Royal Society of New South Wales

OFFICERS FOR 1958-1959

Patrons :

His Excellency the Governor-General of the Commonwealth of Australia,
Field-Marshal Sir WILLIAM SLIM, G.C.B., G.C.M.G., G.C.V.O., G.B.E., D.S.O., M.C.

His Excellency the Governor of New South Wales,
Lieutenant-General Sir ERIC W. WOODWARD, K.C.M.G., C.B., C.B.E., D.S.O.

President

J. L. GRIFFITH, B.A., M.Sc.

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B. A. BOLT, M.Sc.
F. W. BOOKER, D.Sc., Ph.D.
A. A. DAY, B.Sc., Ph.D. *vice* A. BOLLIGER, D.Sc., Ph.D. resigned July, 1958.
J. A. DULHUNTY, D.Sc.
R. M. GASCOIGNE, Ph.D.
E. J. J. HARRISON, B.Sc.
D. P. MELLOR, D.Sc.
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G. TAYLOR, D.Sc., B.E. (*Min.*) (*Syd.*), B.A. (*Cantab.*), F.A.A.
H. F. WHITWORTH, M.Sc.

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* Published October 15, 1958.
† Published February 10, 1959.
‡ Published April 21, 1959.

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† Published September 30, 1959.

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SEAMER AND ARUNDEL STS., GLEBE, SYDNEY

JOURNAL AND PROCEEDINGS

OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOL. 92

PART 1

1958

Edited by the Honorary Editorial Secretary

PUBLISHED BY THE SOCIETY
SCIENCE HOUSE, GLOUCESTER AND ESSEX STREETS, SYDNEY

ISSUED OCTOBER 15, 1958

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A

Royal Society of New South Wales

REPORT OF THE COUNCIL FOR THE YEAR ENDED 31ST MARCH, 1958.

PRESENTED AT THE ANNUAL AND GENERAL MONTHLY MEETING OF THE SOCIETY, 2ND APRIL, 1958, IN ACCORDANCE WITH RULE XXVI.

At the end of the period under review the composition of the membership was 331 ordinary members; 2 associate members and 8 honorary members. Nine new members were elected; four resigned; four names were removed from the list of members under Rule XVIII. It is with regret that we announce the loss by death of Mr. Peter Beckmann, Dr. George Harker, Mr. George Petersen and Mr. Orwell Phillips. Dr. Harker had been a member of the Society since 1905. Also, we regret to announce the death of Sir Charles J. Martin, an honorary member since 1912, who died in 1955.

Nine monthly meetings were held. The Proceedings of these meetings, which have been published in the notice papers, will appear in the fourth part of volume 91 of the "Journal and Proceedings". The Members of the Council wish to express their sincere thanks and appreciation to the 15 speakers at the symposia and the seminar and also to the members who read papers at the September monthly meeting.

The Annual Social function was held on 20th November, 1957, at which the attendance was 46. Some items of interest from the Society's library were on display and Professor Taylor lent one of Shackleton's volumes, which had been used by Captain Scott at the Antarctic.

The Clarke Medal for 1958 was awarded to Professor T. G. B. Osborn for distinguished contributions in the field of botany.

The Society's Medal, which represents the Society's appreciation of service not only to science but also to the welfare of the Society itself, was awarded to Associate Professor R. C. L. Bosworth.

The Edgeworth David Medal for 1957 was awarded conjointly to Dr. J. M. Cowley for outstanding work in the study of crystalline structure of matter by electron diffraction and to Mr. J. P. Wild for outstanding work in the field of radio astronomy.

The Archibald D. Olle Prize and the James Cook Medal for 1957 were not awarded.

The Clarke Memorial Lecture for 1957 was delivered by Professor A. H. Voisey on 30th July. The title of the lecture was "Further Remarks on Sedimentary Formations in New South Wales".

The Society together with the other owner bodies of Science House applied to the Court for a redetermination of the rents of Science House. The new rentals have applied for only part of the last financial year. The Society has received a net income of £996 3s. 4d., an increase of £174 1s. 7d. It is anticipated that this return will be higher in the coming year.

The Society has again received a grant of £500 from the Government of New South Wales. (The amount of £750 appearing on the Balance Sheet includes £250—a lag from 1953, when the subsidy was paid in quarterly instalments, thus excluding the March and June (1953) instalments from the Society's financial year ending 28th February, 1953. For the Government's current financial year, the Subsidy has been made in one payment). The Government's continued interest in the work of the Society is much appreciated.

Also, Council desires to express its appreciation of a donation of £50 from the "Advancement of Science" Fund established by a number of members of the Chamber of Manufactures of New South Wales with a view to assisting scientific publications.

The Society's financial statement shows a small deficit of £35 2s. 0d.

During the year five parts of the Journal were published. The cost of publication has been £1547 12s. 9d. Eighteen papers have been accepted for reading and publication in volume 91.

A complete list of the periodicals received by exchange with the Journal has been made. This list is being reviewed by the Executive Committee and will be published in due course. Members may consult this list at the office of the Society.

The section of Geology held five meetings during the year. Dr. Lawrence was Chairman and Dr. Koch was Honorary Secretary. The average attendance was 30.

Council held eleven ordinary meetings and two special meetings. The attendance of members of Council was as follows: Mr. F. N. Hanlon, 13; Rev. T. N. Burke-Gaffney, 12; Mr. H. A. H. Donegan, 8 (on leave for 3 meetings); Mr. F. D. McCarthy, 9; Dr. C. J. Magee, 10; Dr. Ida A. Browne, 10; Mr. J. L. Griffith, 12; Dr. F. W. Booker, 9; Prof. G. Bosson, 2; Dr. G. W. K.

