pleochroic amphibole with an extinction of about 20°, occurs closely associated with a micaceous mineral. The epidote, associated with biotite, is a strongly pleochroic type, optically negative with a large 2V. Pleochroism is from yellow (Z) to colourless (Y). Enhedral titanite, apatite, epidote, and magnetite are accessory minerals.

The approximate composition is microcline 35 per cent., oligoclase 30 per cent., quartz 25 per cent., biotite and amphibole eight per cent., titanite, epidote and apatite two per cent.

(c) *Granite from dyke* (22518).

This is a light grey, fine-grained, gneissic granite which occurs as a small dyke intrusive into the granitic gneiss.

The microstructure is allotriomorphic granitic with slight gneissosity due to flowage. The minerals are saussuritised oligoclase, grain-size 0.5 - 1.0 mm. (45 per cent.); clear microcline 0.5 mm. in diameter and rare phenocrysts up to 5 mm. in diameter (20 per cent.); quartz generally in very small rounded inclusions in the microcline and oligoclase poikiloblasts about 0.1 to 0.2 mm. in diameter and more rarely in larger irregular grains (20 per cent.); and greenish biotite associated with epidote (5 per cent). Apatite, zircon, and rutile are accessories.

(d) *Pegmatites and aplites.*

Pegmatite and aplite veins are frequent in the granites especially the uniform granite. Pegmatite, aplite, and quartz veins occur with less frequency in the granitic gneiss. Possibly some of these veins are genetically related to the Younger Granite. A small graphic granite outcrop occurs in the western band of metasediments in the southern part of the Area. This is a very coarse-grained, white graphic pegmatite (22575), composed of microcline (80 per cent.) up to two inches in grain-size and quartz (20 per cent.), frequently occurring at the edge of microcline crystals. Its genetic relationship is unknown.

A very coarse-grained magnetite-microcline pegmatite (22522) occurs in the granitic gneiss and is thought to have been derived from it in the end stages of crystallisation. Microcline (80 per cent.) grains are one to two inches in size and frequently have a graphic intergrowth of quartz within the grains. Irregular graphic quartz (8 per cent.), saussuritised plagioclase (6 per cent.) and magnetite (2 per cent.) make up the rest of the rock.

The coarse pegmatites, aplogranites, and aplites intrusive into the younger granites are all composed of quartz, saussuritised oligoclase, clear microcline (frequently microperthitic) and accessory epidote and green mica. The average composition is microcline 40 per cent., oligoclase 35 per cent., quartz 25 per cent.

No rare minerals have been found in any of the pegmatites.

Origin of the Younger Granites.—All the younger granites have the same mineral assemblage which is almost identical with the minerals of the granitic gneiss; there appear to be relic minerals (some oligoclase, hornblende, and quartz) of the granitic gneiss in the Younger Granite, and the rounded xenoliths in the porphyritic granite are very similar mineralogically to the xenoliths in the granitic gneiss, (the bluish green hornblende, one to two per cent. titanite and other minerals being common to both). So the Younger Granites appear to be the result of the palingenesis of the granitic gneiss and the xenoliths in the porphyritic granite are relics of the xenoliths in the granitic gneiss.

The "phenocrysts" of microcline with inclusions of all the other minerals were evidently of very late crystallisation. They occur as isolated crystals (fig. 5.) similar to the rapakivi ovoids which develop in the country rocks surrounding the rapakivi granite (25, p. 76) and they have evidently grown from potash emanations from the granite. Granitization, rather than crystallisation from a magma, is thought to have formed these poikiloblasts.

The reason for difference in texture between the porphyritic and the uniform-grained granite is not understood.

The granite dyke and many of the pegmatites are thought to be genetically related to the Younger Granites.

The retrograde metamorphism of sillimanite and cordierite of the metasediments to sericite and possibly the addition of silica in the formation of the cordierite-anthophyllite rock are thought to be the result of contact metamorphism by the Younger Granite.

2. Quartz Dolerites.

These are uniformly hard, dark grey, melanocratic rocks, holocrystalline, with fine to medium grain and a uniform texture.

Under the microscope an ophitic texture, uniform in character, is seen. The pyroxene is a pale purplish, non-pleochroic type, subhedral in form, in grains up to 1.5 mm. diameter partially changed to green uralite on the borders. It is optically positive with very weak dispersion, twinning, 2V approximately 40°, $\beta = 1.656$, extinction $c \wedge Z = 31°$—indicating pigeonitic diopside. The plagioclase is in euhedral laths (0.5 to 1.0 mm. long) showing albite twinning and more rarely pericline twinning. This plagioclase is perfectly fresh labradorite (Ab_{45} An_{55}) with normal gradational zoning sometimes developed. Ilmenite occurs in irregular opaque areas up to one mm. in diameter. It appears to have crystallised in the interstices between the earlier formed plagioclase and pyroxene grains. There is a peripheral reaction rim round the ilmenite of a brownish chloritic material and chlorite stringers pass out into the plagioclase. Quartz and apatite are accessory minerals. Approximate mineralogical composition is labradorite 50 per cent., pyroxene 40 per cent, ilmenite nine per cent., quartz one per cent. The rock is slightly uralitised quartz dolerite.

The borders of the dykes are made up of fine-grained uralitised dolerite showing more advanced uralitisation than the central parts. In these finer-grained rocks the pyroxene is seen to be extensively uralitised to a greenish amphibole which is moderately pleochroic, X = light purplish colour, Y = green, Z = bluish green and the extinction is approximately 16°. Anhedral plates of strongly pleochroic biotite are seen with X = light brown, Y and Z = very dark brownish green. The ilmenite is partially leucoxenised. There are occasional veinlets of epidote.

Order of crystallisation:—pyroxene and labradorite, then ilmenite, and lastly quartz (primary minerals), and, resulting from end phase hydrothermal action and subsequent movement between dyke and country, biotite, epidote, leucoxene, and actinolite. All the dykes are more uralitised at the edges because of subsequent movement between dyke and country rock. Prider (22, pp. 46-48) has studied this phenomenon in more detail at Armadale. The approximate composition is labradorite 48 per cent., pyroxene 25 per cent., actinolite 15 per cent., ilmenite seven per cent., quartz two per cent., biotite and epidote three per cent.

Origin of the quartz dolerites.—These hypabyssal, slightly uralitised quartz dolerites are thought to be part of a very widespread dyke intrusion throughout the State in Late Pre-Cambrian or Lower Cambrian time (24). The dykes were intruded along lines of weakness caused by mild diastrophism.

A narrow zone showing slight contact metamorphism—largely epidotisation of the country rocks—surrounds the dykes.

V. ECONOMIC GEOLOGY.

Refractory minerals and banded iron ore, in the south-west of the area are the only minerals of economic importance in the area.

A. REFRACTORIES.

(i) *Sillimanite.*

Refractory clays derived from the kaolinisation of sillimanite mica schists of the Jimperding Series have been quarried for the manufacture of firebricks at Clackline for some years (26, p. 11; 16, p. 13). The sillimanite content of the clay is estimated to vary from five to 10 per cent. of the rock (26, p. 12).

(ii) *Sand.*

A pure white quartz sand derived from the quartzites in the west of the area is being utilised by the Clackline Firebrick Company.

B. CHARCOAL IRON.

Banded iron ore deposits occur two miles west-north-west from Clackline Railway Station. These have been mapped and described by Hobson (G.S.W.A. File 237/1910) who states that up to the end of 1907 they had produced 18,253 tons of iron ore for use as a flux. These deposits are the result of lateritisation of iron-rich metajaspilites of the Jimperding Series. The area of iron-rich rocks is approximately 60 square chains according to Hobson's map; and the average iron content is 45.5 per cent. A plant is being erected at Wundowie, about 10 miles to the west-south-west of Clackline, to obtain pig iron from similar ore, using charcoal as a fuel for smelting.

[Hobson's Map and Report "Proposed drilling in the vicinity of the Clackline ironstone deposits" has since been published in the W.A. Mines Dept. Ann. Rept. for 1945, pp. 58-60.—Ed.]

VI. HISTORY OF THE AREA.

1. In early Pre-Cambrian time argillaceous, arenaceous and iron-rich sediments (jaspilites) were deposited along with contemporaneous tuffs and basic igneous lava flows or sills.

2. An orogenic period accompanied by the intrusion of a granitic magma followed.

At this stage the sediments suffered regional metamorphism under sillimanite zone conditions and considerable plastic flowage took place in the less competent argillaceous facies. There was no further orogeny or regional metamorphism after this period.

3. The granitic magma did not completely crystallize until after the folding had ceased (23, p. 109). It consolidated as granitic gneiss sills of huge size which indicates that the folding had taken place at considerable depth (4, p. 294, 2, p. 81).

4. A relatively short time, geologically speaking, after the complete consolidation of the granitic gneiss, palingenesis of the granitic gneiss and sediments of the Jimperding Series took place. At the end of the orogenic period the base of the orogene would be at a great depth and under great pressure due to the superincumbent load of sediment. A lag in isostatic adjustments appears to occur after orogeny in which the surface projections of the orogene are eroded. The erosion of the surface part of the orogene would reduce the pressure on the acid rocks at depth so that palingenesis may have followed (18, pp. 330-332).

This palingenic granite magma (the Younger Granite) was now intruded into the Jimperding Series. Some contact metamorphism was effected by this intrusion, probably the most important change being the retrograde metamorphism of the earlier formed high-grade sillimanite and cordierite to sericite.

5. In Late Pre-Cambrian (Nullagine) or Lower Cambrian time (24), after considerable erosion had taken place, quartz dolerite dykes were intruded along lines of weakness possibly caused by mild diastrophism.

The cataclasis noted in some of the granitic gneisses and quartz veins and the epidotisation of country along veins emanating from the dykes may have occurred at this stage.

6. A long period of erosion followed, culminating in a peneplain on which residual laterite deposits were formed in Miocene (29, p. 17, 32, p. 125) or Pliocene times. There was probably a moderate to high rainfall at the time of formation of the laterite (20, p. 47, 29, p. 19).

7. A new cycle of erosion was initiated by the epeirogenic uplift of the ancient peneplain to form the Great Plateau of Western Australia in Pliocene and Pleistocene times (8, p. 288). The area is now a dissected plateau with laterite-capped mesas and buttes representing residuals of the old peneplain, above which project ridges of more resistant quartzites.

VII. ACKNOWLEDGMENT.

I wish to express my deepest thanks to Professor E. de C. Clarke for his many helpful suggestions and discussions during the preparation and revision of this paper.

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VIII. LIST OF REFERENCES.

1. Alderman, A. R., 1942, "Sillimanite, Kyanite and Clay Deposits near Williamstown, South Australia." *Trans. Roy. Soc. S. Aust.*, Vol. 66 (1), pp. 3-14.
2. Balk, R., 1937, "Structural Behaviour of Igneous Rocks." *Geol. Soc. America, Mem.* 5.
3. Bastin, E. S., 1909, "Chemical Composition as a Criterion in Identifying Metamorphosed Sediments." *Journ. Geol.*, Vol. 17, pp. 445-472.
4. Bucher, W. H., 1933, "The Deformation of the Earth's Crust. An inductive approach to the problems of Diastrophism." Princetown University Press, Princetown.
5. Canavon, F., and Edwards, A. B., 1938, "The Iron Ores of Yampi Sound, Western Australia." *Proc. Aust. Inst. Min. & Met.*, NS. No. 100.
6. Clarke, E. de C., 1930, "The Pre-Cambrian Succession in Some Parts of Western Australia." *Rept. Aust. Assoc. Adv. Sc. for 1930*, pp. 155-192.
7. Clarke, E. de C., 1938, "Middle and Western Australia." *Bd. 1 Abs. VII of Reg. Geol. der Erde, Akad. Verlag.* (Leipzig).
8. Clarke, E. de C., Prider, R. T., and Teichert, C., 1944, "Elements of Geology for Western Australian Students." (Univ. of W.A. Text Books Board, Perth.)
9. Cole, W. F., and Gloe, C. S., 1940, "The Geology and Physiography of the Malkup Area." *Journ. Roy. Soc. W. Aust.*, Vol. XXVI, pp. 139-171.

10. Ellis, H. A., 1939, "The Geology of the Yilgarn Goldfield South of the Great Eastern Railway." *Geol. Surv. West Aust. Bull.* 97.

11. Fermor, L. L., 1909, *Mem. Geol. Surv. India*, Vol. XXXVII, pp. 381-3.

12. Forman, F. G., 1937, "A Contribution to our Knowledge of the Pre-Cambrian Succession in some parts of Western Australia." *Journ. Roy. Soc. W. Aust.*, Vol. XXIII, pp. xvii-xxviii.

13. Harker, A., 1932, "Metamorphism" (Methem and Co. Ltd., London).

14. Jutson, J. T., 1912, "Geological and Physiographical Notes on a Traverse over Portions of the Darling Plateau." *Geol. Surv. W. Aust., Bull* 48, pp. 138-173.

15. Jutson, J. T., 1934, "The Physiography (Geomorphology) of Western Australia." *Geol. Surv. W. Aust. Bull.* 95.

15a. Kleeman, A. W., 1937, "The nature and origin of the so-called diorite inclusions in the granite of Granite Island." *Trans. Roy. Soc. S. Aust.*, Vol. LXI, pp. 207-220.

16. Matheson, R. S., 1938, "Report on the Clackline Firebrick Clay Pits (South-West Division)." *Geol. Surv. West Aust. Ann. Rept. for 1937*, p. 13.

17. Miles, K. R., 1941, "The Jasper Bars and Related Rocks of Western Australia. (Unpublished D.Sc. Thesis at the University of Western Australia.)

18. Nevin, C. M., 1936, "Principles of Structural Geology, Second Edition." (John Wiley & Sons Inc., New York.)

19. Phillips, F. C., 1937, "A Fabric Study of some Moine Schists and Associated Rocks." *Q.J.G.S.*, Vol. XCIII, pp. 581-620.

20. Prescott, J. A., 1931, "The Soils of Australia in Relation to Vegetation and Climate." *C.S.I.R. Australia, Bull.* 52, pp. 9-70.

21. Prider, R. T., 1940, "Cordierite- Anthophyllite Rocks Associated with Spinel-Hypersthenites from Toodyay, Western Australia." *Geol. Mag.*, Vol. LXXVII, pp. 364-382.

22. Prider, R. T., 1941, "The Contact Between the Granitic Rocks and the Cardup Series at Armadale." *Journ. Roy. Soc. W. Aust.*, Vol. XXVII, pp. 27-55.

23. Prider, R. T., 1944, "The Petrology of Part of the Toodyay District," *Journ. Roy. Soc. W. Aust.*, Vol. XXVIII., pp. 83-137.

24. Prider, R. T., 1948, "Igneous Activity, Metamorphism and Ore-Formation in Western Australia." *Journ. Roy. Soc. W. Aust.*, Vol. XXXI, pp. 43-84.

25. Read, H. H., 1944, "Meditations on Granite, Part Two." *Proc. Geol. Ass.*, Vol. LV, Pt. 2, pp. 45-93.

26. Simpson, E. S., 1935, "Contributions to the Mineralogy of Western Australia, Series I." *Journ. Roy. Soc. W. Aust.*, Vol. XXII, pp. 1-18.

27. Simpson, E. S., 1937, "Contributions to the Mineralogy of Western Australia, Series XI." *Journ. Roy. Soc. W. Aust.*, Vol. XXIV, pp. 107-122.

28. Washington, H. S., 1917, "Chemical Analysis of Igneous Rocks." *U.S. Geol. Surv. Prof. Paper* 99.

29. Whitehouse, F. W., 1940, "Studies in the Late Geological History of Queensland." *Univ. of Queensland Papers (Geol.)*, Vol. 2 (N.S.), No. 1, pp. 1-74.

30. Wiseman, J. D. H., 1934, "Central and South-West Highlands Epidiorites. A Study in Progressive Metamorphism." *Q.J.G.S.*, Vol. XC, pp. 354-417.

31. Woolnough, W. G., 1927, "The Chemical Criteria of Peneplanation. The Duricrust of Australia." *Journ. Proc. Roy. Soc. N.S.W.*, Vol. LXI, pp. 1-53.

32. Woolnough, W. G., 1930, "The Influence of Climate and Topography in the Formation and Distribution of Products of Weathering." *Geol. Mag.*, Vol. LXVII, pp. 123-132.

3.—CONTRIBUTIONES FLORAE AUSTRALIAE OCCIDENTALIS XII.

By

CHARLES AUSTIN GARDNER.

Read 11th June, 1946.

INTRODUCTION.

Amongst the large number of undescribed species selected from the material worked over during the past year, three of unusual interest have been selected for early publication. In September, 1945, whilst engaged on a survey of plants for examination for their economic possibilities as potential sources of drug materials, two interesting psammophytes growing in the sandy flat of the Mortlock River came to notice. A search for fruiting material was subsequently made in October, December and January, but without success, only one ripe and partially damaged fruit being found unattached below one of the plants, but sufficient is now known to place these plants in the family Chenopodiaceae, although they seem to be anomalous in this family. The solitary flowers, strictly unisexual and dioecious, the homomorphic perianth, and the absence of bracteoles, together with the stamens isomerous with and opposite to the perianth-segments, and the three-partite styles, make these plants quite distinct from anything hitherto described, and show a certain affinity to the Caryophyllaceae, although the position of the stamens and the nature of the styles is entirely that of Chenopodiaceae. Remarkable too is the the difference in the phyllotaxis of the two species,—in one closely spirally imbricate leaves; in the other opposite leaves or the leaves in opposite fascicles, with elongated internodes and spinescent branches. The former has the habit of some species of *Pycnophyllum* (Caryophyllaceae); the latter is reminiscent of *Rhagodia* (Chenopodiaceae). This genus I have named *Roycea*, after my companion of these travels, who first noticed *R. pycnophylloides* by reason of its bright orange-red anthers protruding from the sand-covered tufts of the plant. The second species was discovered while searching for fruits of the first. Until ripe fruits have been found, it would be unwise to assign this new and interesting genus to any particular section of the family.

The second genus is of exceptional interest from the point of view of plant-geography, since it forms another link between the American and Australian continents.

In March, 1944, Mr. C. D. Hamilton, the District Forester at Mundaring, a township less than thirty miles from Perth, brought me a branch of *Daviesia pectinata* from which protruded the flowers of a species of *Pilostyles*, of the Section *Eupilostyles*. The occurrence of this genus in South Western Australia is of more than passing interest; not only is it the first record of any of the

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Rafflesiaceae in Australia, it is also a species belonging to a Section of a genus hitherto recorded only from America, and it is, apart from *Trichocline*, the only genus restricted to South America and South Western Australia. This relationship, usually exhibited by the Antarctic Element, is, as a rule, more strongly represented in New Zealand, Tasmania and Victoria than in any other part of Australasia, and is exemplified most strongly by Proteaceae, *Centrolepis*, Stylidiaceae and Epacridaceae.

The distribution of the Rafflesiaceae is interesting. Of the four Tribes, the Rafflesieae, all large-flowered species, are restricted to the Indo-Malayan region ;—*Rafflesia* with 12 to 13 species being found in Malaya, Malacca, Borneo and Sumatra ; *Sapria*, with one species endemic in the Eastern Himalayan region, and *Rhizanthus* with two species from Java, Sumatra, Borneo and Malacca. All of these are found on the roots and stems of the Vitaceae. The Tribe Mitrastemoneae, with the single genus *Mitrastemon*, comprising three species, extends from Southern Japan to Sumatra, and is parasitic on the roots of Fagaceae. The Tribe Cytineae includes two genera, *Cytinus* and *Bdallophyton* ; the former, with six species, extends from the Mediterranean Region to South Africa and Madagascar, and has various host plants, while the latter genus, *Bdallophyton*, with four species, is restricted to Mexico, and also has various host plants.

The Tribe Apodantheae comprises two genera, *Apodanthes* and *Pilostyles*. The former, with two species, is parasitic on the Flacourtiaceae (*Casearia*) and is restricted to Tropical America. *Pilostyles* on the other hand, is the most widely distributed genus of the family. §*Eupilostyles* Harms, has fifteen species extending from California and Texas to Brazil and Chile. The various species are parasitic on the three families of the Leguminosae, each species occurring on a single genus, five occurring on *Calliandra* and *Mimosa* (Mimosaceae), three on *Bauhinia* (Caesalpiniaceae) and the remainder on *Dalea*, *Adesmia*, *Galactia* and *Parosela* (Papilionaceae). The new species described below is the first extra-American species to be recorded, and is parasitic on a genus of the Podalyrieae (Papilionaceae). § *Astragalanche*, with one species, is restricted to Persia, where it occurs as a parasite on species of *Astragalus* (Papilionaceae-Galegeae), and the § *Berlinianche* with two species is restricted to tropical Africa, where it occurs as a parasite in the branches of *Berlinia* and *Brachystegia* (Caesalpiniaceae-Amherstieae).

Pilostyles is perhaps the smallest-flowered genus of the Rafflesiaceae, and all appear to be stem parasites with a restricted range of host-plants. The new species is related to the American plants, just how closely I do not know, but the absence of a distinct perianth-tube, the clawed perianth-segments, and the canal or tube of the column of the male flower are points which I have not been able to associate with any other species of this Section.

The evidence suggests that *Pilostyles* is an Antartic Element which had its origin in the great southern land. The main branch (§ *Eupilostyles*) had two migration routes—one northwards in the American continent, where its distribution now extends over the tropical and warm regions, and a second migration route of which the only evidence we possess is this new species in South Western Australia. The § *Berlinianche* of tropical Africa, represent a third migration route which may have terminated there, and this appears probable, for there are structural peculiarities in this Section which indicate that the Persian species is not derived from them. The Persian species (§ *Astragalanche*) seems to be most closely related to the South American species. If this is true, then it is probable that is has reached Persia by way of the great traffic route which formerly extended from Antarctica to Europe by way of Australia and Persia, with India and the Mediterranean as intermediate points. If such is the case, then *Pilostyles* should be looked for in Eastern Australia. The fact that it has only now been discovered in South Western Australia, and so close to the Metropolis, indicates how little known the Australian flora is today, and further, the species which is only in evidence when in flower (and perhaps also in fruit) may easily be mistaken for some monstrosity, such as a gall-flower.

Pilostyles Hamiltonii *C. A. Gardn.* sp. nov.

Alabastra 2 mm. diam., ovoideo-globosa, solitaria, e cortice irregulariter erumpentia, saepe numerosa. Flores carnosi, exterius atro-purpurei, intus roseo-sanguinei. Bracteae plures, fere 9–11, biseriatae, imbricatae, exteriores ovatae vel ovato-orbiculatae, obtusae, minores longitudine medio perianthii, interiores (fere 5) oblongae vel ovato-oblongae, obtusae, concavae, integrae vel eroso-laceratae. Perianthii segmenta 4–6, soluta, imbricata, ad basin attenuata vel constricta, oblonga vel oblongo-spathulata, integra, obtusa, et sicut bracteae tenuiter striata. Discus epigynus carnosus, sub-verticalis. Columna in floribus masculis cylindrica, fere equalis perianthio vel rare longior, apice incrassata et alte convexa vel capitata, tubulata et breviter bilobata, margine fimbrio-papillosa minutis papillis; antherae numerosae, submargine dense biseriatae, uniloculares, poris terminalibus aperientes, demum evanescentes ita ut raro maturae videri possint. Ovarium in floribus feminis ovoideum vel ovoideo-cylindricum, semi-inferum vel fere superum, uniloculare; discus carnosus, parvus, cum ovario et stigma plus minusve continuus; stigma alte convexa seu capitata, sine additamenta; ovula numerosa, utrinque in parietibus placentae; placentae primum distinctae, demum pandentes, et tunc ovula undique in ovarium sparsa. Fructus ignotus.

Habitat in distr. Darling dicto prope flumen Helena in pago Mundaring Weir, parasitica in caulibus et ramis plantae *Daviesia pectinata*: fl. mense Martio. *C. D. Hamilton*, Martius 1946. (Typus in Herbario Perthense).

Haec planta est memoratu digna non solum quia est unica species huius subgeneris (*Eupilostyles*) extra Americam, sed etiam ob angustam et tubulatam partem genitalium in masculo, et ob segmenta perianthii cum basibus angustis et quasi-ungulatis in floribus amborum sexuum. Haec est prima species in Australia inventa, et inventa fuit parasitica in quodam genere *Podalyriearum*.

Haec planta vocata fuit in honorem Caroli Donaldi Hamilton cuius sapientibus observationibus ego in notitiam plantae veni. Nomen etiam praestat avo suo mortuo, A. G. Hamilton, qui suis operibus, notatu dignis, scientiae plantarum Australiae contulit.

ROYCEA.

Roycea *C. A. Gardn.* gen. nov. (Chenopodiaceae-Chenopodioideae).

Flores dioici, ebracteati et ebracteolati, profunde 4–5-fidi, tubus breviter turbinatus, segmenta perianthii imbricata, aequalia vel leviter inaequalia, ovata vel obovata (rarius orbicularis), concava obtusa, marginibus membranaceis et ciliatis, dorso pubescentibus, post anthesin persistentia et immutata. Flos masculis: stamina numero partium perianthii isomera iisque opposita; staminodia nulla; filamenta subulata, libera, hypogyna, perianthio longiora vel breviora, antherae dorsifixae, didymae, ovatae, biloculares, loculi paralleli; ovarium rudimentarium. Flos femineus; Perianthium ut in masculis; stamina et staminodia nulla; ovarium superum, ovoideum, vertice in stylum brevem angustatum, uniloculare; stylus terminalis, rami 2–3, obscuro-purpurei, elongati, introrsum papillosi (vel stigmata 2–3 sessilia basi connata vel fere libera, interdum elongata); ovulum solitarium, amphitropum e funiculo basali elongato suspensum. Fructus probabiliter utriculus membranaceus, perianthio inclusus, indehiscens, in statu maturo non visus.—Suffrutices humiles, glabri vel pubescentes; caules teretes, erecti vel decumbentes. Folia exstipulata, spiraliter disposita et arcte imbricata, vel opposita cum longis internodiis, integra, plus minusve concava. Flores virides, parvi, sessiles, solitarii, axillares vel terminales. Perianthium post anthesin persistens, immutatum.

Nominavi in honorem Roberti Dunlop Royce, adjutoris Herbarii Perthensis, qui has species mecum legit.

Hoc genus videtur esse aliquantulum anomalum in familia Chenopodiacearum, et ejus locum systematicum, fructu maturo non viso, remanet obscurum. Plantae videntur esse stricte unisexuales, et foliorum copia est insueta. Genus habet quandam similitidinem cum *Caryophyllaceis* (*Alsinoideis-Pycnophylleis*), sed stamina hypogyna stylusque etc. sunt Chenopodiacearum. Plantae occurrunt cumulatae in salinis arenis in alveo fluminis "Mortlock" prope Meckering, in caules foliique earum remanent fere totaliter sepulti in terra; solis antheris de facto, conspicuis remanentibus, specialiter in *R. pycnophylloides*, et plantae adhuc non florescentes facile inadvertuntur. Variis conatibus non obstantibus a mense Septembri usque ad Januarium fructum maturum non fuit inventum; et semina frondes inventa, sunt semina cuiusdam plantae e *Caryophyllaceis*. Attamen evidentia sufficiens obtenta est ad affirmandum factum quod fructum sit utriculum. In abscentia melioris materialis (fructus) hic ponendus est forsitan immediate post *Enchylaena*.

1. **Royeca pycnophylloides** *C. A. Gardn.* sp. nov.

Suffrutex ramosus, ramulis numerosis, plus minusve fastigiatis, pubescentibus; foliis dense spiraliter dispositis, arcte imbricatis. Folia ovato-oblonga vel ovata, sessilia, exstipulata, plus minusve concava, uninervia, glaucescentia, marginibus membranaceo-ciliata, 2 mm. longa. Flores parvi, virides, terminales vel in axillis superioribus solitariis, sessiles, inconspicui. Perianthium vix 1 mm. longum, 4–5–partitum, tubus brevissimus aut plus minusve nullus, segmenta ovata vel obovata, raro orbicularia, obtusa, marginibus membranaceis et albo-ciliatis, dorso pubescentibus. Stamina in floribus masculis 4–5, perianthii segmentis opposita et isomera; filamenta subteretia, glabra, segmentis perianthii aequilongis; antherae roseo-auratae, magnae, late ovatae; ovarium rudimentarium. Flos femineus; Perianthium sicut in floribus masculis. Ovarium liberum, ovoideum, stylus brevis, profunde divisus, lobis erecto–patentibus, perianthii segmentis longe excedentibus. Fructus ignotus.

Hab. in distr. Avon, prope Meckering, in flumine "Mortlock River," in aperte arenosis salinis, fl. m. Septem. *Gardner* 7659. (Typus in Herbario Perthense).

2. Roycea spinescens *C. A. Gardn.* sp. nov.

Suffrutex ramosus, ramis ramulisque erectis, rigidis, ramulis in spinam terminantibus. Folia opposita vel in fasciculis oppositis, oblonga, integra, sericeo-pubescentia, demum glabriuscula, ad basin in calcarem breviter resoluta infra insertionem, concava vel leviter carinata, coriacea, obtusa, apice paulu-lum recurva, 2·5–3·5 mm. longa. Flores solitarii vel gemini, sessili in axillis vel fasciculis foliorum. Perianthium globosum, profunde 4–5 fidum, segmenta fere libera, late obovata, ovata vel orbicularia, marginibus membranaceis et ciliatis, late hyalinis exterius pubescentibus, 2 mm. longa. Stamina segmentis opposita eisque isomera, libera, filamenta segmentis vix excedentia. Ovarium in floribus masculis abortivum, cylindricum, pubescens. Perianthium in flore feminea ut in masculis. Ovarium ovoideum, sursum pubescentem, stylus brevis, profunde divisus, lobis atro-purpureis, perianthii segmentis longe excedentibus, demum patentibus.

Hab. in distr. Avon prope Meckering, in locis depressis salinis (ita dictis "Mortlock River") fl. m. Oct. *Gardner* 7659a. (Typus in Herbario Perthense).

Haec species tam dissimilis *R. pycnophylloides* in habitu et phyllotaxis (seu foliorum formationem) crescit simul cum specie dicta, sed in locis leviter minus salinis.

Plate I.

Pilostyles Hamiltonii *C. A. Gardn.*

Parasitic on stems of *Daviesia pectinata* Lindl.

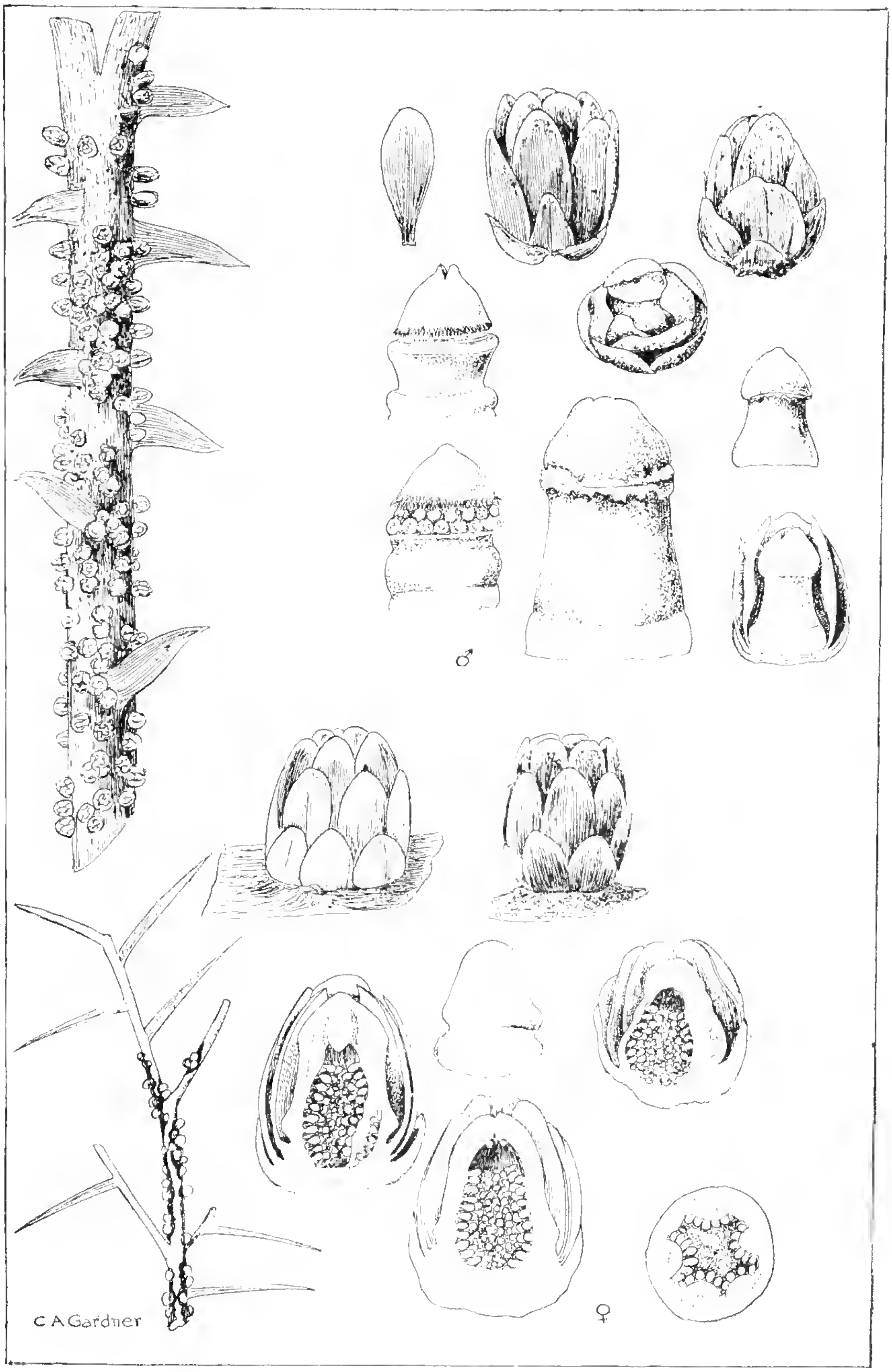
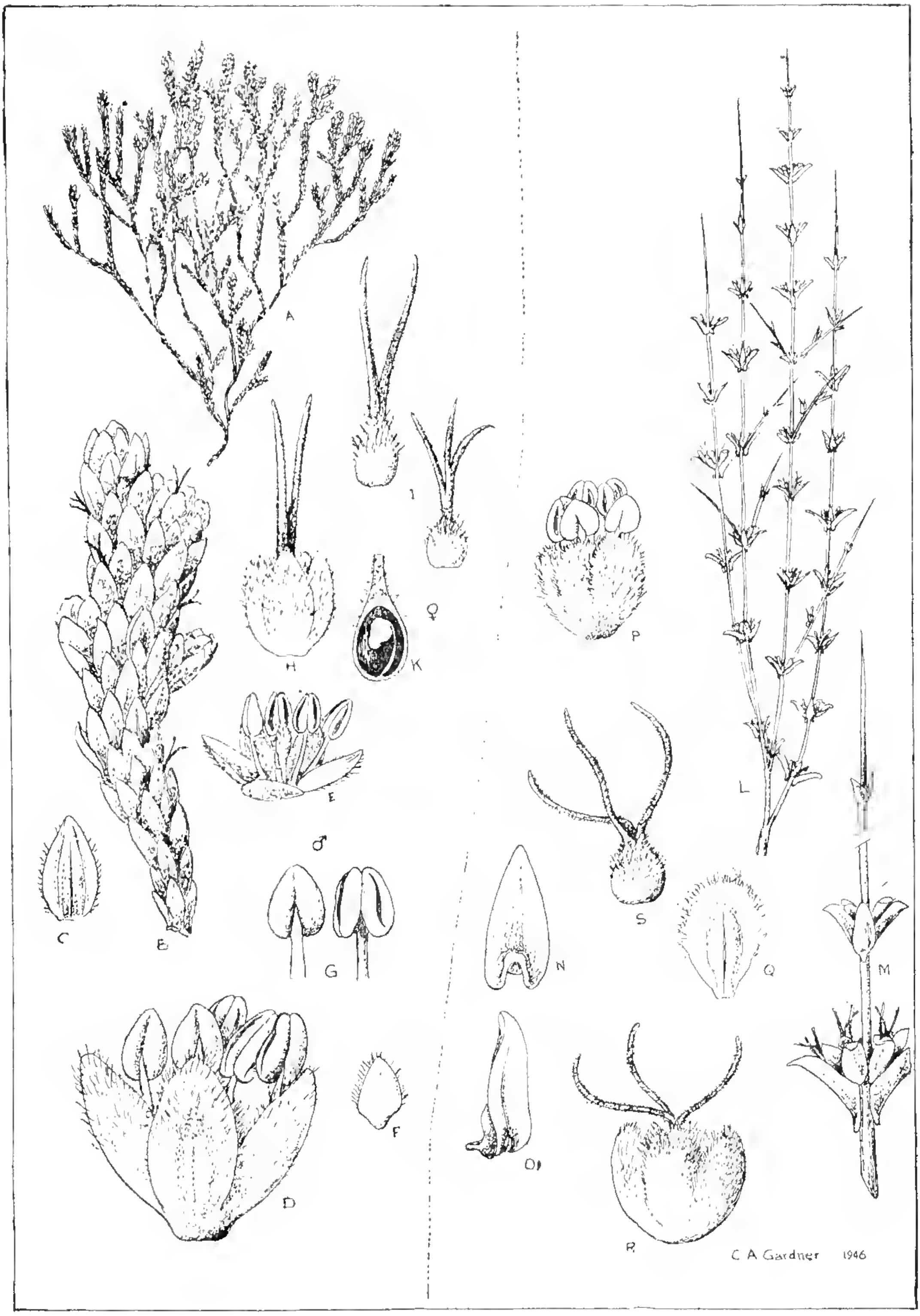

♂
♀
C A Gardner

Plate II.

Roycea *C. A. Gardn.*

A–K, **R. pycnophylloides** *C. A. Gardn.* A, habit. B, branchlet. C, leaf. D and E, ♂ flowers. F, perianth-segment. G, anthers. H, ♀ flower. I, ovaries and styles. K, section through ovary. L–S, **R. spinescens** *C. A. Gardn.* L, habit. M, branchlet. N, under-surface of leaf. O, side view of leaf. P, ♂ flower. Q, perianth-segment. R, ♀ flower. S, ovary and style.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4.—TERTIARY DEPOSITS NEAR NORSEMAN, WESTERN AUSTRALIA

By

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(With an Appendix by IRENE CRESPIN.)

Read: 9th April, 1946.

CONTENTS.

I. INTRODUCTION.

1. LOCALITY.

Norseman, one of the most southern gold-mining towns of Western Australia, is about 350 miles east of Perth and 100 miles north of the southern port Esperance. It lies on an auriferous "greenstone" belt on the east shore of Lake Cowan and is connected by rail with Esperance and with Coolgardie on the Trans. Australian Line.

Gold was discovered in the Norseman district in 1892 and is still being produced: the output in 1943 was about 40,000 oz.