Cavill, 9 (on leave for 3 meetings); Dr. J. A. Dulhunty, 5; Mr. A. F. A. Harper, 10; Prof. D. P. Mellor, 7; Mr. W. H. G. Poggendorff, 6; Dr. Phyllis M. Rountree, 9; Prof. G. Taylor, 10; Mr. H. F. Whitworth, 8; Mr. H. W. Wood, 9.

The Society's representatives on Science House Management Committee were Dr. Magee, Mr. Hanlon and Mr. Donegan (*vice* Dr. Magee); Mr. Harper and Mr. Wood were substitute representatives.

The President, accompanied by the Honorary Secretary, waited on His Excellency the Governor of New South Wales on 26th June and reported on the progress of the Society.

The President attended the State Reception to His Excellency Lieutenant-General Sir John Northcott, K.C.M.G., K.C.V.O., C.B., prior to his relinquishing his appointment as Governor of New South Wales.

Council has pleasure in informing members that His Excellency Lieutenant-General Sir Eric W. Woodward, K.C.M.G., C.B., C.B.E., D.S.O., is pleased to grant his patronage to the Society during his tenure as Governor of New South Wales.

The President attended the Official Welcome to His Excellency Sir Eric W. Woodward held in the Botanic Gardens on 1st August.

During the Royal Visit, the President was present at a State Reception in honour of Her Majesty, Queen Elizabeth, the Queen Mother, on 21st February and Dr. Phyllis Rountree attended a Reception at the Trocadero in honour of Her Majesty, Queen Elizabeth, the Queen Mother on 24th February.

The Society was represented by the President-Elect on the Board of Visitors of the Sydney Observatory on 19th March.

The Library.—Periodicals were received by exchange with 376 societies and institutions. In addition, the amount of £101 6s. 3d. was expended on the purchase of periodicals.

During the year the amount of £482 0s. 6d. was received from the sale of out-of-date periodicals.

Mrs. Ruth Huntley was appointed Assistant Librarian and commenced duties on 29th April, 1957.

Among the institutions which made use of the library through the inter-library loan scheme were: C.S.I.R.O.-C.S.I.R.O., Brisbane; Division of Food Preservation, Cannon Hill; Tobacco Research Institute, Mareeba; Head Office, Melbourne; Library, Canberra; Animal Genetics, Sydney; Coal Research, Sydney; Division of Fisheries, Cronulla; National Standards Laboratory, Sydney; Division of Plant Industry, Canberra; Sheep Biology Laboratory, Parramatta; Wool Textile Research Laboratory, Parkville; Division of Industrial Chemistry, Melbourne; Australian Atomic Energy Commission; Alfred Hospital Medical Research Unit, Prahran; B.A.L.M., Concord; Lewis Berger, Rhodes; B.H.P. Ltd., Shortland; Botanic Gardens, Sydney; C.S.R. Co. Ltd., Sydney; Conservation Department, Sydney; Customs Department, Sydney; Institute of Dental Research, Sydney; Department of Health, Sydney; Department of Public Works, N.S.W., Sydney; Electricity Commission; Institution of Engineers; Forestry Commission; Geigy (A'sia) Ltd.; James Hardie & Co.; M.W.S. & D. Board, N.S.W.; Mining Museum, Sydney; Patent Office, Canberra; Public Library of South Australia; Queensland Institute of Medical Research; Royal Newcastle Hospital; South Australian Museum; Snowy Mountains Hydro-Electric Authority; Standard Telephones & Cables; Sydney Hospital; University of Adelaide, Barr Smith Library; University of Melbourne, General Library; N.S.W. University of Techology; Sydney Technical College; Newcastle University College; University of New England; University of Queensland; University of Sydney; University of Tasmania; University of Western Australia; Waite Agricultural Research Institute, Adelaide.

F. N. HANLON,
President.

THE ROYAL SOCIETY OF NEW SOUTH WALES.

BALANCE SHEET AS AT 28th FEBRUARY, 1958.

LIABILITIES.

1957. £		£ s. d.	£ s. d.
28	Subscriptions Paid in Advance		23 2 0
206	Life Members' Subscriptions—Amount Carried forward		195 9 0
	Trust and Monograph Capital Funds (detailed below)—		
	Clarke Memorial	1,890 6 6	
	Walter Burfitt Prize	1,103 13 7	
	Liversidge Bequest	711 9 2	
	Monograph Capital Fund	4,069 3 5	
7,741	Olle Bequest	90 3 7	7,864 16 3
23,528	ACCUMULATED FUNDS		23,474 2 1
	Contingent Liability (in connection with Perpetual Lease)		
£31,503			£31,557 9 4

ASSETS.

1957. £		£ s. d.	£ s. d.
386	Cash at Bank and in Hand		142 13 8
	Investments—		
	Commonwealth Bond and Inscribed Stock—At Face Value—held for :		
	Clarke Memorial Fund	1,800 0 0	
	Walter Burfitt Prize Fund	1,000 0 0	
	Liversidge Bequest	700 0 0	
	Monograph Capital Fund..	3,000 0 0	
	General Purposes	2,460 0 0	
8,960			8,960 0 0
	Debtors for Subscriptions	102 6 0	
	Less : Reserve for Bad Debts	102 6 0	
			—
14,835	Science House—One-third Capital Cost		14,835 4 4
6,800	Library—At Valuation		6,800 0 0
502	Furniture and Office Equipment—At Cost, *less* Depreciation		800 10 4
19	Pictures—At Cost, *less* Depreciation		18 1 0
1	Lantern—At Cost, *less* Depreciation		1 0 0
£31,503			£31,557 9 4

TRUST AND MONOGRAPH CAPITAL FUNDS.