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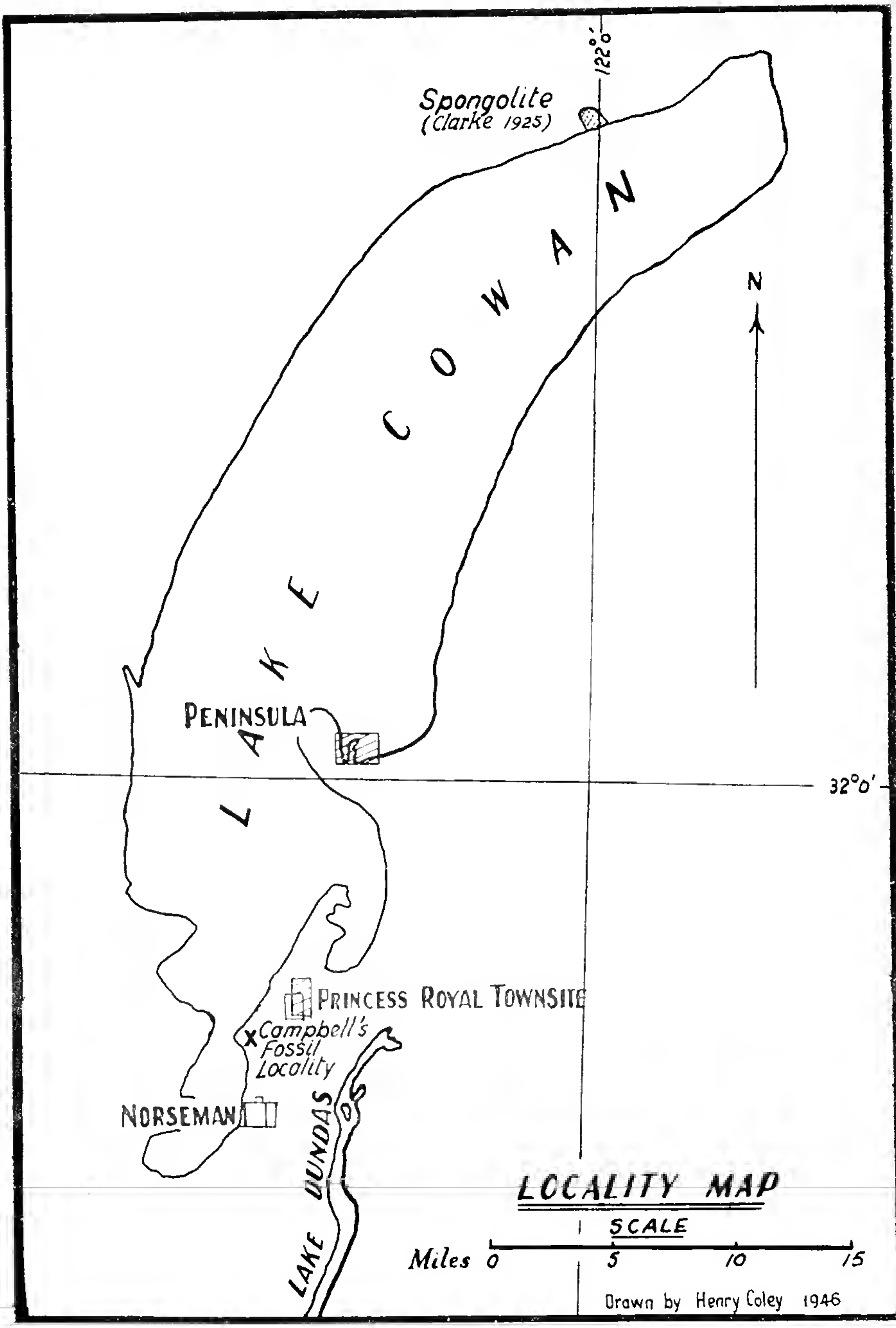


Text fig. 1.
Locality Map showing occurrences described in this paper.

2. Topography.

The average annual rainfall of this part of the State is about 10 inches and the average evaporation is well over 100 inches; consequently Lake Cowan, like the many lakes farther inland, is nearly always dry.

The floors of the salt lakes of Western Australia are almost perfectly smooth and, after heavy rain, may for a short time be covered with water which is rarely as much as three feet deep.

Lake Cowan, and Lake Dundas 5 miles farther east, occupy shallow depressions, about 900 feet above sea-level which are elongated in a north-south direction approximately parallel to the strike of the Pre-Cambrian rocks on which they lie. A bore sunk in 1896 in the lake-bed just west of Norseman traversed 377 feet of lacustrine muds before reaching Pre-Cambrian rocks (Campbell, 1906, p. 15), so that the depth of part of the depression occupied by Lake Cowan was once of the order of 400 feet.

Most of the auriferous greenstone belts of Western Australia are more hilly than the surrounding country, apparently because the greenstones are more resistant to the agents of arid erosion than are the other rocks of the Pre-Cambrian complex, but the Norseman greenstone belt with its long, narrow, steep, north-trending ridges and v-shaped valleys shows unusually high relief. A large dyke of norite (Campbell, 1906, p. 24 and fig. 5) with an easterly strike forms a line of hills cutting across the

Text fig. 2.
Norseman and the southern part of Lake Cowan from the ridge just east of the town.

greenstone ridges: it appears to continue for many miles across the plain country which borders the greenstone belt and which is probably composed of the more easily eroded "whitestones" of the Kalgoorlie-Yilgarn System.

3. PREVIOUS WORK.

Fossiliferous deposits in this district were discovered by W. D. Campbell. He described them briefly (1906, p. 22), as a "unique opalized remnant of an old sea beach at about 35 feet above the present level of Lake Cowan containing either late Tertiary or Recent marine shells, such as *Turritella, Pecten, Cardium* or *Cardita*, and *Magellania*, and numerous fragments of other shells, *Echinii* and *Polyzoa*." He also found several outcrops of unfossiliferous dolomite (*loc. cit.* p. 21) in the area north and north-east of Norseman which he regarded as being of the same age, presumably Tertiary.

Mr. Gibb Maitland, the State Government Geologist at that time, stressed (1907) the interest of Campbell's discovery. Hinde (1910) reported on some siliceous rocks from a "deep lead" (the inverted commas are Hinde's) at Princess Royal Township, eight miles north of Norseman. This deep lead had been discovered in 1901 (Woodward, 1902) and gold had been obtained from it at a depth of 88 feet. Hinde found that the rock penetrated by the workings was a spongolite in which he identified many different types of sponge spicule. Its relationship to the gold bearing rocks was not recorded. He suggested that the spongolite is probably "newer than Cretaceous" in age.

That spongolite rocks have a wide distribution in the Norseman district was suggested by the discovery (Clarke, 1925, p. 12) of low cliffs of sponge spicule rock on the north shore of Lake Cowan, about 30 miles N.N.E. of Princess Royal.

Although no further field investigation of the fossiliferous rocks had been made, Gregory (1916) suggested, mainly from the identification of some Bryozoa, that the rocks in which Campbell had found marine shells were of Miocene age.

Chapman and Crespin (1934) published determinations of a number of pelecypod and gastropod species and of one brachiopod (*Magellania insolita*) from Campbell's "opalized sea beach", but they did not discuss the age of the beds, though it is clear from the context of their paper that they regarded them as Miocene.

4. PRESENT INVESTIGATIONS.

It is obvious that the occurrence of Tertiary rocks so far inland on the Pre-Cambrian shield throws light on the later geological history of this part of Australia but no further field study of the fossiliferous beds had been made since Campbell's time, until in 1943, Mr. H. W. B. Talbot informed us of the discovery of a new fossil locality at the Peninsula, 15 miles north of Norseman, and gave some specimens of fossiliferous limestone to the Department of Geology. In May, 1944, we were able to spend two weeks in the Norseman district examining the fossiliferous and other sedimentary deposits along the eastern side of Lake Cowan between Norseman and the east coast of the Peninsula, including the

Princess Royal deposits. We also visited an area near the northern end of Lake Dundas, where Campbell had reported the occurrence of unfossiliferous dolomites.

5. ACKNOWLEDGMENTS.

The expenses of the excursion were defrayed by the Commonwealth Research Grant to the University of Western Australia. Transport in the Norseman district was generously provided by Central Norseman Gold Mines. We wish to express our gratitude to Mr. W. Lindesay Clark, director of the Western Mining Corporation, to Mr. H. W. B. Talbot, geologist to the Corporation, and to Mr. W. Dutton, superintendent of the Central Norseman Gold Mines for their courtesy and help, without which these observations could not have been made. We are also indebted to Dr. R. T. Prider for help in revising the text.

II. SITUATION OF OUTCROP AREAS OF THE TERTIARY SEDIMENTS.

So far as known at present the Tertiary sediments occur in patches, isolated by erosion, along the east side of Lake Cowan and near the north end of Lake Dundas about five miles north-east of Norseman. The occurrences which we examined may be grouped into the following five "outcrop areas":—

(1) Campbell's "opalized sea beach," three miles north of Norseman.

(2) The spongolite deposits which underlie part of the old Princess Royal Townsite and extend west of it. To the north, between Princess Royal and Lake Cowan and on the shores of the lake itself are several disconnected patches of unfossiliferous dolomite which might be included in this outcrop area.

(3) A number of limestone and dolomite outcrops, mostly fossiliferous, along the north side of the Peninsula, about 15 miles north of Norseman.

(4) Unfossiliferous dolomite outcrops on the north shore of Lake Dundas, five miles north-east of Norseman.

(5) A spongolite occurrence at the north end of Lake Cowan. This was visited by one of us (E. de C.C.) many years ago.

It is to be expected that a close survey of the shores of Lake Cowan and Lake Dundas will reveal the presence of additional outcrops.

III. ROCK TYPES.

There are three main rock types in these Tertiary deposits:—spongolite, unfossiliferous dolomite, and fossiliferous limestone and dolomite.

1. The *spongolite* is porous, white to orange-red in colour, and very light in weight. It is composed of the spicules of siliceous sponges of which many species were identified by Hinde (1910). Associated with the typical spongolite are beds of blue clay and white shale only a few feet thick. The blue clay is a light bluish-grey rock with occasional white

spots up to 15 mm. in diameter and irregularly scattered reddish-brown spots. Microscopic examination and heavy mineral determinations showed that it is largely composed of extremely fine particles of clay minerals with a smaller amount of fine-grained, angular quartz, iron ores, and hypersthene; the hypersthene was no doubt derived from the adjoining norite dyke which was mentioned in the introduction. The white shale is exceedingly fine-grained, white, and slightly friable and contains a minute amount of very fine-grained quartz, iron ores, and hypersthene. Sponge spicules occur in both rocks but are not numerous.

2. The *unfossiliferous dolomite* (Campbell, 1906, p. 21) is a hard, white, fine-grained rock. Staining tests (Rodgers, 1940) show that it is an almost mono-mineralic dolomite containing occasional fragments of quartz up to one mm. in diameter and still rarer rounded bodies of ferruginous material up to three mm. in diameter which may be concretions but are more probably pebbles. Neither fossils nor any sign of bedding can be seen in this rock which is included in the Tertiary series because it overlies the Pre-Cambrian rocks and occurs near strata known from their fossils to be Tertiary in age.

3. There are several varieties of *fossiliferous limestone*. Some are unaltered, others have been changed diagenetically to siliceous or to dolomitic rocks. They vary in character even in one outcrop, and will therefore be discussed in the next section.

IV. DESCRIPTION OF OUTCROPS.

1. CAMPBELL'S "OPALIZED SEA BEACH."

A very gently undulating area of about 100 acres covered with unfossiliferous dolomite (Campbell, 1906, fig. 11) occurs near the Norseman end of the causeway over Lake Cowan, about three-and-a-half miles north of Norseman on the south side of the great norite dyke. At the eastern end of this occurrence there are two small fossiliferous outcrops, about 10 yards apart which underlie the unfossiliferous dolomite. About 100 yards farther east is a knoll over which are scattered many fragments of chrysoprase. The fossiliferous rocks are opalized and it is difficult to determine their original characteristics, but there appear to have been three types:—

(a) Fine laminated sandstone.

(b) Very fine-grained mudstone with conchoidal fracture and few fossils.

(c) Sandy limestone with opalized fossils and rounded to angular sand grains.

The sandy limestone is more fossiliferous than the other two, but the fossils are very much altered diagenetically and good specimens are hard to obtain.

Miss Irene Crespin (see Appendix) has determined the following Bryozoa from this locality:—*Macropora clarkei* (T. Woods), *Amphiblestrum sp.*, *Hincksina geminata* (Waters), *Cellepora fossa* (Haswell), *Adeonellopsis clavata* (Stol.), *Retepora aciculifera* McG., *Crisia acropora* Busk.

Some years ago Chapman and Crespin (1934, p. 126) gave a list of fossils, other than Bryozoa and sponges, from "Norseman". Since no other fossil beds, with the exception of the Princess Royal spongolite, were then known from the district, these fossils must have come from Campbell's discovery. The list is as follows:—*Magellania insolita* (Tate), *Lima bassi* (T. Woods), *Venericardia spinulosa* (Tate), *Venericardia cf. scabrosa* (Tate), *Corbula* sp., *Turritella tristria* (Tate), *Semiactaeon microplocus* Cossm.

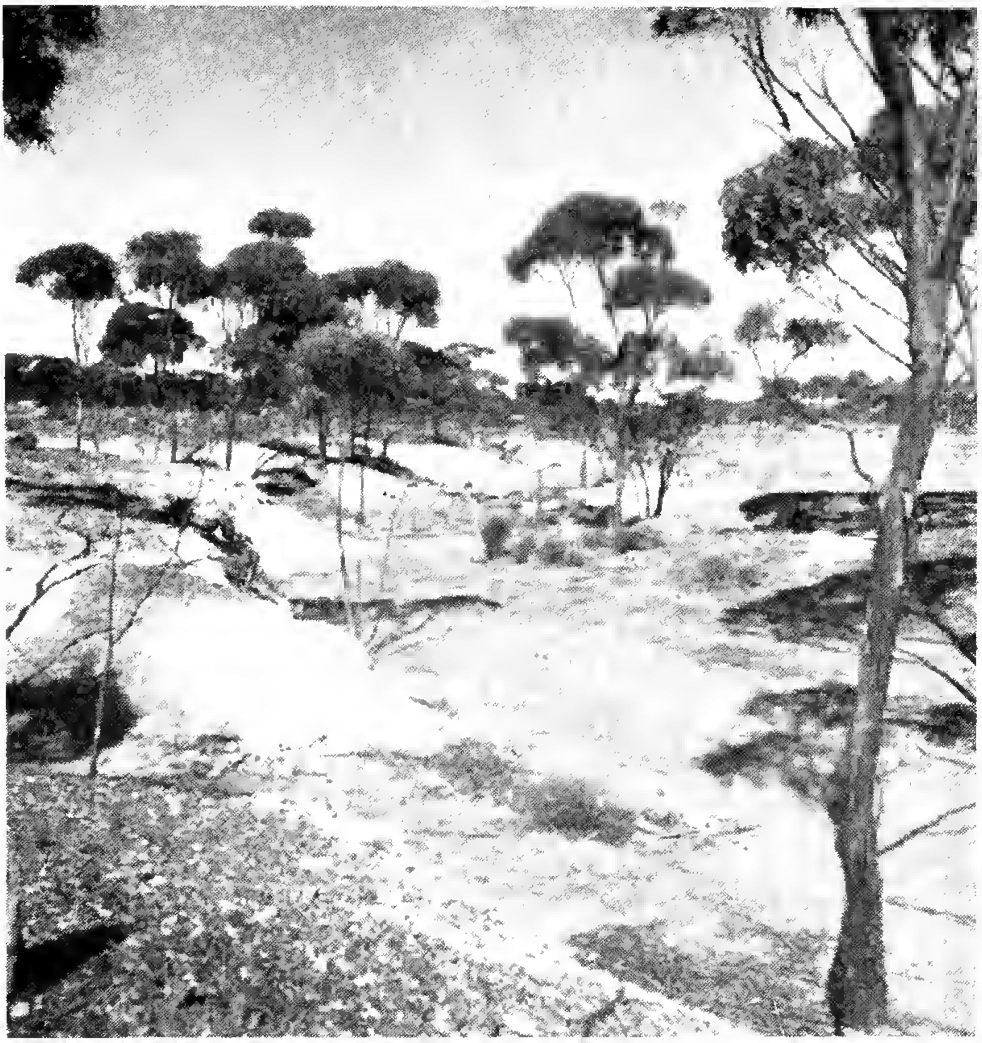
Most of these species have also been recognized in our collections from this locality. We also found representatives of the following:—

Glycimeris sp., *Barbatia* sp., *Cardita* sp., *Cardium arcaeformis* (Chapman and Crespin), *Chlamys aldingensis* (Tate).

Our collection also includes some unidentified gastropods, one or two corals, *Cidaris* spines, and a columnal of *Pentacrinus*.

2. PRINCESS ROYAL.

Spongolite beds occupy an area about one mile long and a quarter mile wide, in the vicinity of Princess Royal (Plate 1). As mentioned above, the spongolite was first discovered in the deep lead under the main street



Text fig. 3.
Breakaway of spongolite, three-quarters of a mile north-west of Old Main Shaft, Princess Royal.

of Princess Royal, but there are rather extensive outcrops in a gully which runs north just west of the townsite and in low breakaways north-west of the townsite.

Text fig. 4.

Contact of Pre-Cambrian and Tertiary rocks in a small gully about eight feet deep, 10 chains west of Old Main Shaft at Princess Royal townsite. Weathered Pre-Cambrian rocks are exposed in the bottom of the gully, blue clay and white shale along the sides. The contact is marked by a black line.

The sediments lie with marked unconformity on Pre-Cambrian rocks which appear to be chiefly amphibolites with occasional porphyry dykes and to belong to the Kalgoorlie-Yilgarn System. The surface of the Pre-Cambrian, at its contact with the spongolite series, is weathered and uneven and is overlain by two feet of blue clay; then come two to four feet of white shale, followed by a bed of spongolite 20 to 25 feet thick which in some places is white and is composed very largely of sponge spicules; in others, where it is red, spicules are not nearly so abundant. These three beds are conformable.

The sediments thicken as we approach L. Cowan because they occupy a north-south depression in the Pre-Cambrian rocks which deepens northwards. On the west, south, and east sides Pre-Cambrian rocks constitute the higher ground so that their contact with the sediments can be mapped, whereas the northern boundary is obscured by alluvium.

The dumps along the deep lead contain spongolite, siliceous oolite, and an oolitic carbonate rock. The oolitic rocks are not found at the surface, and, all the shafts being inaccessible, it can only be assumed that they occur somewhere in the Tertiary series.

About 200 yards north of the last spongolite outcrop is an exposure of dolomite north-west of which there are six or seven others all mapped by Campbell (Campbell 1906, fig. 3). They are all unfossiliferous. The relation of the spongolite to the dolomite has not been seen but the base of the spongolite is about level with the top of the dolomite.

The only palaeontological work on the spongolites was done by Hinde (1910). He considered that the spicules were identical with or closely similar to, those of the following forms previously described:—Monaxonid. *Latrunculia; Desmacidon (Homaeodictya) grandis* Ridley and Dendy; *Petrosia variabilis* Ridley; *Halichondria infrequens* Carter; *Stronggylophora durissima* Dendy; *Forcepia crossancho̦rata* Carter; *Tethya* Lam., *Myxilla hastata* Ridley and Dendy.

Tetractinellid. *Stelletta reticulata* Carter; *Erylus* Gray; *Craniella* Schmidt; *Cydonium mulleri* Fleming; *Geodia zetlandica* Johnston.

Lithistid. *Ragadinia* Zittel; three species of *Discodermia* Bocage; *Corallistes* Schmidt; *Theonella swinhoei* Gray; *Vetulina* Schmidt; *Dactylocalycites* Carter.

Hexactinellid. *Rossella antarctica* Carter.

3. PENINSULA.

The shore of the Peninsula is broken into small bays, islands, sandspits, and promontories (Plate II). Outcrops which we call A, B, and C, of horizontal or very nearly horizontal fossiliferous limestone occur in three of the bays, the shores of which are generally steep banks, in places undercut, two to 15 feet high, formed by various agents of arid erosion and by very occasional corrasion by the lake water. In some of the bays there is a "laterite" layer two to three feet above the bed of the lake but well below the present soil surface.

Locality A is the west bank of the most southern of the bays. The outcrop at locality B in the third bay north of this extends across the floor of the lake to the north side where it disappears under a sand ridge 100 yards wide, on the other side of which, in the next bay, is locality C— a limestone bank 12 feet high and 130 yards long.