	Clarke Memorial.			Walter Burfitt Prize.			Liversidge Bequest.			Monograph Capital Fund.			Olle Bequest.		
	£	s.	d.	£	s.	d.	£	s.	d.	£	s.	d.	£	s.	d.
Capital at 28th February, 1958	1,800	0	0	1,000	0	0	700	0	0	3,000	0	0	—		
Revenue—															
Balance at 28th February, 1957	76	0	6	143	14	2	13	3	9	956	10	8	77	14	1
Income for twelve months	63	7	9	35	4	5	24	12	11	112	12	9	42	9	6
	139	8	3	178	18	7	11	9	2	1,069	3	5	120	3	7
Less Expenditure ..	49	1	9	75	5	0	—			—			30	0	0
Balance at 28th February, 1958	£90	6	6	£103	13	7	£11	9	2	£1,069	3	5	£90	3	7

ACCUMULATED FUNDS.

	£	s.	d.	£	s.	d.
Balance at 28th February, 1957				23,528	11	1
Add—						
Decrease in Reserve for Bad Debts				18	9	0
				23,547	0	1
Less—						
Bad Debts Written Off	37	16	0			
Deficit for twelve months	35	2	0	72	18	0
Balance at 28th February, 1958				£23,474	2	1

Auditors' Report.

The above Balance Sheet has been prepared from the Books of Account, Accounts and Vouchers of the Royal Society of New South Wales, and is a correct statement of the position of the Society's affairs on 28th February, 1958, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants (Aust.)

Prudential Building,
39 Martin Place, Sydney.
25th March, 1958.

(Sgd.) F. W. BOOKER,
Honorary Treasurer.

INCOME AND EXPENDITURE ACCOUNT.

1st March, 1957 to 28 February, 1958.

1957. £			£ s. d.
7	Annual Social Function		12 7 4
31	Audit		31 10 0
106	Cleaning		104 0 0
27	Depreciation		43 1 8
41	Electricity		43 8 5
4	Entertainment		1 10 0
39	Insurance		38 14 1
212	Library Purchases		106 7 0
89	Miscellaneous		133 9 2
138	Postages and Telegrams		135 11 10
	Printing Journal—		
	Vol. 90, Parts 2–4	£898 9 9	
1,330	Vol. 91, Parts 1–2	649 3 0	
			1,547 12 9
112	Printing—General		108 13 0
132	Removal Expenses		8 14 0
62	Rent—Science House Management		62 12 0
10	Repairs		4 9 7
104	Reprints		9 17 3
1,040	Salaries		1,115 15 2
32	Telephone		28 15 11
£3,516			£3,536 9 2

1957. £		£ s. d.
845	Membership Subscriptions	838 8 6
10	Proportion of Life Members' Subscriptions	10 10 0
117	Subscriptions to Journal	216 12 6
500	Government Subsidy	750 0 0
822	Science House Management—Share of Surplus	996 3 4
99	Rentals Received—Reception Room	45 15 6
85	Interest on General Investments	87 17 10
750	Sales of Periodicals ex Library	482 0 6
231	Sales of Back Numbers of The Journal	23 19 0
—	Publication Grant	50 0 0
57	Deficit for twelve months	35 2 0
£3,516		£3,536 9 2

ABSTRACT OF THE PROCEEDINGS

OF THE SECTION OF

GEOLOGY

Chairman : L. J. Lawrence, Ph.D., B.Sc.
Honorary Secretary : L. E. Koch, Dr.phil.habil.

Meetings.—Five meetings were held during the year 1957 alternating with the monthly meetings of the Geological Society of Australia. The average attendance was 30 members and visitors.

March 15th : *Annual Meeting* : Election of office-bearers : Chairman, Dr. L. J. Lawrence ; Hon. Sec., Dr. L. E. Koch.

Business : Notes and Exhibits. The following contributions were made : Dr. L. J. Lawrence pyromorphite and coronadite from Broken Hill ; Mr. R. O. Chalmers, spinels from Sapphire and Tumbarumba, N.S.W., blue tourmaline from an unknown locality ; Mr. W. E. Baker, pseudomorphs of a svanbergite-like mineral after pyromorphite from Dundas, Tas. ; Mr. H. G. Golding, skeleton-shaped leucoxene grains from Oxford Falls, Narrabeen, N.S.W. ; Dr. T. G. Vallance, pink andalusite from Newbridge, near Bathurst, N.S.W. ; Messrs. E. Chaffer and H. G. Golding, pyritic sandstone from Oxford Falls, near Narrabeen, N.S.W.

May 17th :

Address by Miss F. M. Quodling entitled " Mineralogical and Geological Highlights of a Sabbatical Year Abroad ".

July 19th :

Address by Dr. L. E. Koch entitled " The Meaning of the Term : ' Roches Moutonées ' and Other Geological and Mineralogical Names (Demonstration of a General Method of Analysis of Common and Scientific Names) ". The " Law of Naming " and the " Law of Identification " of natural things were announced and illustrated by examples, the two laws being constituent parts of a " Theory of descriptive natural science and related lexical semantics " which was presented and outlined.

September 13th :

Address by Professor Richard P. Goldthwait, of the Ohio State University, U.S.A., entitled " Glaciological Techniques ".

November 15th :

Address by Dr. Germaine A. Joplin, of the Australian National University, Canberra, entitled " The Question of Primary Magmas ".

Obituary

ORWELL PHILLIPS, a member of the Society since 1935, died on 28th July, 1957. He was a prominent Sydney businessman and took an active part in the direction of several large commercial undertakings.

GEORGE HARKER received his training at the University of Sydney, from which he graduated Bachelor of Science in 1899, with honours in Chemistry. Two years later he was recommended for an 1851 Exhibition Scholarship and proceeded to London, where he continued his researches in Organic Chemistry at the Central Technical College, South Kensington, under Professor H. E. Armstrong, eventually gaining his degree of D.Sc. of the University of London. Returning to Sydney in 1903, he received an appointment as research chemist on the staff of the Colonial Sugar Refining Company; this he relinquished in 1914 to become Lecturer and Demonstrator in Organic Chemistry at the University of Sydney. From 1929 to 1938 he was research officer to the Cancer Research Committee of the University and, thereafter, retired from active work. A Fellow of the Australian Chemical Institute, he was Chairman of its Council in 1922. He joined this Society in 1905 and, at the time of his death on 15th August, 1957, was the second oldest member. He contributed six papers to the "Journal and Proceedings".

GEORGE PETERSEN was born on 30th June, 1893. He was educated at Forest Lodge School and, afterwards, studied Architecture, but was prevented from practising by the outbreak of World War I. He enlisted in 1915 and, as a member of the 56th battalion, 5th division, A.I.F., saw active service in France, where he received his commission in the field. Returning to Australia after the war, he joined the staff of the N.S.W. Government Tourist Bureau and in 1939 was appointed manager of the Hotel Kosciusko and, after its destruction by fire, of the Chalet. He was noted for his urbanity and kindness of heart and, in particular, he was the very good friend of scientific parties visiting the Kosciusko area. Ill health, the result of war injuries, forced him to retire in 1952, and he died on 7th January, 1958. He had joined this Society in 1956.

During his residence in the Kosciusko area, he developed a keen interest in its geography and geology and in the history of the early exploration and settlement of the Monaro region generally, on which, after his retirement, he wrote articles for various periodicals. A keen and successful landscape photographer, he possessed a large and valuable collection of pictures of Kosciusko in its various moods. Most of these, unfortunately, were destroyed in the Hotel Kosciusko fire, but he replaced many of them with colour photographs and his illustrated lectures helped to bring home to Sydney audiences the beauties and the interest of our mountain country.

PETER BECKMANN, who died on 3rd February, 1958, the seventeenth anniversary of his arrival in Australia, had been a member of this Society since 1947. Born at Olmutz, Moravia, on 7th April, 1924, he left Czechoslovakia with his parents at the age of 14 and lived in Switzerland and Italy before coming to Australia. He studied Applied Chemistry at Sydney Technical College and, in 1946, went to Glen Davis as a chemist to the National Oil Proprietary Ltd. His work was concerned largely with problems related to the retorting and refining of the shale oil and, in collaboration with the Chief Chemist, Mr. G. E. Mapstone, he published five papers dealing chiefly with analytical techniques. In 1948 he joined the staff of the Sydney Technical College and was appointed Lecturer in Chemistry at Wollongong. A special interest of his was Polarography, particularly in its bearing on electrochemical study of corrosion problems. For his work he was awarded the M.Sc. degree of the N.S.W. University of Technology.

After a year's sabbatical leave in 1955, spent in the Corrosion Laboratory at the University of Cambridge, he was promoted Senior Lecturer and made Lecturer-in-charge of Chemistry at Wollongong, a position which he held until his death.

LIST OF MEMBERS.

A list of members of the Royal Society of New South Wales up to 1st April, 1957, is included in volume XCI.

During the year ended 31st March, 1958, the following have been elected to membership of the Society :

Baker, William Ernest, B.Sc.(*Tas.*), School of Mining Engineering and Applied Geology, N.S.W. University of Technology, Kensington.

Cameron, John Craig, M.A., B.Sc., 15 Monterey Street, Kogarah.

Clancy, Brian Edward, B.Sc., Dip. Ed., Dept. of Mathematics, N.S.W. University of Technology, Wollongong.

Groden, Charles Mark, M.Sc., Dept. of Mathematics, N.S.W. University of Technology, Kensington.

Hla, U., Chief Planning Officer, Ministry of Mines, Rangoon, Burma.

Leechman, Frank, 79 Pitt Street, Sydney.

Reichel, Alex., B.Sc.(*Syd.*), Dip. Ed., Dept of Mathematics, N.S.W. University of Technology, Kensington.

Roberts, Herbert Gordon, 3 Hopetoun Street, Hurlstone Park.

Thornton, Barry Stephen, M.Sc., Dept. of Mathematics, N.S.W. University of Technology, Kensington.

During the same period resignations were received from the following :

Birch, Arthur John.
Coombs, Arthur Roylance.
Goulston, Edna Maude.
Mapstone, George E.

and the following names were removed from the list of members under Rule XVIII :

Burton, Gerald.
Everingham, Richard.
Luber, Leonard.
Sergeyeff, William P.