Thin sections show that the Tertiary rocks at the Peninsula are composed of fine-grained matrix of dolomite and ferruginous material in which there is a varying percentage of complete or fragmentary fossils with angular, medium-grained quartz particles and more rounded ferruginous fragments and concretions, up to two mm. in diameter. Staining (Rodgers, 1940) shows that calcite occurs only in some of the casts, replacing the original shelly matter, but in most instances the replacing material is dolomitic, and, in some places it is secondary ferruginous matter.

Text fig. 5.
Limestone cliff at Locality A, on the Peninsula, Lake Cowan.

Locality A is a miniature, almost vertical cliff of fossiliferous limestone extending for a quarter of a mile along the west side of the bay. It is 12 feet high and flat-topped at the southern end, but only two or three feet high at the northern end. Like the outcrops at the other localities at the Peninsula it shows great lateral variation in lithology and fossil content. The cliff for 200 yards from the southern end of the outcrop is composed of a hard, massive, light yellow-brown limestone, of which algal fragments and concretions constitute as much as 40 per cent., and echinoid spines and plates, and rare pelecypods five per cent.; the matrix is partly dolomitic and partly ferruginous. For the next 100 yards farther north small pelecypods are very numerous, but Bryozoa and a few gastropods and brachiopods also occur. The section here is 12 feet thick and shows distinct vertical variation in colour and texture. Lensing bands of shell grit compose the upper five feet, well-preserved fossils being found only in the lower seven feet. For the next 50 yards farther north the rock is a dolomitic limestone, being made up in great part of Bryozoa with very subordinate numbers of brachiopods and echinoids. The exposed thickness of this bryozoan limestone is between four and five feet. Outcrops are discontinuous farther to the north, where algal concretions with less frequent gastropods and pectinids occur. The rock is very similar lithologically to the algal limestone at the southern end of Locality A.

Among the more common fossils are *Barbatia dissimilis* Tate, *Cardium arcaeformis* Chapman and Crespin, *Venericardia* sp., *Chlamys murrayana* (Tate), and *Chlamys aldingensis* (Tate). In addition the limestone contains two species of brachiopods and several species of gastropods, as yet unidentified. In samples from the same deposit Miss Irene Crespin has found twelve species of cheilostomaceous and cyclostomaceous Bryozoa (see Appendix).

Locality B consists of four disconnected outcrops on the lake-bed. On the northern shore of the bay the exposed thickness of the bed is two to three feet, elsewhere only one foot is visible. There is considerable lateral

Text fig. 6.
Limestone exposures on lake floor at Locality B, on the Peninsula, Lake Cowan.

variation of species in these disconnected outcrops although they are probably all of the same bed. About 10 chains from the southern headland of the bay is a very fossiliferous limestone composed almost entirely of gastropods. After deposition the shells were dissolved, leaving cavities which have since been lined with crystalline calcite so that the external features of the shells have been lost. The other outcrops are less fossiliferous, containing but a few species of gastropods, pelecypods, Bryozoa, and some echinoid spines. On the north shore of the bay the limestone is very massive and rather similar lithologically to the algal limestone of Locality A but algal concretions are rarer.

The gastropods in this deposit seem to belong to such genera as *Marginella*, *Natica*, *Fusus*, *Bullaria*, and possibly others as well. Among the pelecypods *Barbatia dissimilis* (Tate), and *Cardium arcaeformis* Chapman and Crespin, could be recognized. Some *Cidaris* spines are also present.

At *Locality C* limestone is exposed almost continuously for a distance of about 130 yards in a cliff rising in places to 20 feet above the lake floor. It shows the usual lateral variation in fauna and some lensing of the beds.

Text fig. 7.
Locality C, on the Peninsula, Lake Cowan.

The beds are generally horizontal except at the western end where for a few feet there is a dip to the south of 30° probably due to the action of growing roots and of slumping consequent on undercutting.

The lowest layer of the limestone is about eight feet thick and contains very numerous complete pectinid shells, the lower one or two feet being grey with a light-coloured yellow-brown limestone above. A layer about five feet thick and made up almost entirely of fragments of Bryozoa overlies the pectinid bed. Dolomite two feet thick forms the top of the section and a superficial calcareous travertine rock, a product of arid weathering, overlies the dolomite. The number of species in this deposit is small.

The predominant pectinids are *Chlamys murrayana* (Tate) and *Chlamys aldingensis* (Tate). Other pelecypods include *Modiolaria* cf. *arcacea* (Tate).

4. LAKE DUNDAS.

Dolomite.—At the extreme north end of Lake Dundas, about five miles north-east of Norseman, there are scattered outcrops of unfossiliferous dolomite on the edge of the lake and farther inland. A considerable thickness of superficial gravel and finer alluvial material forms low headlands and terraces along the west side of the lake and in them dolomite crops out. Several short gullies, a mile or two long, which drain the hills of Pre-Cambrian greenstone enter the lake near its northern end and have exposed other patches of dolomite but nowhere is its contact with the Pre-Cambrian visible. Most of the smaller patches are shown on Campbell's map, but the largest which is farthest north-east, on the lake shore near an old track to Israelite Bay, is outside its limits. It is a conspicuous white hill over 100 yards long and rising steeply to about 40 feet above the lake, into which it extends as a narrow headland for about 70 yards. The hill consists of dolomite which is a massive, crystalline, almost monomineralic rock with occasional angular quartz fragments and rounded limonitic pebbles as in the dolomites described earlier in this paper. Weathering of this rock produces a rough, sculptured surface. Low outcrops extend south-west from the hill for 150 yards and the rock appears again in a promontory about 250 yards south of the hill where it is overlain by gravel.

Eucalypt Beds.—Campbell (1906, p. 22) reported the occurrence of silicified specimens of true eucalypt wood (determined by R. Etheridge Jun.) "on the valley flat of the Mary Cater Gully and on the laterite flat on the north side of Israelite Bay Track near Lake Dundas. In the latter locality it occurs in a semi-chalcedonized matrix." Campbell and Etheridge suggested that the wood-bearing strata may be part of the Tertiary series. We were unable to visit the locality.

5. NORTH SHORE OF LAKE COWAN.

The sponge spicule beds at the north end of Lake Cowan were not visited on this trip. Clarke reported that they form "low white cliffs overlooking a small bay on the north shore of Lake Cowan south of the Paris Group." He mapped the approximate outline of the occurrence and submitted a specimen to Simpson (Clarke, 1925, p. 13) who described it thus:—

"The rock is moderately tough, very fine-grained and carries no carbonates. Under the microscope it is seen to be a fine-grained marine silt composed of kaolin and finely-divided quartz with a few recognisable sponge spicules in some bands, and in other bands innumerable siliceous spicules, both hexactinellid and lithistid. There is little doubt that this is an outlier of the Miocene Plantagenet Beds."

V. CORRELATION AND PALAEOGEOGRAPHY

A complete examination of the faunas of the various fossiliferous deposits described in this paper has not yet been made. From a study of the Bryozoa in the rocks of Campbell's "opalized sea beach" and in the limestones at the Peninsula, Miss Crespin (see Appendix) concludes that they are of Middle Miocene age. Other palaeontological evidence is not at variance with this conclusion.

At present there is no evidence as to the age of the sponge spicule deposits of Princess Royal, except the statement by Hinde that it is probably younger than Cretaceous. The stratigraphic evidence presented in this paper is, of course, far from conclusive, but if the fossiliferous beds of Campbell's "opalized sea beach" underlie the unfossiliferous dolomite, if this dolomite is contemporaneous with that north of Princess Royal, and if the latter overlies the spongolites, then it would appear that the spongolite is Middle Miocene.

The base of the sediments is everywhere about 900 feet above sea level. As to the conditions under which the spongolites were formed Hinde (1910, p. 21) stated—

"It seems to me that this Norseman sponge-rock is not a merely local deposit, but that it was formed in the open ocean, at some distance from a coastline, so as to be away from sediment-bearing currents, and probably at a considerable depth. The sponges which furnished the materials of the deposit may have lived, died, and been disintegrated in the same area."

The blue clay and white shale below the spongolite at Princess Royal suggest that sedimentation began under still-water conditions. The amount of coarser detrital matter increases higher up in the sequence, some of the spongolites being quite sandy. The surface of Pre-Cambrian rocks on which the sediments rest is uneven, suggesting a period of subaerial erosion before submergence.

The fossiliferous limestones and dolomites are rather free from detrital material so that they may have been deposited at some little distance from the shoreline. On the other hand many of the shells are broken, and, in the outcrop C at the Peninsula, there is a layer which is almost exclusively composed of worn and rounded fragments of small Bryozoa. It seems likely, therefore, that these beds were formed in rather shallow, disturbed water.

The geographical position of the Norseman sedimentary area is intermediate between the huge limestone platform of the Nullarbor Plain which begins 100 miles farther east and the smaller area, occupied by the Plantagenet Beds, which stretches westward along the coast from the neighbourhood of Ravensthorpe, 150 miles south-west of Norseman. Both the Eucla limestone of the Nullarbor Plain and the Plantagenet Beds are of Miocene age, and it seems most likely that the Norseman sediments are remnants of a sheet of sediments which must have once covered a considerable area of the southern part of the Western Australian shield.

The Miocene transgression in Western Australia has been discussed in recent papers by Clarke (1935) and Teichert (1944). These writers have suggested that at the time of maximum submergence the surface of the shield might have stood about 1500 feet lower than now, i.e., that the sea which covered the area with which this paper deals might have been about 600 feet deep. The sea was almost certainly shallower than this—possibly not more than about 60 feet deep—when the fossiliferous limestones were deposited. Perhaps soon afterwards the sea-floor emerged and the Post-Miocene period of denudation began.

Miss Crespin in the appendix suggests interesting correlations of the Norseman beds with the Balcombian deposits in Victoria and in South Australia.

VI. APPENDIX.

NOTES ON THE BRYOZOA FROM LIMESTONES AT LAKE COWAN AND NORSEMAN, WESTERN AUSTRALIA

BY

IRENE CRESPIN.
(Commonwealth Palaeontologist.)

The preservation of the Bryozoa in the limestones from the above localities is poor, the majority of the specimens being very worn and encrusted. Consequently specific determination of forms is limited.

The following species have been recognized:—

1. LIMESTONE CLIFF, OUTCROP A, PENINSULA

(a) Cheilostomata.

Macropora clarkei (T. Woods)
Cellaria depressa (Maplestone)
Cellepora fossa (Haswell)
Porina gracilis (M. Edwards)
Retepora sp.
Schizellozoon permunitum (McG.)

(b) Cyclostomata.

Spiroporina verticillata (Goldf.).
Mecynoecia proboscidea (M. Eds.)
Idmonea incurva (McG.)
Idmonea sp.
Tecticavea cf. *schnapperensis* (McG.)
Lichenopora radiata (Audouin)

2. CAMPBELL'S "OPALIZED SEA-BEACH" NORSEMAN

(a) Cheilostomata.

Macropora clarkei (T. Woods)
Amphiblestrum sp.
Hincksina geminata (Waters)
Cellepora fossa (Haswell)

Adeonellopsis clavata (Stol.)
Retepora aciculifera (McG.)
Retepora spp.

(b) Cyclostomata.
Crisia acropora Busk.

The species listed above include forms some of which are recorded only as fossils and others are found living in waters around the Australian coast. The fossil species are *Macropora clarkei, Cellaria depressa, Hincksina geminata, Retepora aciculifera, Idomonea incurva, Spiroporina verticillata* and *Tecticavea* cf. *schnapperensis.*

The assemblage of species from both localities is typically Middle Miocene, all the fossil species being described from beds in Victoria and South Australia, which are referable to the Balcombian Stage, and the recent species being found in association with these in deposits ranging from Middle Miocene upwards. It is not always desirable to make long distance correlations of stratigraphic stages, but the following observations may be of interest regarding the relationships of the Lake Cowan and Norseman bryozoal limestones with those of Victoria and South Australia.

Macropora clarkei is the commonest species of Bryozoa in the Lake Cowan limestone, and in Victoria it ranges from the Janjukian Stage up to the Mitchellian Stage. The assemblage to which the species belongs in Western Australia is typical of the Balcombian Stage in Victoria where it is always associated with a characteristic assemblage of foraminifera. Foraminifera appear to be absent in the material under consideration, and the absence of these microscopic forms suggests a close relationship of the Western Australian deposits with those in York Peninsula, South Australia. It is further suggested that the Lake Cowan limestone can be correlated with the lower portion of the Balcombian stage as developed in Gippsland, Victoria.

The genus *Retepora* is the common form in the limestone from Norseman, where the bryozoal assemblage is associated with the gasteropod *Turritella aldingae* Tate, a form which is common not only at Aldinga, South Australia, but also in the fossiliferous marls in the deep bores in Gippsland, which are referred to the Janjukian Stage. But the species ranges up into the Balcombian Stage, and until some evidence based on the occurrence of zonal foraminifera can be found in the Norseman beds the limestones are referred to the basal portion of the Balcombian.

["Lake Cowan limestone" is material collected from Outcrop A at the Peninsula, "Limestone from Norseman" is material from the occurrence discovered by Campbell near the causeway north of Norseman. (E. de C. C. and C. T.)]

VII. REFERENCES.

Campbell, W. D., 1906: The geology and mineral resources of the Norseman District, Dundas Goldfield. *Geol. Sur. West. Aust., Bull.* 21.

Chapman, F., and Crespin, I., 1934: The palaeontology of the Plantagenet Beds of Western Australia. *Journ. Roy. Soc. West Aust.*, Vol. XX, pp. 103-136.

Clarke, E. de C., 1925: The geology of a portion of the East Coolgardie and North-East Coolgardie Goldfields including the mining centres of Monger and St. Ives. *Geol. Surv. West Aust., Bull.* 90.

Clarke, E. de C., 1935: Report of committee on the structural and land forms of Australia and New Zealand. *Aust. and N.Z. Ass. Adv. Sci.*, Vol. XXII, p. 467.

Gregory, J. W., 1916: Age of Norseman limestone, Western Australia. *Geol. Mag.*, New Ser., Dec. VI., Vol. III, pp. 320-321.

Hinde, G. J., 1910: On the fossil sponge spicules in a rock from the deep lead (?) at Princess Royal Township, Norseman District, Western Australia. Part of *Geol. Surv. West. Aust., Bull.* 36.

Maitland, A. Gibb, 1907: Recent advances in the knowledge of the geology of Western Australia. *Aust. Ass. Advt. Sc.*, Vol. XI, pp. 152-3.

Rodgers, J., 1940: Distinction between calcite and dolomite on polished surfaces. *Amer. Journ. Sci.*, Vol. 238, pp. 788-98.

Teichert, C., 1944: The genus *Aturia* in the Tertiary of Australia. *Journ. Paleon*, Vol. 18, pp. 73-82.

Woodward, H. P., 1902: The Dundas Goldfield. *Ann. Prog. Rep. Geol. Surv. of West Aust. for 1901*, p. 15.

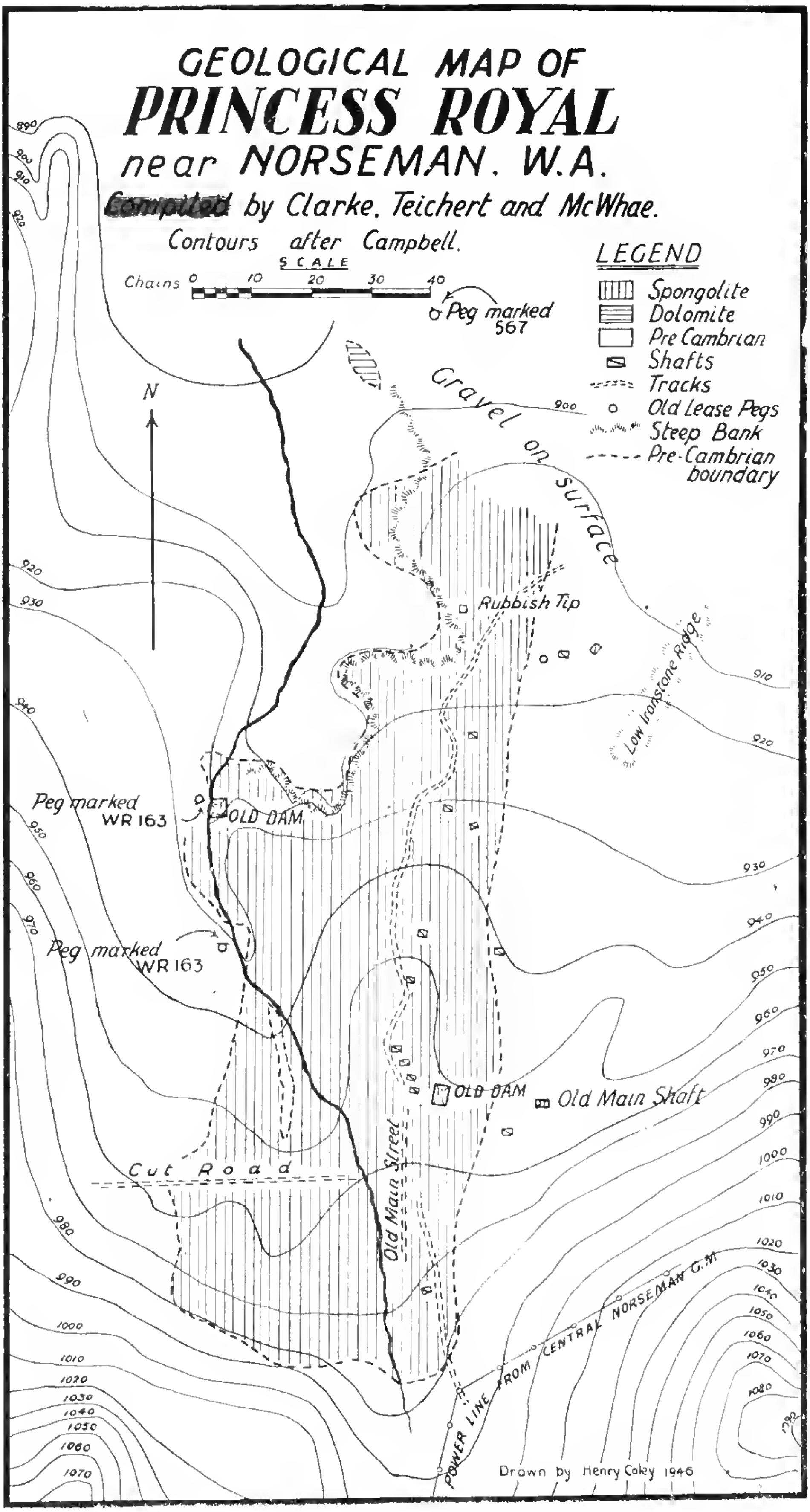


Plate I.—Geological Map of Princess Royal.