Obituary, 1957-58.

1947 Peter Beckmann.
1905 George Harker.
1956 George Peterson.
1935 Orwell Phillips.

AWARDS.

The Clarke Medal.

1958 Osborn, Theodore G. B., D.Sc., F.L.S., St. Mark's College, Pennington Terrace, North Adelaide South Australia.

The Edgeworth David Medal.

1957 Cowley, John M., D.Sc., Ph.D., C.S.I.R.O., Division of Industrial Chemistry, Melbourne.
Wild, John Paul, B.A., C.S.I.R.O., Division of Radiophysics, Sydney.
} Joint Award.

The Society's Medal.

1957 Bosworth, Richard C. L., D.Sc., Ph.D., School of Physical Chemistry, N.S.W. University of Technology, Sydney.

PRESIDENTIAL ADDRESS

By F. N. Hanlon, B.Sc.

With Plates I and II.

Delivered before the Royal Society of New South Wales, April 2, 1958.

Part I.

I am pleased to be able to report that the Society has had a successful year. The number of papers submitted and published in our Journal is satisfactory and the publication of our Journal is up to date. For the latter we are indebted to the efforts of our Honorary Editorial Secretary, Dr. Ida A. Browne. However, it is unfortunate that the costs of publication are so high and this has been one of the main worries of your Council.

I would like to place on record my appreciation of the assistance given to me in carrying out my duties by the Members of Council, the Office Staff and particularly the Members of the Executive. If one person should be singled out for mention it is Mr. J. L. Griffith, the Secretary and President-Elect, who has worked unstintingly, not only in arranging the Monthly and Council Meetings and ordinary secretarial duties, but also in the organization of the Office and Library Exchanges.

The activities during the year have been covered by the Annual Report of the Council and the Abstract of Proceedings and will not be repeated here. However, I would like to express the pleasure all members of the Society felt in being able to welcome the Queen Mother, Queen Elizabeth, during her visit to Australia in February this year.

The last year has been one of great scientific progress. Unfortunately many of the great advances and achievements go unnoticed and unrecognized by the general public, the industrial leaders, or for that matter the governments. One event, which did catch the public imagination, was the epoch-making and successful launching of earth satellites, first by Russia and then by the United States of America. This achievement highlighted the dearth of trained scientific and technological personnel in this country, as compared with many other countries of the world and stressed our need to train more and more scientists and technologists, and to train them quickly. However, assuming it were possible, merely training the personnel would not solve our problems. I feel that if Australia, at the present time, had the same ratio of trained scientists and engineers to total population as Great Britain, where the ratio is considerably less than in Russia and the United States of America, many of them would find difficulty in obtaining employment in suitable positions and where the remuneration would be adequate to recompense them for the years of effort and loss of earning capacity during their training. I feel that concurrently with the training of scientists there is a need for a campaign to prove to our industrialists the necessity for the employment of more trained personnel in our industries and the value to the industries of carrying out their own fundamental and applied research. Also our governments, among the largest employers of scientific personnel in the various Commonwealth and State Departments and Instrumentalities, and the Universities, which are subsidized by the governments, should give a lead in attracting our young people to train as scientists by offering adequate conditions and returns to them, so that they would be on a par with members of some other professions.

Part II.

GEOLOGY AND TRANSPORT

With Special Reference to Landslides on the near South Coast of New South Wales

With Plates I and II.

The influence of geological formations, structures and processes on the lay-out of our lines of communication is well-known. Trunk roads and railways often follow broad, open valleys because of the ease of access and construction. In many cases these valleys owe their origin to the presence of softer and more easily weathered formations or of weaker zones caused by faulting. The great harbours of the world, of which our own Sydney Harbour is an example, are often drowned river-valleys. Whether the foundations for our roads and railways are safe or unstable depends on the nature of the underlying rock formations.

The presence of mineral deposits often governs the necessity for major roads or railways to what are relatively barren and inhospitable areas, where transport requirements would otherwise be comparatively minor, a few examples from Australia being Broken Hill, Mt. Isa and Kalgoorlie. The presence of coal deposits has governed the location of many of our industrial centres. The supply of suitable clays, aggregates and other raw materials has a fundamental influence on the costs of building and contruction both in the centres of population and the road and railways connecting them.

The main part of my address tonight will set out the results of an investigation carried out in the near South Coast of New South Wales. It will relate the areas of instability, which are subjected to landslides, to the underlying rock formations and the geological structures. Problems of control will also be discussed.

The main area which has been mapped in detail lies between Stanwell Park and Scarborough. The general geology of the near South Coast is set out in Table I. The rock formations with which we are concerned in the area under consideration are those from the Hawkesbury Sandstone at the top to the Illawarra Coal Measures at the base. The geology has been dealt with in reports to the Department of Mines (Hanlon, 1956*a*, 1956*b*) and a paper in our own Journal written in collaboration with Dr. G. D. Osborne and Dr. H. G. Raggatt (Hanlon, Osborne and Raggatt, 1953).

The landslide problem in the area is an old one. As long ago as 1890, W. Shellshear published a paper in our Journal entitled " On treatment of Slips on the Illawarra Railway at Stanwell Park ". This was at a time when the railway line occupied the position of the present main road (the Lawrence Hargrave Drive). In subsequent years the railway was re-routed to its present position, because of serious movements which took place, and the old permanent way from the bottom of Bald Hill to near Coal Cliff Station was taken over for the main road.

In the pre-war years a committee comprising representatives of several government departments, including Railways, Roads and Mines, was formed to investigate the problem. Several meetings were held and certain investigations were carried out, but no comprehensive plan to overcome the problems was instituted and remedial measures were left to individual authorities concerned.

The Geological Survey Branch of the Department of Mines commenced a detailed survey of the area in 1951 and the writer was assigned to this work. Further research on the problem was carried out during 1954, while the writer held the position of Lecturer in Geology at the University of Technology.

Nature and Nomenclature of Landslides.

The phenomena which are referred to as landslides in this address cover a variety of effects, and different authors would use a varying terminology to classify them. For this reason it is necessary to describe the types of movement which have taken place and to define the terms used.

Terzaghi (1950) defines a *landslide* as a " rapid displacement of a mass of rock, residual soil, or sediments adjoining a slope, in which the centre of gravity of the moving mass advances in a downward and outward direction. A similar movement proceeding at an imperceptible rate is called *creep* ". This definition, which is a wide one, is used in this address. The fundamental cause of a landslide

Table I.

Pleistocene and Recent	Soil, alluvium, sand, gravels, talus and detritus.
Tertiary	Sills, dykes and flows.
Triassic	
Wianamatta Group	Mainly shales
Hawkesbury Sandstone	
Including Undola Sandstone Member	
Narrabeen Group	
Gosford Formation	Shales, claystones and siltstones with some greywackes
Clifton Sub-Group	
Bald Hill Claystone	
Bulgo Greywacke	
Stanwell Park Claystone	
Scarborough Greywacke	
Wombarra Shale, including Otford Greywacke Member	
Coal Cliff Greywacke	
Permian	
Illawarra Coal Measures	Greywackes, shales, claystones, tuffs, sandstones, cherts and coal seams. Minnamurra Latite, Berkeley Latite and Tappitallee Mountain Tuff.
Gerringong Volcanics	
Cambewarra Latite	
Saddleback Latite	
Broughton Tuff	
Jamberoo Tuff Member	
Bumbo Latite	
Kiama Tuff Member	
Rifle Range Tuff Member	
Blowhole Latite	
Westley Park Tuff Member	
Shoalhaven Group	
Berry Shale	
Nowra Sandstone	
Wandrawandian Siltstone	
Conjola Conglomerate	Formal naming in abeyance pending detailed work
Ulladulla Mudstone	

instead of a creep is the presence of sufficient stress to produce a shear failure. The most comprehensive discussion of the terminology of landslides is that by Sharpe (1938) in " Landslides and Related Phenomena ". This book includes a comprehensive bibliography and reviews work prior to the date of its publication. Sharpe restricts the term landslide to a " relatively dry mass of earth, rock, or a mixture of the two ". It is one end of a series (involving little water, large load, moderate to high angle) grading through debris-avalanche, earthflow, mudflow, sheetflood, slopewash to ordinary stream flow (involving much water, small load, low angle). On this basis, landslides in the area under review are of much more restricted occurrence. One good example is between Stanwell Park and Coal Cliff, and occurs along the Lawrence Hargrave Drive in a section previously occupied by the Railway Line (see Plate I, Figures 5 and 6). The material comprising the slide consists mainly of rock ; soil and subsoil is of minor importance. Water, too, was probably only a minor constituent at the time the slide took place. Large sections of rock retained their original relationships, although dips in places are now steep, in distinction to the normal dips of the rocks *in situ*, which are low. A similar slide, probably on a much bigger scale, appears to have taken place between Wollongong and Moss Vale in the vicinity of Dumbarton Siding.

At the extreme, where there are the conditions of most rapid movement and the least soil and water involved, there is the rockfall type of landslide. These occur typically in the Coal Cliff-Clifton area, where undermining along the shale bands reduces the support for the overlying vertically-jointed sandstones and eventually leads to slabs falling off along the vertical joint faces. These are very likely to occur from the Scarborough and Bulgo Greywackes above the Lawrence Hargrave Drive (see Plate I). The retreat of the coastline and the Hawkesbury Sandstone escarpment are also brought about by rockfalls.

Many of the slides in the South Coast and Camden-Picton areas are what Sharpe would describe as earthflows. These are characterized by slumping at the top, there being a distinct break between the moving ground and the higher stable area, and flowage or bulging at the bottom. There is normally a sharp break along the sides also. The earthflow type is usually elongated down the slope, but can have its longest dimension along the slope.

Failure normally takes place along a surface of slipping and in homogeneous material a cross-section through the slide has an approximately circular arc as a slip surface. In other cases, because of the relationship of the rock strata to the ground surface (*e.g.* dip or depth of weathering) the slip surface commences at the top as a circular arc but is then elongated parallel to the surface, the sliding material moving down and forming a bulge at the bottom. In either case there is a tendency for a rise in the ground surface at the foot of the slide. This was very well demonstrated in a slide which took place during 1950 between Coledale and Austinmer, south of the area mapped, and which affected the railway line. The underlying rocks belong to the Illawarra Coal Measures, below the horizon of the Wongawilli Seam and above the Tongarra Seam, and probably consist mainly of shales and claystones. The slide was located in detritus and near the top of the slide the ground movement led to the breaking up of houses (see Plate II, Figures 1 and 2). At its foot the ground rose upwards carrying with it the " up-line " to Sydney. The " down-line " was hardly affected, but in places there was a wall of sticky clay, feet high, past which trains on the " down-line " had to pass. Had the slide extended a few feet further eastwards both lines would have been affected and railway connection between Sydney and the South Coast completely cut off. Detritus extends up and down the slope for some distance above and below the slide.