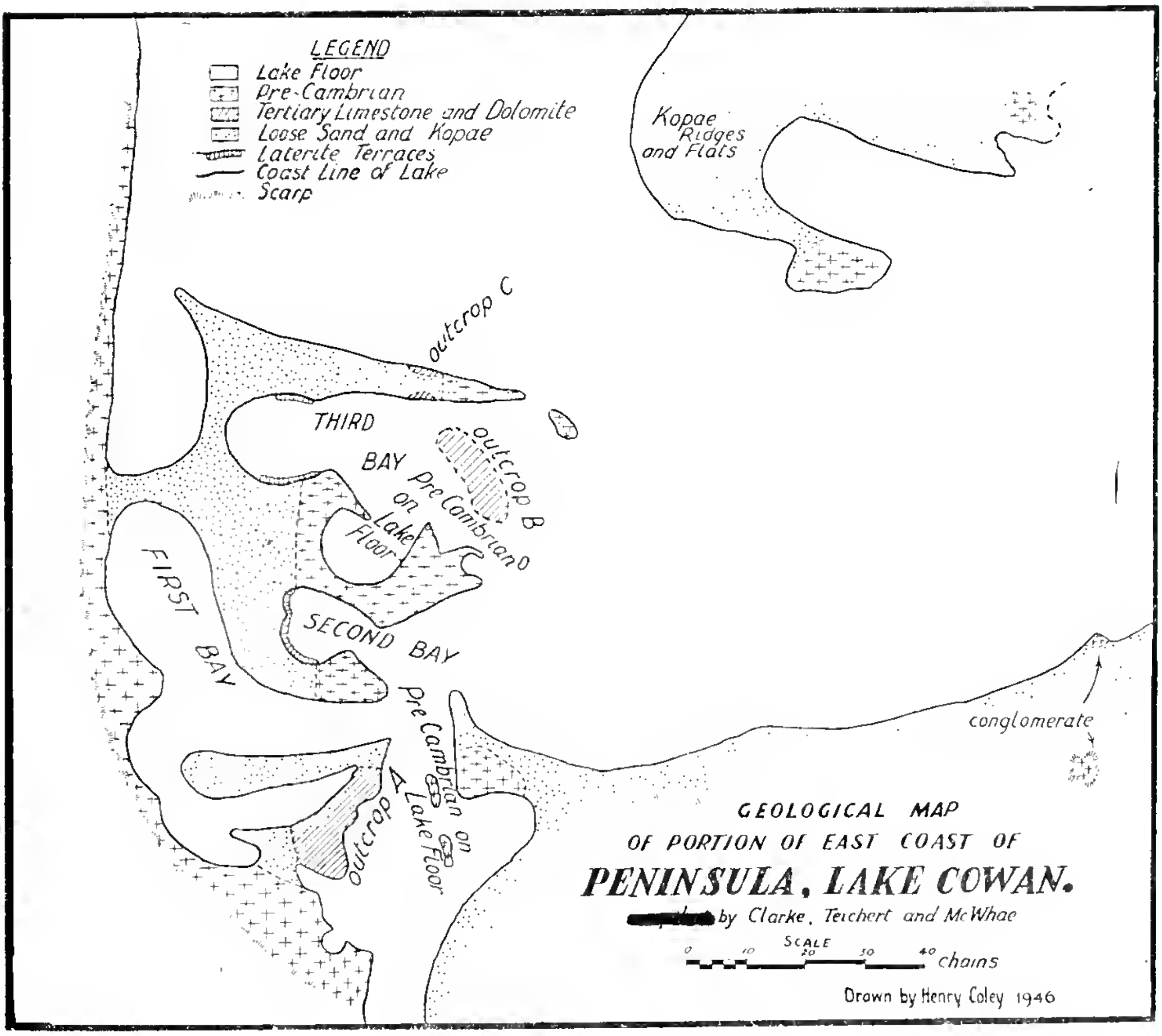
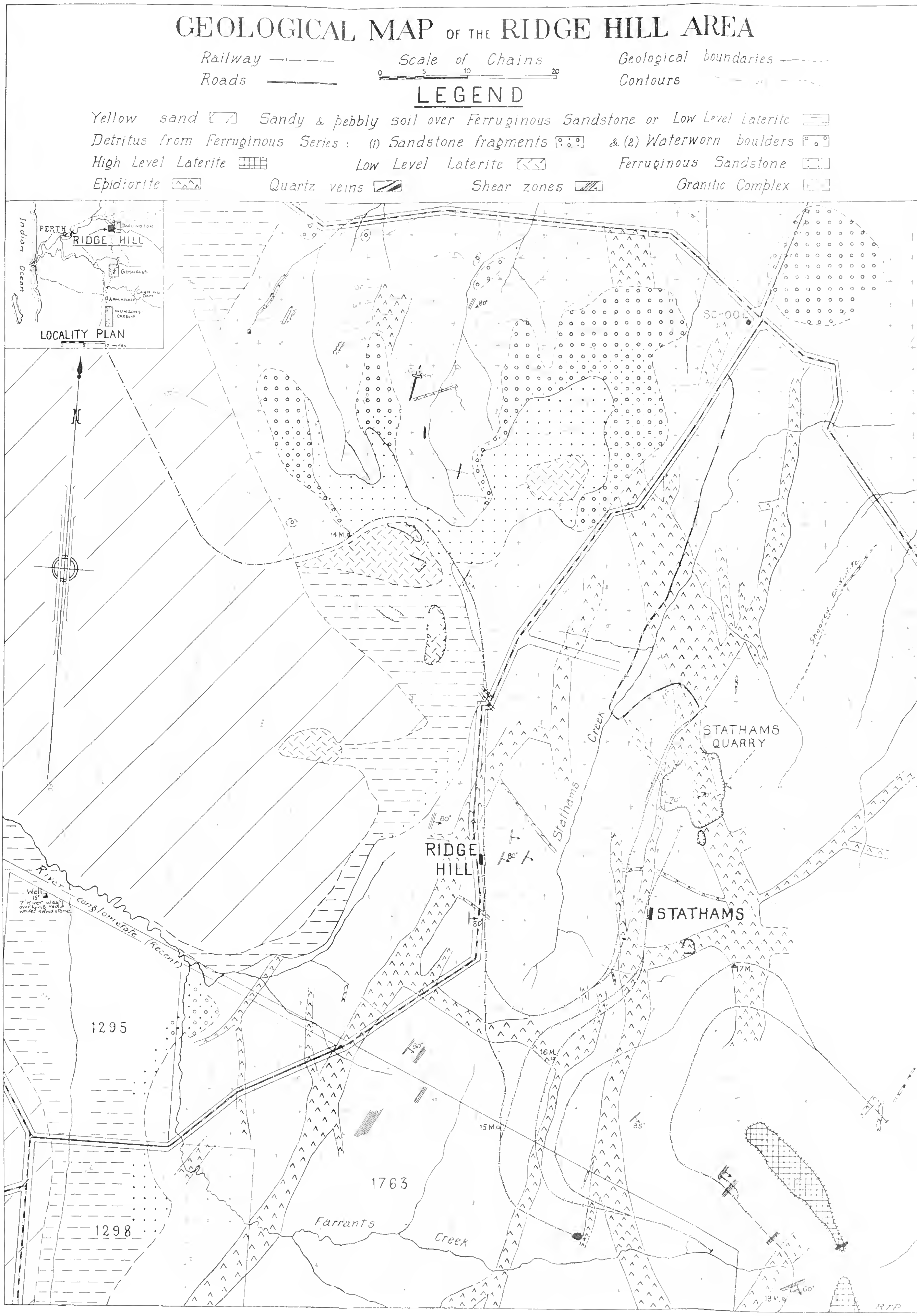


Plate II.—Geological Map of part of Peninsula, Lake Cowan.


GEOLOGICAL MAP OF THE RIDGE HILL AREA
Railway
Roads
Scale of Chains
0 5 10 20
Geological boundaries
Contours
LEGEND
Yellow sand
Sandy & pebbly soil over Ferruginous Sandstone or Low Level Laterite
Detritus from Ferruginous Series: (1) Sandstone fragments & (2) Waterworn boulders
High Level Laterite
Low Level Laterite
Ferruginous Sandstone
Epidiorite
Quartz veins
Shear zones
Granitic Complex
Indian Ocean
PERTH
RIDGE HILL
LOCALITY PLAN
N
SCHOOL
14 M.
STATHAMS QUARRY
Stathams Creek
RIDGE HILL
STATHAMS
17 M.
River Conglomerate (Recent)
Well
1295
16 M.
15 M.
1763
1298
Farrants Creek
18 M.
RTP

5.—THE GEOLOGY OF THE DARLING SCARP AT RIDGE HILL

By

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(Department of Geology, University of Western Australia).

Read: 11th June, 1946.

CONTENTS.

I. INTRODUCTION.

The Darling Scarp which forms the western edge of the Darling Plateau has generally been regarded as a fault scarp (Saint-Smith, 1912, p. 70; Jutson, 1912, p. 149 and 1934, p. 86) but closer examination of some critical areas in recent years throws some doubt on this hypothesis. Thus the slaty rocks at Armadale considered by Saint-Smith (1912, p. 71) to be evidence of the Darling Fault have, on closer examination (Prider, 1941, p. 52), yielded evidence that the earth movements recorded in these rocks are exactly the opposite of that required by the Darling "Fault". A characteristic feature of the Darling Scarp in the vicinity of Perth is a laterite-covered shelf at an elevation of approximately 200 feet above sea-level (Woolnough, 1920, p. 16) which Woolnough calls the Ridge Hill Shelf and which he considers is a step-faulted portion of the high- level laterite (Darling)

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plateau and thus confirmatory evidence of the Darling Fault which he supposes is a step fault. Further, in his article "The physiographic significance of laterite in Western Australia" (1918, p. 390) he puts forward the general conclusion that "*extraordinary differences in laterite level in adjacent areas indicate block faulting*," citing as evidence the laterite-covered Ridge Hill Shelf. These conclusions appear to be based on the supposition that the high-level laterite on the Darling Plateau which is exposed at an elevation of approximately 700 feet on Gooseberry Hill to the east of the Ridge Hill Shelf is the same as the laterite covering the Ridge Hill Shelf (at an elevation of approximately 250 feet). No detailed investigation of these laterites has previously been made and in order to test Woolnough's conclusions and to obtain further information about the vexed question of the origin of the low-level laterite and of the Darling Scarp a detailed survey of an area of approximately two square miles in the vicinity of Ridge Hill has been made by senior students of the Department of Geology of the University of Western Australia working under the author's guidance. In the course of this survey (made in part by plane table - telescopic alidade and in part by chain-compass-barometer methods) further study was made of the Pre-Cambrian complex of the Darling Range, a group of previously unrecorded sedimentary rocks was discovered, the relationships of the high- and low-level laterites were examined and an investigation into the origin of the extensive sand areas fronting the Darling Scarp was made. The present paper sets out the results of these investigations.

II. PHYSIOGRAPHY.

The area examined is situated on the south side of the Helena valley adjacent to the western boundary of the Darlington Area (Clarke and Williams, 1926, plate XXIII). It lies entirely on the Darling Scarp and extends from the high-level plateau, outliers of which occur in the south-eastern corner of the area, almost to the flat, low-lying country of the coastal plain to the west. It therefore covers the area represented on Woolnough's generalised section (1920, p. 20) from the Darling Plateau to the Swan Coastal Plain in the same way as the area mapped at Armadale (Prider, 1941) covers a somewhat similar generalised section of the Scarp approximately 15 miles to the south of Ridge Hill which has been published by Woolnough (1918, p. 391).

The main characteristics of the Darling Scarp have been sufficiently described by previous authors (see for example Jutson, 1934, pp. 84-87) and require no further consideration here, and attention will be confined to the topographic features of the Ridge Hill area itself.

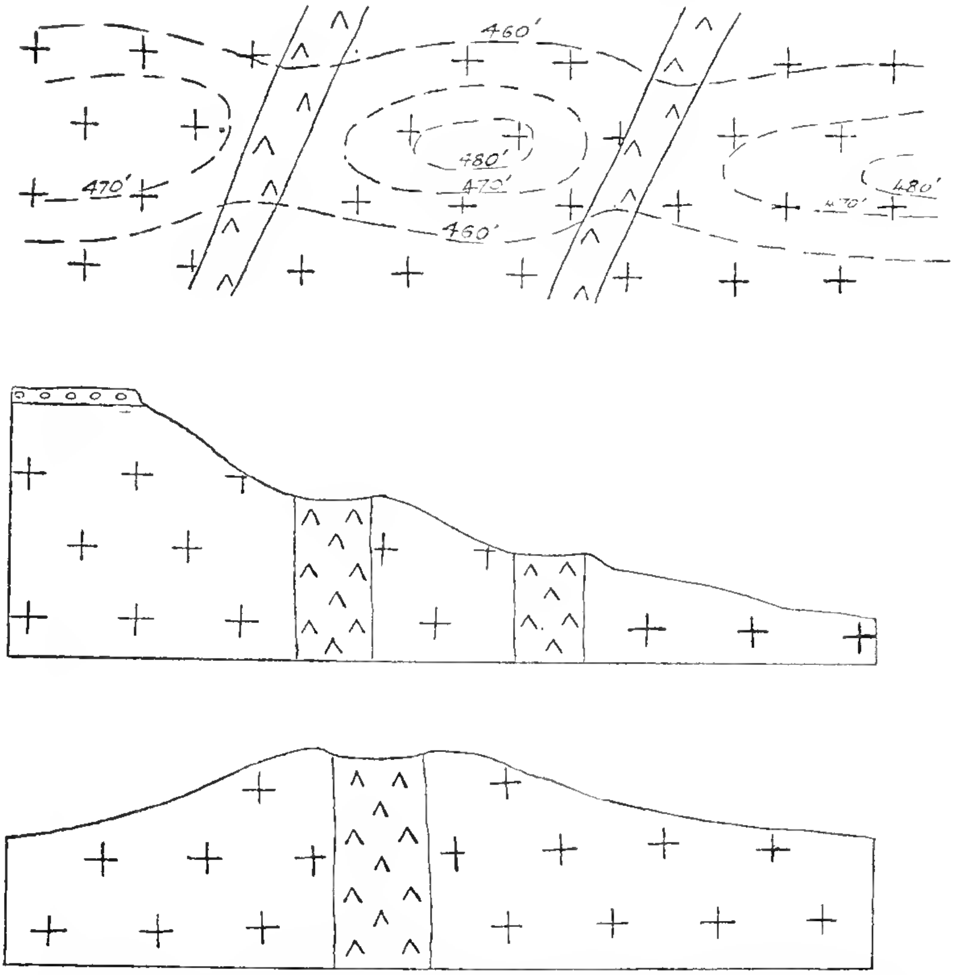
The Drainage Pattern.—The Scarp is dissected by: (a) the westerly flowing streams, the Helena River and Farrants Creek, which are consequent streams owing their development to uplift of the Darling Plateau to the east; (b) minor streams flowing approximately parallel to the scarp which have produced the dissected foothill zone mentioned by Woolnough (1920, p. 15). Such streams are Stathams Creek draining into the Helena to the N.N.E. and the tributary of Farrants Creek draining to the S.S.W. These appear to be subsequent streams (Clarke, Prider and Teichert, 1944, p. 78) whose direction has been determined by the N.N.E. strike of the shear structures in the granitic rocks and also by the presence of epidiorite dykes. The divide between these two streams, at 15 chains south of Ridge Hill siding, is occupied by an epidiorite dyke.

The role that the epidiorite dykes play in the development of these minor topographic features of the Darling Range is of interest. In most places in the Darling Scarp area the granitic rocks are more resistant to erosion than the basic dykes which are generally represented by shallow depressions (text fig. 1A) or flattened areas on otherwise uniform slopes

A.

B.

C.



Text fig. 1.—*Relative resistance to erosion of granitic rocks and basic dykes in the Darling Ranges:*

A. Diagrammatic sketch plan of granite ridge at Armadale (not to scale) showing that dolerite dykes occupy the saddles in granite ridges.

B. Diagrammatic sketch section (not to scale) of upper part of the Darling Scarp at Ridge Hill showing minor flattened benches which are underlain by epidiorite dykes.

C. Diagrammatic sketch section (not to scale) of geological structure of ridges in the Toodyay District showing that although ridges are cored by dolerite dykes there is a shallow central depression.

(Granitic rocks are indicated by crosses, basic dykes by arrow heads and laterite by circles.)

(text fig. 1B). Similarly at Toodyay a most noticeable feature is that the main ridges in the granite gneiss areas have a central core of dolerite but the crest of such ridges has a shallow central depression over the dolerite dyke (text fig. 1C). It is evident, therefore, that in the Darling

Range area the basic dykes are *less* resistant to erosion than the adjoining granite and not more resistant as indicated by Aurousseau and Budge (1921 p. 35) and Clarke and Williams (1926, p. 167), but at the same time they have contact metamorphosed the adjoining granite slightly thus rendering it more resistant to erosion than the unaffected granite at some distance from the basic dykes, thus accounting for the anomalous behaviour of the less resistant basic dykes forming the ridges. This observation of the relation of topography to the less resistant dykes is of some importance in geological mapping in the Darling Range area—if shallow gullies or depressions are examined more closely it will generally be found that the underlying rock is either basic dyke rock or else sheared granite.

The Darling Plateau capped by the high-level laterite is exposed in several outliers of the plateau in the south-east corner of the area. These outliers are flat-topped and surrounded by breakaways (Clarke, Prider and Teichert, 1944, p. 60).

The Ridge Hill Shelf forms almost the entire western part of the mapped area. To the north-west of Ridge Hill siding it is laterite-covered at an elevation of 250 feet above sea level and from here it slopes down gently and uniformly to the west where it passes eventually into the flat coasal plain. It is immaturely dissected in the north-west part of the area by north-flowing tributaries of the Helena River which flows almost parallel to the northern boundary of the mapped area and at some 10 to 20 chains to the north of it.

As noted above, Woolnough considers this shelf to be the top of the downfaulted laterite-capped Darling Plateau but evidence will be put forward later in this paper which indicates rather that this shelf is actually an erosion feature such as a wave-cut bench and bears no relation to the Darling Plateau.

Clarke and Williams (1926, p. 167) have recognised *high-level terraces* in the Helena Valley just to the east of the Ridge Hill area. These terraces fall into two series, one lying at about 450 feet, the other at about 250 feet above sea level. The 250 feet series may be represented in the Ridge Hill area by the Ridge Hill Shelf and the 450 feet series by the flattened spur south from Stathams quarry, but otherwise these terraces cannot be detected in this area. The flattened spurs both in the Darlington area (with the exception of the terrace on which the village of Darlington stands) and above Stathams quarry are cored with epidiorite dykes. As has been noted above the epidiorites are less resistant to erosion than the granitic rocks—is it possible therefore that these flattened spurs or terraces are due to the differential erosion of weakly resistant epidiorite, more resistant granite and most resistant contact altered granite as indicated in text figure 1, rather than to two periods of still-stand during the uplift of the Darling Plateau?

III. GEOLOGY.

A. FIELD DISTRIBUTION AND RELATIONSHIPS OF THE ROCKS.

The diagonal joining the north-east and south-west corners divides the area conveniently into two parts. To the east and south of this line the rocks are those of the Pre-Cambrian granitic complex with associated epidiorite dykes which is overlain in the extreme south-east corner by the high-level laterite. To the north and west of this line the surface is covered by younger sedimentary rocks—a thin series of ferruginous sandstones and conglomerates—which, in the northern dissected part of the area, can be seen lying unconformably on the Pre-Cambrian rocks. This ferruginous sandstone series is in turn overlain by a thin crust of laterite and is bounded to the west by sandplain country which slopes gently and uniformly down to the coastal plain still farther west. An attempt has been made in the course of the mapping to differentiate between actual outcrop of the ferruginous sandstone series, the detritus (talus) derived from the weathering of this series, the sandy and pebbly soils overlying the ferruginous sandstones and low-level laterites, and the sandplain country underlain by yellow sand. The areas occupied by these various formations are indicated on the accompanying geological map (Plate 1).

B. THE PRE-CAMBRIAN ROCKS.

These include granites, sheared granites (sericite schist), epidiorite and quartz veins.

(1) *The Granites* are the basement rocks and form a complex of two main types—a coarse-grained porphyritic type with a slightly gneissic structure, and a finer even-grained type with no trace of banding. In addition end-phase pegmatites (graphic microcline pegmatites) are also to be found. It was found impossible to map the two different types of granite separately but the relations between the two can be clearly seen in the freshly exposed surfaces in Stathams quarry. In the south-western corner of this quarry large angular xenolithic blocks of the coarse-grained porphyritic and slightly gneissic granite occur in the massive finer-grained granite, thus indicating that the latter is the younger.