In some areas it would appear that the weathered material underlying the cover of surface vegetation has become thoroughly waterlogged and has suffered spontaneous liquefaction ; it has flowed out as a slurry and has left the surface soil and vegetation to settle, breaking up to some extent, but still forming a surface mat. The immediate cause of the spontaneous liquefaction may have been vibrations from passing traffic or blasting. In other cases increase in the rate of percolation of water beneath the surface may remove sufficient material to lead to the formation of channels, with ultimate settling of the overlying mat of vegetation. In extreme cases the soil and vegetation are broken up completely and become incorporated in the sliding material.


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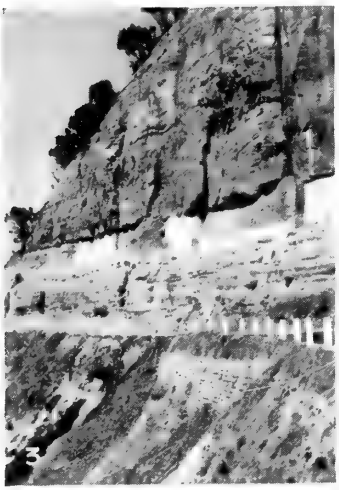
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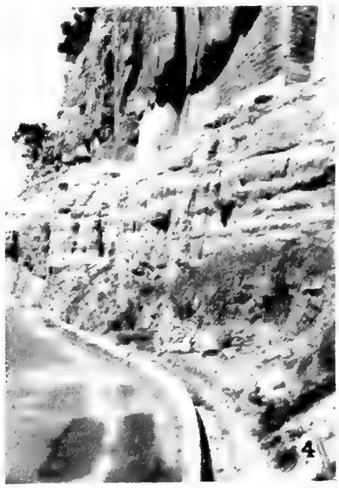
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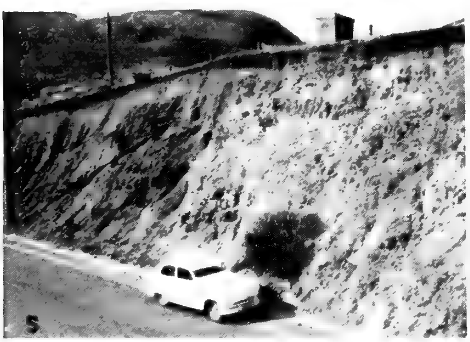
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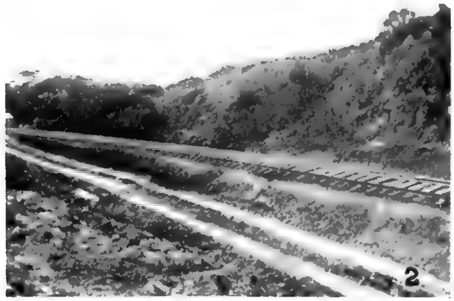
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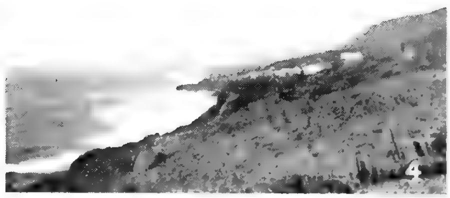
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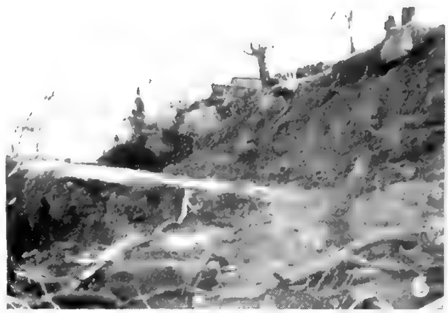
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Settlements in the railway and roadway embankments have been serious, but normally these also involve sliding in the detritus which forms the foundation for the embankment, or are influenced by the nature of the fill. Similarly with cut and fill along sidehill sections.

Relationships of Landslides to Geology.

Nature of Detritus

The detritus comprises the remaining part of the weathered and eroded material from the total of the formations at and above the level at which it occurs. At one extreme the Hawkesbury Sandstone would, in general, provide only blocks of sandstone or sand grains. At the other the shale and claystone formations would provide a high proportion of clayey material. The normal detritus is, therefore, a mixture of blocks of sandstone and greywacke set in a matrix comprising varying proportions of clayey, silty and sandy material.

Although the detritus can include material from any higher formations, its composition often reflects the nature of the formations immediately underlying it. At many points the approximate boundaries of the Bald Hill Claystone can be confidently mapped by the abundance of reddish-brown claystone fragments in the detritus. In general the detritus overlying the shaly and claystone formations is much more clayey. This is a reflection both of the supply of clay-rich material from the underlying formation and the fact that the more gentle slopes overlying these formations enables the accumulations of detritus to remain in place for longer periods than on the steeper slopes and therefore to be more completely weathered.

The properties of the detritus depend mainly on the clay-size fraction. Fortunately there do not appear to be any extra sensitive or " quick " clays present in the area. These are usually glacial lake clays or leached marine clays. In these types the failure spreads from the foot of the slope uphill and is not preceded by tension cracks along the upper boundary of the slide area, as in the case of clays with low to medium sensitivity (Terzaghi, 1955). The closest approach to the type of movement which characterizes the " quick " clays are those cases where the material underlying the surface vegetation has flowed out and allowed the surface soil and vegetation to settle and crack, as described earlier (page 4).