The younger of these two granites exposed in Stathams quarry is very similar to the Younger Granite of Canning Dam which has been fully described in an earlier paper (Prider, 1945, p. 142) and no further petrographic details are required here. There is, however, some difference between the older granite of Stathams and the hybrid gneisses (Older Granite) of Canning Dam—the Older Granite from Canning Dam generally has a migmatitic structure and is free from microcline whereas the older granite phase at Stathams has no migmatitic structure and contains abundant microcline. It is similar in mineralogical composition to the younger granite but differs from it in being much coarser-grained and slightly gneissic. Phenocrystal microcline in well-shaped crystals to one cm. or more diameter is an abundant constituent and the peripheral zone one or two mm. wide of such phenocrysts consists generally of micropegmatite. The microclines contain inclusions of sericitised oligoclase and clotted biotite flakes which are the most abundant constituents of the groundmass. The slight gneissoid structure of these granites is due to the sub-parallel flow orientation of the microcline phenocrysts. In some places this primary flow structure is very well developed, e.g., at 17 chains south-east from the centre of Stathams quarry it strikes 55°.

In view of the close similarity in mineralogical composition of the fine-grained granites and coarse-grained gneissoid granites of the xenoliths it appears most probable that they both belong to the same magma (the Younger Granite magma) and that the xenoliths represent an earlier crystallised flow-banded crust which has been fractured and the resultant blocks incorporated into the residual magma. There does not appear to be such a long time gap between the two granites at Stathams as there is at Canning Dam (Prider, 1945) and Armadale (Prider, 1941) and both appear to belong to the same main period of granite intrusion (the Younger Granite) the parent magma being of syntectic origin as outlined in the Canning Dam paper (Prider, 1945, p. 143).

(2) *The Sericite schists.*—All the granites of this area show, on microscopic examination, the effects of considerable stress in the form of crushed quartz and quartz with undulose extinction. The stress has been localised in certain zones along which the granite has been converted into sericite schist. These shear zones (see geological map) are distributed fairly uniformly throughout the area and all strike in a N.N.E. direction and dip steeply to the east. The best developed of these shear zones is exposed in the railway cutting near the 18-mile peg. The cleavage surfaces of the schist from this well developed shear zone are traversed by innumerable minute corrugations which are arranged horizontally—unfortunately these tiny drag structures are not sufficiently well developed to enable any positive determination of the nature of the earth movements responsible for the shearing. Since these corrugations are arranged horizontally the movements appear to have been dominantly vertical.

There is considerable divergence between the N.N.E. direction of these shear zones and the almost due north trend of the Darling Scarp which indicates that these shears bear no relation to the supposed Darling Fault.

(3) *Quartz veins.*—These have been noted in several places. They have a general trend parallel to the shear zones and their direction has evidently been controlled by the earlier imposed shear pattern. The occurrence and petrology of the quartz veins and shear zones in the Darling Scarp have been sufficiently dealt with in previous publications (Clarke and Williams, 1926, p. 174; Prider, 1941, p. 48; Davis, 1942, p. 256) and require no further consideration here.

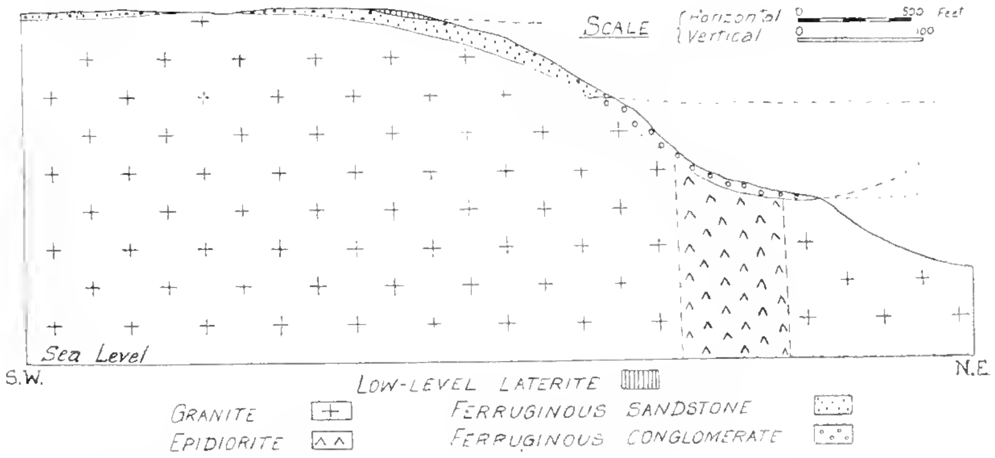
(4) *The basic dykes* also have a general N.N.E. trend following the structure of the granites. There appears to be one age only represented and all the specimens examined prove to be epidiorites consisting essentially of fibrous uralite (recrystallised around the borders of the aggregates to prismatic blue-green hornblende) and plagioclase with smoky appearance. Relicts of ophitic texture and the presence of end-phase micropegmatite point to a close relationship of these epidiorites with the quartz dolerites in other more distant parts of the Darling Range. This matter has been dealt with more fully in a previous paper (Prider, 1948, pp. 43-84).

The epidiorites have been quarried at Stathams for road metal and concrete aggregates. In the exposures in the quarry basic pegmatite segregations may occasionally be found and the occurrence of stilbite has been recorded by Simpson (1910, p. 36 and 1931, p. 36) from zeolite-calcite veins at the edges and also in the centre of the main dyke in Statham's Quarry.

C. THE LATER ROCKS.

The Later Rocks include the ferruginous sandstones and conglomerates, the high- and low-level laterites and the yellow sands of the sandplain forming an apron in front of the scarp.

(1) *The ferruginous sandstone series* forms a thin cover on the Ridge Hill Shelf where it lies unconformably on highly kaolinised granites. The unconformity is an undulating surface (see text fig. 2). The eastern contact of this series with the granite trends in a north easterly direction and thus bears no relation to the supposed Darling Fault which trends due north. In the north-west part of the area small streams have cut down through this series to expose the underlying Pre-Cambrian rocks to the west of the ferruginous sandstone outcrops.



Text fig. 2.—S.W.-N.E. section of South side of Helena Valley from the Helena Valley to the Ridge Hill shelf showing unconformity between the ferruginous sandstone series (sandstone underlain by conglomerate and overlain by low level laterite) and the Pre-Cambrian (granite and epidiorite).

The series consists mainly of ferruginous sandstones underlain in places by boulder conglomerates. Outcrops of the boulder conglomerates occur at 60 chains N. 10° E. and 67 chains N. 5° W. from Ridge Hill Siding. The slopes below the outcrop of ferruginous sandstone in the northern part of the area are strewn with well-rounded waterworn boulders which appear to have been derived from this conglomerate. These boulders have not been found in other parts of the area suggesting that the conglomerates are confined to that part of the ferruginous sandstones closest to the present Helena River. Since the known outcrops of conglomerate are at levels below the sandstones and are confined to the small area lying to the south of the Helena River it appears that they form a localised basal layer in the sandstones probably indicating an old stream channel or narrow embayment in the coast. It is interesting to note that Fletcher and Hobson (1932) have described a similar occurrence of ferruginous sandstone with rounded quartz pebbles underlying a low-level laterite in the Swan Valley at Upper Swan. This deposit they refer to as the "Older Alluvium". It occurs at an elevation of from 250 to 300 feet (the same as the Ridge Hill ferruginous sandstones).

(i) The **conglomerates** at Ridge Hill consist mainly of boulders and cobbles of granite, epidiorite and quartz, up to 18 inches diameter. All are strongly rounded and one water-worn granite boulder collected from a spot 65 chains N. 10° E. from Ridge Hill siding is a perfect ellipsoid of revolution with major diameter 11 inches and minor diameter five inches. This has the appearance of a beach boulder but it is doubtful whether such shape is indisputable proof of beach action (Wentworth, 1922, p. 82). The fact that the boulder beds are confined to a comparatively small area seems indicative of either a fluviatile origin or as an accumulation of beach boulders in a small bay. From the degree of rounding of the sand grains in the associated sandstones (to be described presently) the possibility of fluviatile origin seems remote. It appears most probable that these boulders were derived by direct marine abrasion of the nearby coast which was made up of these Pre-Cambrian rocks since the rock types noted amongst the boulders can be matched with the rocks in the Ridge Hill area.

(ii) The **sandstones** form the bulk of the exposure of this series. They are reddish in colour, have no bedding, are unfossiliferous and no certain means exist of accurately determining their geological age. They contain occasional water-worn quartz pebbles which are well-rounded and in some instances highly polished. The sand grains are almost entirely quartz and two types can be distinguished:—(a) grains with a rough irregular surface which nevertheless shows signs of considerable abrasion and (b) smooth-surfaced rounded grains with dull to polished surface textures which appear to be the result of a polish superimposed on earlier frosting. Crescentic percussion marks are generally well developed on the larger grains. A specimen (22798) of this ferruginous sandstone from three feet below the low-level laterite capping on the Ridge Hill Shelf was disintegrated by boiling in HCl and mechanical-, heavy mineral-, and shape- analyses of the insoluble residue (70 per cent. of the sample) were made. The results of these analyses are set down in Table III and in Column D of the histograms of figures five and six. The results of a chemical analysis of this specimen are recorded in Table I and the heavy mineral analyses are shown in Table V.

The main features disclosed by these analyses are:—

(a) The mechanical analysis (by hand sieving with Tyler screens) indicates that the insoluble material is fairly well graded, 48 per cent. lying between $\frac{1}{2}$ and $\frac{1}{4}$ mm. diameter and 30.5 per cent. lying between $\frac{1}{4}$ and $\frac{1}{8}$ mm. diameter. No significance should be attached to the relatively high (11 per cent.) proportion which passed 250 mesh (i.e. less than 0.061 mm. diameter) as microscopic examination shows that it consists largely of broken tuberose fragments of white material which, because of its irregular and branching forms, appears to be an authigenic mineral unrelated to the original detrital sand grains. This material is isotropic with refractive index varying between 1.52 and 1.54 and the refractive indices do not vary after ignition. It is insoluble in HCl and stains readily with malachite green. It therefore appears to be either montmorillonite or a dehydrated alumina-silica gel with $Al_2O_3 : SiO_2 = 1 : 2.8$ (Splichal, 1922, p. 288) and in view of its tuberose nature more probably the latter.* The $Al_2O_3 : SiO_2$ ratio of approximately 1 : 3 is confirmed by the chemical analysis of the rock (Table I, column 1) which shows that the rock contains alumina and combined silica in the molecular ratios 31 : 90. This material forms practically all of the minus 250 mesh fraction (11.2 per cent.) and approximately half the 115-250 mesh fraction (3.6 per cent.) but very little was present in the coarser grades and if this

*Mr. A. J. Gaskin has recently (1947) made a thermal examination of the clayey fraction of two soil samples from over the ferruginous sandstones and low-level laterites and finds from the thermal data that they contain limonite and kaolinite (much of which is semi-amorphous) with a possibility that some gibbsite is also present.

material be disregarded it will be seen that the actual detrital material is well graded, 92 per cent. lying between ⅛ and ½ mm. diameter.

(b) Heavy mineral analyses were made of the three finest grades, the material passing 250 mesh being separated by centrifuging. The light fractions consist entirely of quartz with the alumina-silica (allophaneid) mineral. The heavy fractions were further separated into magnetic and non-magnetic fractions, the magnetic fraction (largely ilmenite) in each grade forming approximately 75 per cent. of the heavy fraction. The heavy minerals identified are recorded in Table V and of these zircon is the most abundant of the non-opaques and is worth further mention as there are two distinct varieties present, the predominant type in both the 60-115 and 115-250 mesh fractions being perfectly rounded and colourless, the other type being slightly worn to perfectly euhedral colourless to purplish zoned. This is indicative of derivation of the detrital material from two different parent rocks such as an igneous rock (e.g. granite) to yield the euhedral zircons and a sedimentary or metasedimentary rock to yield the well-rounded zircons (roundness 0.9) which have undoubtedly passed through more than one cycle of erosion. The association of these two types of zircon may indicate derivation in the one cycle of erosion from a distributive province of the nature of the present Toodyay area (Prider, 1944) which is situated in a belt of igneous and meta-sedimentary Pre-Cambrian rocks lying some 30 to 40 miles inland from the Darling Scarp.

(c) Visual projection roundness (Krumbein, 1941) and sphericity (Rittenhouse, 1943) values were determined for the light fractions of the 16-32, 32-60, 60-115, 115-250 Tyler mesh grades. The results (shown graphically in column D in figures five and six) indicate that the average sphericity in all fractions is approximately the same (0.83) and that the degree of rounding decreases with decreasing size but there is still appreciable rounding of some grains down to 0.124 mm. diameter. During the roundness analysis and subsequent examination of the surface texture of the grains it was evident that there are two distinct types of quartz sand grains present—a well rounded set and another the grains of which are much more angular although still showing considerable abrasion. The proportion of well-rounded to poorly-rounded grains increases with increasing grade thus:

Grade	·124–·246 mm.	·246–·495 mm.	·495–·991 mm.
% of well-rounded grains	5	50	90

The occurrence of a small proportion of well-rounded grains in the ⅛ to ¼ mm. grade seems indicative of the derivation of the detrital material from several different sources. The high proportion of well-rounded grains in the ½ to 1 mm. grade indicates, however, very considerable abrasion during the last cycle of erosion and since this rounding is well marked down to the grains of ¼ mm. diameter it must be assumed (following Twenhofel, 1945, p. 66) that this final stage of abrasion must have taken place on a sea beach. The smaller well-rounded grains may be due to an admixture of some aeolian-transported sand with the beach sand, or may have been derived from some pre-existing sediment. No such sedimentary rocks are known to the east of the Darling Scarp, although there are metasedimentary rocks which could have yielded the well-rounded zircons but these rocks (mica schists and quartzites) would not yield directly the small well-rounded quartz grains since the quartz in these rocks has been completely recrystallised and in the rock occurs as irregular interlocking grains (Prider, 1944, p. 92).

(d) The surface texture of the sand grains of the 16 to 32, 32 to 60, and 60 to 115 Tyler mesh grades was examined with the binocular microscope in dry mounts on a dark ground for the quartz grains and on a white ground for the heavy minerals, with the following results:—

The 60 to 115 mesh grade (⅛ to ¼ mm.) consists of approximately 95 per cent. of rough irregular-surfaced grains with polished or fracture surface and five per cent. of smooth-surfaced rounded grains with polished surfaces which are often pitted but not frosted. The 32 to 60 mesh grade (¼ to ½ mm.) contains rough- and smooth-surfaced grains in approximately equal amounts. The smooth grains are well-rounded with polished (although somewhat pitted) surfaces some grains show slight frosting and crescentic percussion marks are not uncommon. The rough-surfaced grains mostly show slight rounding and are all polished or bounded by vitreous-lustred fracture surfaces. In the 16 to 32 mesh grade (½ to 1 mm.) there is a high proportion (approximately 90 per cent.) of smooth-surfaced grains which vary from dull to polished. Most of these grains have a matte appearance due to minute pitting but this is not a frosted surface but appears rather to be the result of a polish superimposed on earlier frosting. Crescentic percussion marks are generally well developed.

Twenhofel (1945, p. 67) considers that frosting may be developed on quartz grains exceeding one mm. diameter on marine beaches but not on grains smaller than one mm. which can only be frosted by wind action. The above observations on the surface texture of the grains of the Ridge Hill ferruginous sandstone therefore are indicative of beach action.

From these considerations of the mechanical constitution, degree of rounding of the grains and their surface textures it appears most probable that the detrital materials of these ferruginous sandstones and conglomerates were deposited on a sea beach and are not fluviatile deposits. The basal conglomerate layer represents accumulations in a narrow embayment in the coastline existing at this time. The anomalous occurrence of pebbles and cobbles in the sandstones is accounted for by the close proximity to the east of the Pre-Cambrian landmass which yielded the detrital material, these boulders being the result of marine abrasion and having suffered practically no transport except on the beach.

Owing to the absence of fossils the geological age of the ferruginous sandstone series is indeterminable. It may be either—

(a) of Lower Cretaceous (?) age similar to the sandstones and leaf-bearing shales of Bullsbrook (Clarke, Prider and Teichert, 1944, p. 275) which is situated on the Darling Scarp some 16 miles north from Ridge Hill, or

(b) later than the formation of the high-level laterite (?Miocene).

The Lower Cretaceous (?) sandstones of Bullsbrook are lithologically similar to the Ridge Hill ferruginous sandstones, as they contain both angular and well-rounded sand grains. A detailed examination of the roundness and surface textures of the grains of the Bullsbrook sandstone has not yet been made.

Text figure 7 illustrates diagrammatically the structure of the Swan Coastal Plain on the assumption that the Ridge Hill ferruginous sandstone is of Lower Cretaceous age. It may be noted here that Maitland (1919, p. 6) records that the Helena River carries 22,000,000,000 gallons less past Midland Junction per annum than it does further upstream near Greenmount where it is still on the Pre-Cambrian complex. It is probable therefore that this water enters the Coastal Plain Artesian Basin through the ferruginous sandstone series. The unconformity between these Mesozoic and the Kainozoic rocks of the Coastal Plain may be of the nature of an overlap. These ferruginous sandstones, extending along the front of the Darling Scarp, may therefore be the main channel from which water is distributed to the various aquifers in the rocks, ranging in age from Lower Cretaceous to late Kainozoic (Parr, 1938, p. 71), which underlie the Metropolitan Area but, so far as is known, do not outcrop.

The period of formation of the present Ridge Hill shelf is later than that of the high-level laterite which was probably Miocene according to Woolnough (1918). It was formed when the laterite-covered plateau area to the east had been elevated to approximately 400 feet above sea level, i.e present elevation of high-level laterite (700 feet) minus the elevation of the Ridge Hill Shelf (300 feet). If the ferruginous sandstone series be of Lower Cretaceous age then it represents an exhumed Lower Cretaceous shoreline with a wave-cut bench covered with marine sands; if of post-Miocene age then it is a marine wave-cut bench with a thin veneer of beach deposits which have subsequently been cemented by iron-bearing solutions into a ferruginous sandstone.

(2) *The Laterites.*—Laterite occurs at two distinct levels—the high-level laterite in the south-eastern corner of the area at an elevation of 700 feet above sea-level and the low-level laterite on the Ridge Hill Shelf at elevations of 220 feet—280 feet above sea-level. As has been pointed out in the introduction to this paper Woolnough regards these two laterites as being of the same age and origin, their differences in elevation being due to block-faulting. Simpson (1912, p. 400) considers that, broadly speaking, there are two classes of laterite in Western Australia, firstly the primary (or high-level) laterites and secondly the secondary or low-level laterites occurring at lower levels and composed largely of mechanically transported fragments derived from the high-level laterite. I am not aware whether or no Simpson had in mind the low-level laterites fronting the Darling Scarp in his mention of secondary laterite but it seems from his description that he would regard the low-level laterite of Ridge Hill as a secondary laterite (lateritite).

Field mapping has shown that in this area the high-level laterite is developed over the Pre-Cambrian complex whereas the low-level laterite has developed over the ferruginous sandstones described in the previous section of this paper. Moreover the low-level laterite appears to be a true laterite developed in situ on the ferruginous sandstones and not a lateritite as suggested by Simpson for the low-level laterites generally.

(i) The **high-level laterite** varies in character according to the nature of the underlying Pre-Cambrian rocks. In one place in the area where it overlies granite containing quartz veins it is crowded with large quartz fragments. When developed over granitic rocks it generally has a pisolitic structure and is comparatively light-coloured but when over epidiorite (as at the northern end of the high-level laterite outlier in the south-east corner of the area) there is no pisolitic structure but the rock is somewhat cellular and appears to be richer in iron, these iron oxide patches being compact, fine-grained and massive. All the high-level laterites are underlain by a highly weathered (kaolinised) zone which passes down into the unweathered country rocks as described by Simpson (1912). Analyses of two high-level laterites are given in Table I, cols. III and IV. Analysis III is of a laterite developed over epidiorite from the Ridge Hill area. Analysis IV quoted from Simpson (1912, p. 404) is from Gooseberry Hill which is situated approximately one mile south of the Ridge Hill area, but no details of the exact locality are available. Through the courtesy of the Government Mineralogist and Analyst (Mr. H. Bowley) I have been able to examine Simpson's analysed specimen—it is a dense reddish-brown rock with numerous iron-rich concretions scattered uniformly throughout. The Ridge Hill specimen (Analysis III) is a dense brownish coloured rock with occasional cavities producing a slightly cellular structure but concretionary structures are absent. Chemically the two rocks differ in the lower Fe/Al ratio of the Gooseberry Hill rock.

TABLE I.

ANALYSES OF FERRUGINOUS SANDSTONE AND LATERITES FROM RIDGE HILL.

	I.	II.	III.	IV.
SiO_2*	63·93	44·87	10·30	6·41
Al_2O_3	3·17	24·63	22·53	36·74
Fe_2O_3	27·63	14·82	48·56	39·80
TiO_2	0·99	1·25	3·24	1·98
MnO	0·02	0·01	0·05	0·06
H_2O†	4·40	14·61	15·82	14·93
Others	...	...	...	0·51
	100·14	100·19	100·50	100·43
*Combined SiO_2	5·42	8·18	4·94	1·97

†Loss on ignition.

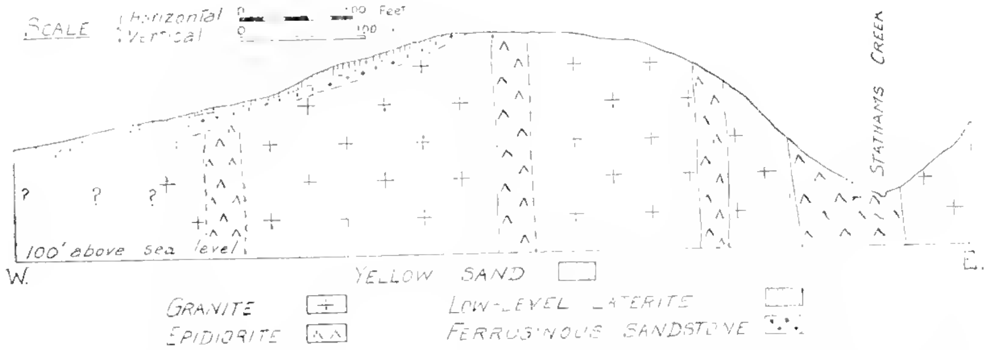
I. Ferruginous sandstone (22798), three feet below laterised surface rock in quarry 25 chains north of Ridge Hill Siding, W.A. (*Anal.* R. T. Prider.)

II. Low-level laterite (24359) overlying ferruginous sandstone, from quarry 25 chains north of Ridge Hill siding, W.A. (*Anal.* R. T. Prider.)

III. High-level laterite (22797) from northern end of outlier of the high-level laterite, 45 chains south-east of Ridge Hill siding, W.A. (*Anal.* R. T. Prider.)

IV. High-level laterite, Gooseberry Hill, W.A. (no further locality details available), (Simpson, 1912, p.404.)

(ii) The **low-level laterite** occurs as a thin discontinuous layer above the ferruginous sandstones on the Ridge Hill Shelf. It has, on the exposed surface, a somewhat fragmental appearance but on breaking the rock these fragments are seen to be of ferruginous sandstone identical in character with the underlying ferruginous sandstones which have been described above. These fragments in a typical specimen (21359) which has been analysed average five mm. diameter and they are coated with a dense layer of light brown, fine-grained and compact bauxitic material and the spaces between the fragments are largely filled with this bauxitic material but some cavities remain giving the rock a slightly cellular structure. This surface lateritic crust passes down into the normal ferruginous sandstone at three or four feet below the ground surface and there can be no doubt that the laterite has formed in situ from the sandstones which in turn overlie the Pre-Cambrian granitic rocks. These granites wherever exposed below the ferruginous sandstones (e.g. at 45 chains north from Ridge Hill siding) are seen to be highly weathered (kaolinised) in the same way as the granites under the high-level laterite (the relationships of these rocks are illustrated in text fig. 3).



Text fig. 3.—E.-W. section at 33 chains North of Ridge Hill siding showing relationship of the Pre-Cambrian granites and epidiorites, ferruginous sandstones and overlying low-level laterite, and the younger yellow sands.

An analysis of the Ridge Hill low-level laterite is given in Table I, analysis II where it is compared with the analysis of the underlying ferruginous sandstone (anal. I) and the high-level laterites (anal. III and IV). It differs from the high-level laterites in its much higher silica content, due largely to the presence of abundant water-worn sand grains residual from the ferruginous sandstone from which it was developed, but also in part to a higher proportion of combined silica. Comparing the composition of the low-level laterite with the underlying ferruginous sandstone the most notable feature is the marked increase during lateritisation of the Al_2O_3/Fe_2O_3 ratio and the development of the hydrated oxides such as limonite and bauxite. In a consideration of the chemical changes sustained by the parent rock during the lateritisation process the only factor which may with some degree of certainty be likely to remain constant is the quartz (free silica) content. In Table II the analysis of the laterite (column 2) has been recalculated to quartz = 58.51, i.e. these figures would then represent the number of grams of each constituent in a volume of the laterite which contains 58.5 grams of quartz. Comparing these figures with those of the parent ferruginous sandstone (column 1) the gains and losses in the various constituents per 100 grams of the original sandstone may be determined (column 4).

TABLE II.

CHEMICAL CHANGES IN THE FORMATION OF THE LOW-LEVEL LATERITE.

	1. Ferruginous sandstone (Weight %)	2. Low-level laterite (Weight %)	3. 2. recalculated to quartz 58·51	4. Gains and losses during lateritisation. (Gms/100 gms. of original rock)
SiO_2 Quartz ...	58·51	36·69	58·51	...
SiO_2 Combined	5·42	8·18	13·05	+ 7·63
Al_2O_3	3·17	24·63	39·27	+ 36·10
Fe_2O_3	27·63	14·82	23·63	— 4·00
TiO_2	0·99	1·25	1·99	+ 1·00
MnO	0·02	0·01	0·02	...
H_2O	4·40	14·61	23·30	+ 18·90
	100·14	100·19	159·77	Gain 63·63 Loss 4·00
Net Gain ...	...	...	...	59·63gms. per. 100 gms. original rock.

There has been a slight loss in Fe_2O_3, slight gain in titania and combined silica but very marked gains in alumina and water. The significant changes are those in the alumina and water content and these are in the molecular proportions alumina : water = 354 : 1050 i.e., 1 : 3 so that the material added to the original rock during the lateritisation process is essentially aluminium hydroxide ($Al(OH)_3$). The source of this aluminium hydroxide is unknown—the ferruginous sandstones are poor in alumina but the alumina may have come from the underlying granitic rocks as there is only a thin veneer of sandstone, but on the other hand it may have been derived from an overlying shale or mudstone which has now been entirely removed by erosion.

The low-level laterite is therefore a true laterite, and not a lateritite, due to the accumulation of alumina in the near-surface layer, formed in situ over the ferruginous sandstone. This laterite formation probably took place shortly after the sand-covered marine bench (the Ridge Hill Shelf) was elevated a few feet above sea-level. This was later than the formation of the high-level laterite.

(3) *The Yellow Sands.*—The Yellow Sands constitute the youngest formation and are exposed in the westernmost part of the mapped area where they form an even gentle slope down to the level of the coastal plain to the west. The boundary between the yellow sands and the earlier rocks is irregular (see Plate I) thus precluding the possibility of a faulted contact or fault scarp against which the sands have accumulated. There is an abrupt change from the ferruginous sandstone and low-level laterite to the yellow sands and this has been well exposed by rainwash in a drain on the south side of the railway line at seven chains south-west from the 14-mile peg. Over the laterite this drain is two feet deep but on reaching the boundary with the incoherent yellow sand it deepens abruptly

to about 12 feet. Downstream from this point the gulley continues as a narrow washout four feet wide by 12 feet deep which is roofed by the roots of the adjacent jarrah trees (text fig. 4).

Text fig. 4.—Washout in yellow sand, seven chains south-west from the 14-mile railway peg. The very recent development of this feature is evident from the uncovered roots of the nearby jarrah trees.

The yellow sand profile exposed consists of 12 to 18 inches of light grey sand with plant roots, the remainder of the profile consisting entirely of yellow sand in which there is absolutely no sign of bedded structure, the whole profile consisting of sand of uniform texture from top to bottom of the exposed section. Throughout the sand at intervals of several inches are small nodules of more compact material averaging ½ inch diameter which project from the vertical sand face. These nodules which can be cut through with a knife consist of the sand weakly cemented with reddish iron oxide. On cutting a fresh surface with a hatchet they appear only as reddish iron-stained spots with a gradual transition to the yellow sand. It is only where they have been exposed to the atmosphere on the walls that a slightly hardened surface has been formed on them. At the bottom of the section exposed in the washed out drain the sand contains an abundance of these nodules, in some places aggregated to nodules several inches in diameter. These larger aggregates are weakly cemented and can be broken across with the fingers. They contain a higher proportion of fine-grained, light brownish to greyish clayey material. They appear to have been enriched in alumina with respect to the surrounding sand and if this material which in places was slightly damp were desiccated it would be similar to non-concretionary laterite. It would appear then that with the development of these aluminous nodules at the base of the exposed profile and of the small iron-stained patches throughout the mass of the sand incipient lateritisation is taking place within this sand deposit.

The yellow sand throughout the mapped area appears to be constant in character, wherever exposed in small pits the profile is similar, i.e. a thin surface layer of grey sand underlain by the structureless yellow sand. Mapping of this formation was facilitated by the numerous small anthills of bright yellow sand brought up from below the surface grey sand. The yellow sand possesses the ability to stand up in vertical walls such as the walls of a pit and in this respect and in its structureless profile it very closely resembles the yellow sand deposits of the Perth Metropolitan Area.

What is the origin of this sand? It is (i) a residual sand derived from the low-level laterite and ferruginous sandstone, (ii) a deposit of the same origin as the yellow sand of the Metropolitan Area or (iii) an aeolian deposit against the Darling Scarp?

These various hypotheses were tested by making mechanical analyses, heavy mineral separations, shape analyses and an examination of the surface textures of the sand grains of the Ridge Hill yellow sand (two samples) and a yellow sand from the vicinity of the Department of Geology at Crawley (since no data exist concerning the yellow sand of the Metropolitan Area), on the lines described above for the acid-insoluble fraction of the Ridge Hill ferruginous sandstone. The results of these determinations are set down in Tables III, IV and V and the histograms of figures five and six.

Trask (1932, p. 72) considers that if the coefficient of sorting is less than 2.5 the sample is well sorted all the samples examined (see Table IV) therefore are well sorted. Moreover in all cases the maximum sorting lies slightly on the fine side of the median as evidenced by the co-

TABLE III.

MECHANICAL ANALYSIS OF YELLOW SANDS.
(hand sieving with Tyler screens.)

Grade.		% by weight of grades indicated.			
Tyler screen mesh.	Size (mm.)	A.	B.	C.	D.
5– 9	> 1·981	*Nil*	*Nil*	0·81	*Nil*
9– 16	·991–1·981	0·58	1·44	3·88	0·04
16– 32	·495– ·991	19·56	12·83	12·33	6·70
32– 60	·246– ·495	50·61	35·42	46·46	48·03
60–115	·124– ·246	22·22	26·96	23·11	30·41
115–250	·061– ·124	3·47	11·85	7·12	3·62
< 250	< ·061	3·56*	11·50*	6·29*	11·20*

*By difference.

A. Yellow sand (22804), Geology Department, Crawley.

B. Yellow sand (21364), from wall of gulley, 7 chains south-west from 14-mile peg, Ridge Hill.

C. Yellow sand (22802), north-west corner Loc. 1298, Ridge Hill.

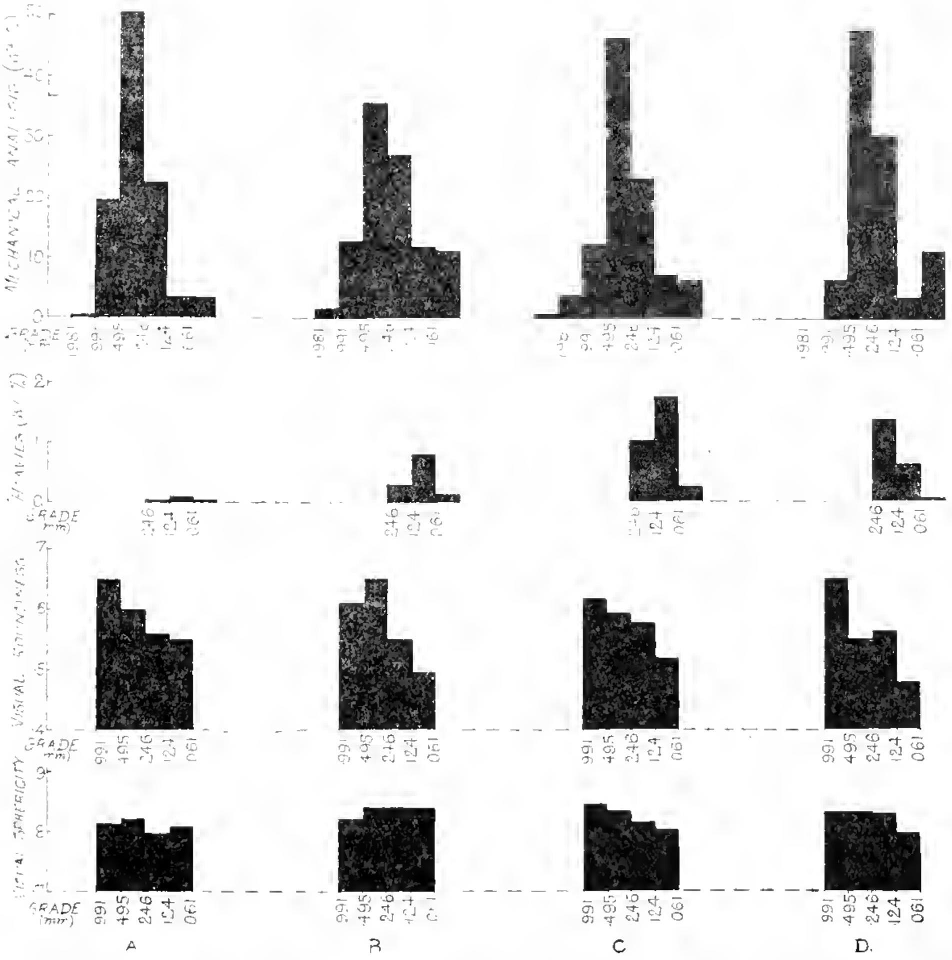
D. Acid-insoluble residue from ferruginous sandstone (22798), Ridge Hill.

TABLE IV.

First, second (Median) and third quartiles and coefficients of sorting (So) and skewness (Sk) of sands of Table III.

Sample.	Q3 (mm.)	M (mm.)	Q1 (mm.)	So	Sk
A.	·469	·341	·225	1·444	·907
B.	·417	·243	·130	1·791	·918
C.	·450	·318	·194	1·523	·863
D.	·384	·263	·172	1·494	·954

efficients of skewness (Table IV). If the secondary allophanoid of the ferruginous sandstone be disregarded it will be seen that the grading of the detrital material of the ferruginous sandstone is of still higher degree than that of the yellow sands. The mechanical analyses indicate that



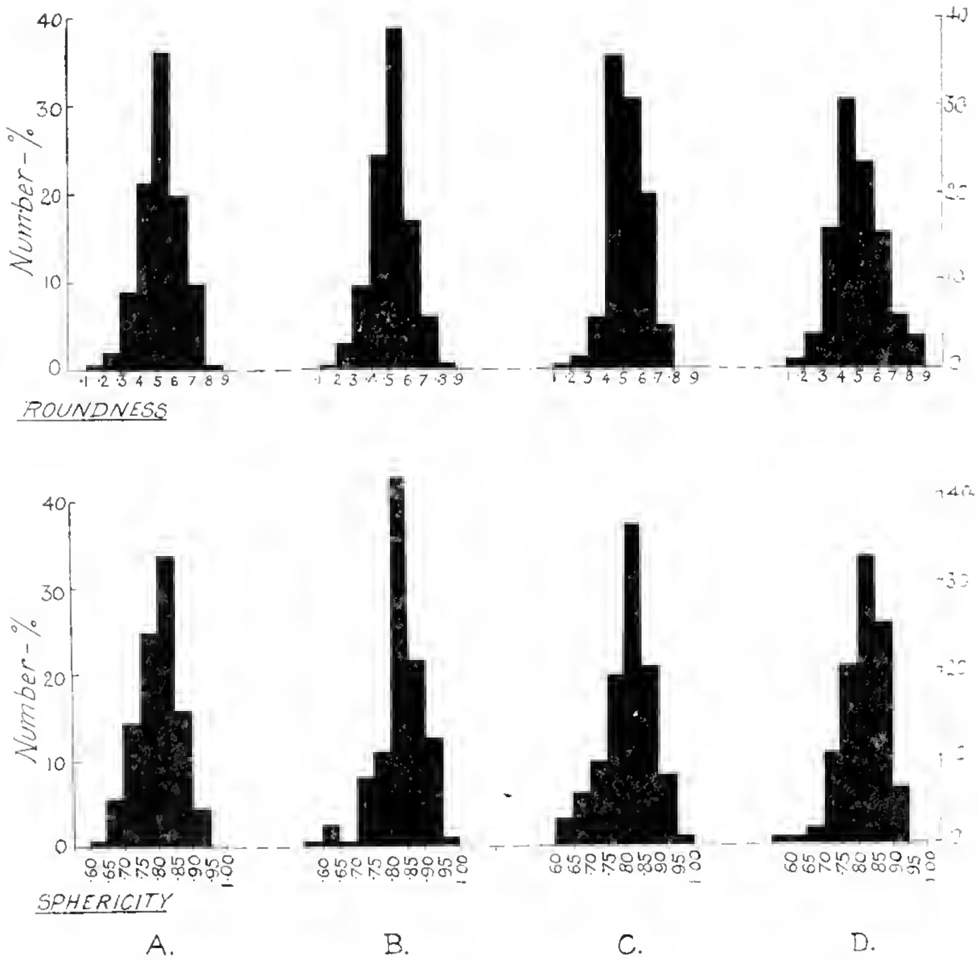
Text fig. 5.—Histograms showing:—(1) Mechanical composition. (2) Heavy mineral content. (3) Average visual projection roundness in different grades (50 grains measured in each grade). (4) Average visual projection sphericity in different grades (50 grains measured in each grade) of:—

A. Yellow sand, Crawley, W.A. (22804).

B. Yellow sand, Ridge Hill, W.A. (21364).

C. Yellow sand, Ridge Hill, W.A. (22802).

D. Insoluble residue in ferruginous sandstone, Ridge Hill, W.A. (22798).



Text fig. 6.—Histograms of visual projection roundness and visual projection sphericity (based on measurement of 200 grains) of:—

A. Yellow sand, Crawley, W.A. (22804).

B. Yellow sand, Ridge Hill, W.A. (21364).

C. Yellow sand, Ridge Hill, W.A. (22802).

D. Insoluble residue in ferruginous sandstone, Ridge Hill, W.A. (22798).

there is some variation in the mechanical composition of the Ridge Hill yellow sand. There are no available data concerning the variation in composition of the metropolitan yellow sand. In their mechanical composition all the samples examined are very similar. The ferruginous sandstones however contain, as has been noted above, an allophanoid with tuberose form—this material is absent from the yellow sand. That this allophanoid persists in the soils formed over the ferruginous sandstones and low-level laterite is evidenced by its presence in the pebbly and sandy soil overlying the low-level laterite or ferruginous sandstone from a locality five chains south-west from the 14-mile peg on the railway line i.e. two chains east of the eastern boundary of the yellow sand. The presence of this allophanoid in the soils over the ferruginous sandstones and low-level laterite and its absence in the yellow sand two chains farther west indicates that the yellow sands are not residual deposits from the ferruginous sandstone series.

The heavy mineral separations indicate that the yellow sands of Ridge Hill contain a much higher proportion of "heavies" than the Crawley sand but in both the Ridge Hill and Crawley sands the "heavies" tend to be concentrated in the 115-120 mesh grade whereas in the ferruginous sandstone they are most abundant in the 60-115 mesh grade (see text fig. 5). The minerals present in the heavy fractions of all samples examined appear, except for the abundance of epidote in the Crawley sand, to be similar (Table V) even to the varietal features, indicating a common provenance for all samples.

Notes on the Heavy Minerals.—The magnetic fraction consists partly of strongly magnetic *magnetite* and partly of weakly magnetic *ilmenite*. The dominant constituents of the non-magnetic fractions of all samples are opaque minerals of which *leucoxene* is predominant. The leucoxene is cloudy and slowly soluble in hot sulphuric acid, the resulting solution yielding positive tests for titanium.

The non-opaque minerals are:—

Zircon. This is the predominant non-opaque mineral in all samples examined. There are two distinct types: (a) perfectly rounded, colourless and (b) euhedral prisms which may occasionally show signs of slight abrasion. The euhedral type includes colourless, colourless with rodlike inclusions, deep purple, and pale yellowish zoned varieties. The purple zircons are particularly characteristic of the Ridge Hill ferruginous sandstone but some occur in the yellow sand of the Coastal Plain. All samples contain both well rounded and euhedral types of zircon.

Kyanite is also present in all the samples examined. Generally colourless but a few grains of blue kyanite were noted in the residue from the ferruginous sandstone. The kyanite occurs in stout prisms and tablets with well rounded terminations.

Staurolite in pleochroic yellow-brown granules of somewhat irregular shape never shows the high degree of rounding of the zircon and kyanite. It appears in all the sands examined but seems to be confined to the coarser grades.

Rutile in deep reddish brown prisms, often well rounded was noted in all samples.

Epidote was the most abundant non-opaque mineral in the Crawley yellow sand. In the other samples it was very rare except in the finest grade (250) of the yellow sand from the south end of the Ridge Hill area (sample C.) where it is very abundant in tiny angular grains. The epidote in the Crawley sand is in stout prisms showing very little sign of abrasion. The abundance of epidote in the Crawley sand is the main point of difference between this sand and the Ridge Hill sands.

Tourmaline, generally well-rounded, is present in all samples although never abundant. The most common variety is a strongly pleochroic clove brown tourmaline. A few greenish brown tourmaline grains were noted in sample C. (Ridge Hill).

Sillimanite was noted only in the Crawley sand and ferruginous sandstone. It is in colourless fairly stout prisms.

Hornblende is of rare occurrence and confined to the coarsest fractions examined. Both brown-green and greenish varieties were noted.

Pleonaste in well rounded, green, isotropic highly refracting grains is of rare occurrence.

TABLE V.

Heavy Minerals in Sands and Ferruginous Sandstone.

Sample	A.			B.			C.			D.		
Grade (Tyler mesh)	60–115	115–250	< 250	60–115	115–250	< 250	60–115	115–250	< 250	60–115	115–250	< 250
Total "heavies" (Wt. % of total sample)	0·04	0·12	0·04	0·30	0·80	0·16	1·02	1·76	0·26	1·35	0·60	Tr.
Magnetic (Wt. % of total "heavies")	Not determined	69	Not determined	41	70	51	76	80	63	71	77	Not examined
Non-magnetic (Wt. % of total "heavies")	..	31	..	59	30	49	24	20	37	29	23	,,
Non-magnetic fraction (figures are number-% of non-magnetic fraction)												
Opaques	Not examined	45	Not examined	80	59	69	65	49	39	54	33	Not examined
Zircon	..	18	,,	5	34	27	15	41	6	27	54	,,
Kyanite	..	3	,,	7	1	P	7	3	....	5	1	..
Staurolite	,,	3	,,	4	1	..	3	1	....	5	1	..
Rutile	,,	4	,,	1	3	3	5	5	P	6	5	..
Epidote	..	24	..	..	P	....	....	P	55	P	3	..
Tourmaline	,,	P	,,	3	1	P	4	1	....	P	1	..
Sillimanite	,,	5	,,	....	..	....	....	....	..	1	P	,,
Hornblende	,,	P	,,	P	..		P	P	....	....	....	,,
Pleonaste	,,	....	..	P	....		P	....	..	P	....	..
Garnet	,,	P	..	..	..	..	P	....	....	....	....	..
Monazite	..		..	P	....	....	P	P	....	1	2	..

Separations were made from original samples of 50 gms.
Number % of non-magnetic fractions based on count of between 300 and 400 grains in each sample. P indicates presence in amounts less than 1%.

A. Yellow Sand, Crawley (22804).
B. Yellow Sand, from wash-out near 14-mile peg, Ridge Hill (21361).
C. Yellow Sand, N.W. corner Loc. 1298, Ridge Hill (22802).
D. Insoluble residue from ferruginous sandstone (22798), Ridge Hill.

Garnet is also very rare, in rounded colourless to pale pink grains.

Monazite in perfectly rounded, pale yellow grains is most abundant in the ferruginous sandstone, but even there is comparatively rare.

Shape analyses indicate that all samples show similar characteristics. As indicated in figure six the average sphericity is constant in all grades for each of the samples examined and the average roundness decreases with diminishing grain size in all samples. Figure six shows the distribution of sphericity and roundness in the whole sample and it will be noted that there is a greater spread in the degree of rounding of the grains of the ferruginous sandstone than in the yellow sands—this is the only appreciable difference in the shape analyses. The similarity in the various samples indicates that so far as the factors affecting shape are concerned they all had a common type of origin.

Examination of the surface textures of the grains in these different samples revealed the following:—

Sample and Grade.	SURFACE TEXTURE		
	60–115 mesh. ($\frac{1}{8}$–$\frac{1}{4}$ mm.)	32–60 mesh. ($\frac{1}{4}$–$\frac{1}{2}$ mm.)	16–32 mesh. ($\frac{1}{2}$–1 mm.)
A. 22804 Yellow sand, Crawley.	5% of grains well rounded, smooth, high polish, but a few grains are frosted. 95% rough, vitreous fracture surfaces. "Heavies" show marked rounding and high polish	10% smooth, frosted with later superimposed polish. 60% rough, vitreous fracture surfaces	90% smooth, frosted crescentic percussion marks common. 10% rough, vitreous fracture surfaces
B. 21364 Yellow sand, Ridge Hill.	5% well rounded, smooth, polished, few grains frosted, some with percussion marks. 95% rough vitreous fracture surfaces. "Heavies" show marked rounding and high polish	Higher proportion of smooth grains than in 60–115 grade. Smooth grains frosted but some are polished. Rough grains slightly frosted	80% smooth, all frosted with slight superimposed polish. Percussion marks common. 20% rough, polished to slightly frosted
C. 22802 Yellow sand, Loc. 1298, Ridge Hill.	5%–10% well rounded, smooth, polished to slightly frosted. 90%–95% slightly rounded, rough, polished or vitreous fracture surfaces	Similar to 60–115 grade but much higher proportion of rounded grains with slightly higher degree of frosting. Crescentic percussion marks on many rounded grains	Similar to 32–60 but degree of frosting on rounded grains is higher. A polish seems to be superimposed on the frosting. Percussion marks common on rounded grains
D. 22798 Insoluble residue from ferruginous sandstone Ridge Hill	5% rounded, smooth, polished, often pitted but not frosted. 95% rough, polished or vitreous fracture surfaces. Contains small amount of tuberose allophanoid	50% rounded, smooth, polished, often pitted, a few grains frosted, some with crescentic percussion marks. 50% rough with polished or vitreous fracture surfaces	90% rounded, smooth, dull to polished with minute pitting and crescentic percussion marks. 10% rough with polished or vitreous fracture surfaces

The examination of the surface textures indicates that the fine sand grains of the ferruginous sandstone show no appreciable frosting. In the yellow sands on the other hand frosting is common down to grains ¼ mm. diameter. Moreover all the yellow sands exhibit similar features so far as the surfaces of the grains are concerned, the proportion of rounded grains and the degree of frosting of such grains increasing with increasing grain size.

The yellow colour of the sands is due to a very small amount of iron. When the yellow sand is heated it changes to a brick red colour. Determinations of the iron content responsible for the yellow colouration of the Crawley and Ridge Hill sands were made by first removing the magnetic minerals (magnetite and ilmenite) and leaching the residue with warm HCl and determining the iron content of the material leached out. The results were as follows:—

Yellow sand, Crawley (22804): 0.39% Fe_2O_3

Yellow sand, Ridge Hill (21364): 0.48% Fe_2O_3.

From the above considerations of mechanical composition, heavy minerals, shape and surface texture of grains, the ferruginous sandstones, in view of the absence of frosted surfaces on the fine sand grains and the presence of the tuberose allophanoid, together with the different size distribution of the heavy minerals and the better grading than the yellow sands, must be regarded as differing in mode and time of origin from the unconsolidated sands. Their provenance however (as evidenced by the heavy mineral species) was similar to that of the yellow sands. In all ways except in their higher heavy mineral content the yellow sands of Ridge Hill are similar to the only examined sample of yellow sand from the Metropolitan Area and each of these must, until further evidence to the contrary be brought forward, be regarded as belonging to the same formation. The presence of frosting on grains less than one mm. diameter (grains down to ¼ mm. are frosted) is indicative of aeolian transportation (Twenhofel, 1945, p. 67). The yellow sands of the Metropolitan Area have not previously been examined in detail although Esson (1926, p. 14) suggests that they are dune sands. It may rather be that they are residuals from the disintegration of the Coastal Limestones. Pending further investigation it is impossible to say whether the yellow sands of Ridge Hill are sands blown from the sea beach and banked up against the Darling Scarp or are residual deposits from the Coastal Limestones (in which the sand grains may prove to have suffered aeolian transport). The complete absence of bedded and other structures in these yellow sands seems to indicate the latter. The observation that the Ridge Hill sands have a much higher heavy mineral content than the yellow sands of the Metropolitan Area also seems to indicate that the sands fronting the scarp are residual rather than sands blown from the west, in which case they would be expected to have a lower heavy mineral index than the sands of the Metropolitan Area. If the Ridge Hill sand be residual from the Coasal Limestone Series it means that the Coastal Limestone once covered the entire plain in this region or that there were belts of coastal limestone representing successive shore lines.

IV. SUMMARY AND CONCLUSIONS.

(a) *Geological history.*—The geology of the area has been described and the geological history may be summarised as follows:—

(i) The oldest rocks exposed are granites, of which there are two main phases:—a coarse-grained porphyritic and slightly gneissic granite and a medium even-grained massive granite. The gneissic type is the older of the two but both are considered to be comagmatic and to belong to the Younger Granite period (late Archaeozoic).

(ii) The granites have been considerably sheared after their emplacement. These shears, because of their Pre-Cambrian age, cannot be related to the hypothetical Darling Fault.

(iii) In Proterozoic times igneous activity is represented by the intrusion of epidiorite dykes.

(iv) There is a complete blank in the succession until late Mesozoic times at least when it is probable that the ferruginous sandstones were deposited on a wave-cut platform and that the eastern boundary of the ferruginous sandstone series represents the shore-line in these times.

(v) The next event recorded is the formation of the high-level laterite on a peneplaned surface, probably in Miocene times.

(vi) An uplift of the area of the order of 400 feet took place in late Miocene times and differential erosion of the soft rocks (Mesozoic and later) to the west and the hard rocks (Pre-Cambrian) to the east led to the formation of a low lying coastal plain (the Ridge Hill Shelf) or alternatively, if the ferruginous sandstones are not of Mesozoic age, the development by marine erosion of a marine platform (the Ridge Hill Shelf) covered with a thin veneer of beach deposits which have later been cemented with ferruginous material to yield the ferruginous sandstones and conglomerates.

(vii) The area was then elevated slightly until the Ridge Hill Shelf stood slightly above sea-level and the low-level laterite developed in situ on this newly emerged terrain.

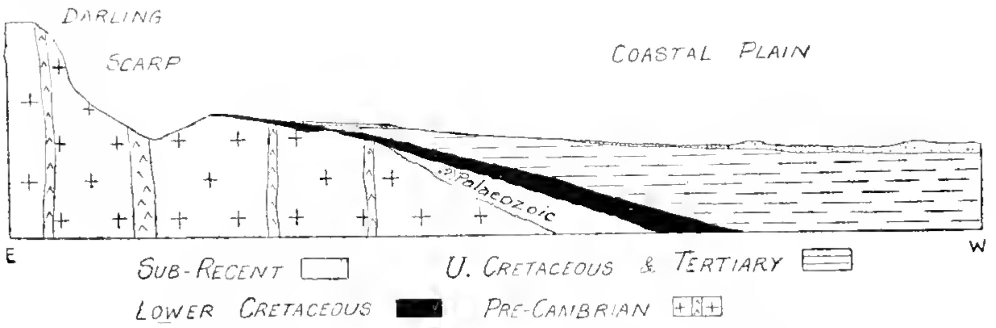
(viii) The area has since been raised approximately 250 feet, after which much of the ferruginous sandstone series was removed by erosion, especially that part which previously extended across the present Helena valley.

(ix) Contemporaneously with these upward movements of the plateau to the east there was continual subsidence (downwarping) of the area lying to the west of the Scarp and deposition in this subsiding trough of the Tertiary deposits of the Swan Coastal Plain.

(x) In comparatively recent times the yellow sands have accumulated either as aeolian deposits blown against the erosion escarpment capped by the low-level laterite or by deposition of the Coastal Limestone formation against this escarpment and the subsequent leaching of the calcareous cement yielding the structureless, unconsolidated yellow sands. As has been indicated on a previous page these sands are not residual from the disintegration of the ferruginous sandstones.

(xi) Laterite formation appears to be taking place within the yellow sands at the present day.

The structure of the Darling Scarp and Coastal Plain based on the assumption that the ferruginous sandstone series is of Lower Cretaceous age is shown diagrammatically in text fig. 7.



Text fig. 7.—Diagrammatic section (not to scale) of the Coastal Plain artesian basin on the assumption that the Ridge Hill ferruginous sandstones are of Lower Cretaceous age (comparable with the Bullsbrook sandstones).

(b) *The Darling Scarp.*—Previous authors have considered that the "fault" hypothesis for the origin of the Darling Scarp is supported by evidence of shear structures in the Pre-Cambrian rocks (Saint-Smith, 1912, p. 71; Blatchford, 1912, p. 59) and by the high and low- level laterites which were considered to be an indication of block faulting (Woolnough, 1920, p. 16). The main conclusions drawn from the evidence set down in this paper are:—

(i) There are no structures in the Pre-Cambrian rocks which can be related to the supposed Darling Fault. The shear structures are considered to be of late Archaeozoic age since some of them have been replaced by quartz veins which are intruded by late Pre-Cambrian epidiorites, and hence much older than the postulated Darling Fault. Moreover they deviate very considerably from the direction of the Darling Scarp.

(ii) The high- and low-level laterites were formed at different periods and are no indication of block faulting and therefore yield no evidence in favour of the Darling Fault hypothesis.

(iii) It has been shown that no fault exists between the eastern and western edges of the area mapped and therefore if the Darling Fault exists it must be situated some distance to the west of the Ridge Hill Area where it is covered by the yellow sands.

If these conclusions are valid there is no positive evidence for the existence of the Darling Fault. Moreover all the observed characteristics of the scarp are explicable by differential erosion of the hard Pre-Cambrian rocks to the east and the softer later rocks to the west of the scarp.

V. ACKNOWLEDGMENTS.

The field survey work in the Ridge Hill Area was done by various parties of senior students of the University Geology Department working under my supervision and their assistance is gratefully acknowledged. I am indebted also to Professor E. de C. Clarke for assistance during the revision of the text.

VI.—LIST OF WORKS TO WHICH REFERENCE IS MADE.

Aurousseau, M., and Budge, E. A., 1921, "The terraces of the Swan and Helena Rivers and their bearing on recent displacement of the strand line." *Journ. Roy. Soc. W. Aust.*, VII, pp. 24-43.

Blatchford, T., 1912, "The possibility of obtaining artesian water in the vicinity of Moora." *Geol. Surv. W. Aust. Bull.* 48, pp. 56-62.

Clarke, E. de C., Prider, R. T., and Teichert, C., 1944, "Elements of Geology" (Univ. West. Aust. Textbooks Board).

Clarke, E. de C., and Williams, F. A., 1926, "The Geology and Physiography of parts of the Darling Range near Perth." *Journ Roy. Soc. W. Aust.*, XII, pp. 161-178.

Davis, C. E. S., 1942, "The Geology and Physiography of the Gosnells Area." *Journ. Roy. Soc. W. Aust.*, XXVII, pp. 245-264.

Esson, A. G. D., 1926, "Peat in Western Australia with particular reference to its geological occurrence in the Bayswater District." *Geol. Surv. W. Aust. Ann. Report for 1925*, pp. 13-23.

Fletcher, R. W., and Hobson, R. A., 1932, "The Geology and Physiography of the Upper Swan Area." *Journ. Roy. Soc. W. Aust.*, XVIII, pp. 23-42.

Jutson, J. T., 1912, "Geological and Physiographical Notes on a traverse over portion of the Darling Plateau." *Geol. Surv. W. Aust. Bull.* 48, pp. 138-173.

Jutson, J. T., 1934, "The Physiography (Geomorphology) of Western Australia." *Geol. Surv. W. Aust. Bull.* 95.

Krumbein, W. C., 1941, "Measurement and geological significance of shape and roundness of sedimentary particles." *Journ. Sed. Petrol.*, 11, pp. 64-72.

Maitland, A. Gibb, 1919, "The artesian water resources of Western Australia" (Extract from "The Mining Handbook"). *Geol. Surv. W. Aust. Memoir 1.*

Parr, W. J., 1938, "Upper Eocene foraminifera from deep borings in King's Park, Perth, Western Australia." *Journ. Roy. Soc. W. Aust.*, XXIV, pp. 69-101.

Prider, R. T., 1941, "The contact between the granitic rocks and the Cardup Series at Armadale." *Journ. Roy. Soc. W. Aust.*, XXVII, pp. 27-55.

Prider, R. T., 1944, "The Petrology of part of the Toodyay District." *Journ. Roy. Soc. W. Aust.*, XXVIII, pp. 83-137.

Prider, R. T., 1945, "Granitic Rocks from Canning Dam." *Journ. Roy. Soc. W. Aust.*, XXIX, pp. 137-149.

Prider, R. T., 1948, "Igneous activity, metamorphism and ore-formation in Western Australia." *Journ. Roy. Soc. W. Aust.*, XXXI, pp. 43-84.

Saint-Smith, E. C., 1912, "A geological reconnaissance of a portion of the South-West Division of Western Australia." *Geol. Surv. W. Aust. Bull.* 44.

Rittenhouse, G., 1943, "Visual Projection Sphericity." *Journ. Sed. Petrol.*, 13, pp. 80-81.

Simpson, E. S., 1910, "Report on Excursion to Zig Zag (Stathams)." *Journ. Nat. Hist & Sci. Soc. W. Aust.*, III, pp. 36-38.

Simpson, E. S., 1912, "Notes on laterite in Western Australia," *Geol. Mag.*, dec. V, vol. IX, pp. 399-406.

Simpson, E. S., 1931, "Contributions to the Mineralogy of Western Australia, Series VI." *Journ. Roy. Soc. W. Aust.*, XVII, pp. 137-149.

Spliehal, J., 1922, "Contribution to the Knowledge of Colloidal Clays." *Min. Abstr.*, I, p. 288.

Trask, P. D., 1932, "Origin and Environment of Source Sediments of Petroleum" (Gulf Publishing Co., Texas).

Twenhofel, W. H., 1945, "The Rounding of Sand Grains." *Journ. Sed. Petrol.*, 15, pp. 59-71.

Wentworth, C. K., 1922, "The Shapes of Beach Pebbles." *U.S. Geol. Surv. Prof. Paper*, 131-C.

Woolnough, W. G., 1918, "The Physiographic Significance of Laterite in Western Australia." *Geol. Mag.*, dec. VI, vol. V, pp. 385-393.

Woolnough, W. G., 1920, "The Physiographic Elements of the Swan Coastal Plain." *Journ. Roy. Soc. W. Aust.*, V, pp. 15-20.

GENERAL INDEX.

Generic and specific names in heavy type are new to science.

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