Four samples of the detritus were collected and the fine grained portion of them examined by means of X-ray and Differential Thermal Analyses, through the courtesy of Mr. F. C. Loughnan of the University of Technology. The samples were chosen in order to obtain a cross-section of typical conditions which might be expected to occur in the area. One pair of samples was collected from two neighbouring cuttings in the Wombarra Area, above the level of the outcrops of the Illawarra Coal Measures, and therefore derived entirely from the rocks of the Narrabeen Group, and the other pair from opposite faces of a cutting between Coledale and Austinmer, where material from the Illawarra Coal Measures is included and may be predominant.

The cuttings at Wombarra are on the access road to the South Clifton Colliery. It was previously a railway siding, but was widened to provide an access road. The cutting nearest the road is still in excellent condition and showed no signs of movement during the record rains of 1950-51. The matrix was found to contain illite and an iron-rich non-plastic chlorite. The other cutting has always tended to be troublesome. It was cut back during the construction of the access road and in the subsequent record rains there was considerable movement and houses at higher levels were badly damaged. It is probable that movement would have taken place in any case, but cutting back the face certainly contributed to lowering the stability of the slope. In this case the matrix contained kaolinite and chlorite plus some mica, either illite or muscovite.

The other two faces sampled were in a cutting on the railway line between Coledale and Austinmer. In this case a major slide (referred to previously on page 4) took place on the slope above the cutting and involved the face of the cutting on the high side. The toe of the slide was located in the centre of the cutting and the face on the low side was not involved. The matrix in the higher face, which was involved in the slide, contains illite and chlorite, while in the low or stable face it contains kaolinite and mica.

It has to be borne in mind in comparing the results that the faces of cuttings which have been involved in slides do not necessarily represent similar conditions to those which were present prior to the slide. The present face is really a section through the slide material and often contains a higher proportion of coarse detritus than would be typical of the slide as a whole. This is due to the coarse material being left behind during cleaning away of the debris and subsequent preferential erosion of the finer material.

There does not appear to be any fundamental difference between the matrix in the detritus in stable and unstable cuttings nor in that derived from rocks of the Narrabeen Group only or that derived largely from the Illawarra Coal Measures. Kaolinite, chlorite and illite occur in both areas. Kaolinite occurs in the stable cutting at Austinmer and the unstable one at Wombarra ; illite in the stable cutting at Wombarra, the unstable one at Austinmer and possibly also in the unstable one at Wombarra ; chlorite in both cuttings at Wombarra and the unstable one at Austinmer. It was thought possible that the unstable cuttings at least may have contained montmorillonite, but the group was not detected in any of the samples tested.

The faces of the stable cuttings appear to be rather more ironstained and may have a " case hardening " due to surface cementation as the result of long exposure. However this might not be characteristic of the material behind the face and the present unstable cuttings may have been similar prior to the involvement in the sliding. Some of the detritus does seem to have become compacted and cemented and relatively impervious to water.

Geological Formations.

The rock formations influencing the incidence of landslides in the South Coast Area can be divided into two main classes.

(i) Sandstone - greywacke
(ii) Shale - claystone

Slides associated with the former are almost entirely of the rock-fall type and result from the breaking off of slabs along the well-marked vertical joints due to their being undermined by the weathering and erosion of the underlying shales or claystones.

The rock units comprising this class are

Hawkesbury Sandstone
Bulgo Greywacke
Scarborough Greywacke
Otford Greywacke Member
Coal Cliff Greywacke
Greywacke Members in the Illawarra Coal Measures, including
Lawrence Greywacke
Kembla Greywacke

The Hawkesbury Sandstone forms the mural eastern escarpment capping the Illawarra Coastal Range. The greywackes, where massive, the Scarborough Greywacke being a typical example, tend to form almost vertical or steeply sloping outcrops. Where they possess well-marked bedding, such as the Bulgo

Greywacke in most places, the slopes tend to be less steep and the surface of the solid rock underlying any detritus or soil cover takes a step-like form giving a relatively firm foundation to the detritus and " keying " into its base.

Slides associated with the greywacke formations, other than rockfalls due to undermining, are found to be related to the occurrence of thin clay bands interbedded with the greywackes. One such area where trouble has occurred is on the roadway close to the mouth of the railway tunnel at Bald Hill. Further south a similar section occurs in a drain below the railway line near the mouth of the tunnel south of the viaduct over Stanwell Creek.

Two very bad sections of the road occur at the ends of cuttings which have been cut in the Scarborough Greywacke and may be thought, at first sight, to be associated with this formation. However, they are not connected with it, the real cause in one case near Clifton being associated with faulting and the other near Coal Cliff being associated with the underlying Wombarra Shale and the proximity of Stoney Creek.

The Shale-Claystone units comprise the following

Bald Hill Claystone
Stanwell Park Claystone
Wombarra Shale
Shales and claystones of the Illawarra Coal Measures.

Of these, by far the worst is the Wombarra Shale. The northernmost outcrop of this formation is in the vicinity and immediately north of Stoney Creek, where it is associated with the trouble mentioned above. Between Coal Cliff and Clifton undercutting along this formation leads to serious rockfalls onto and over the Lawrence Hargrave Drive (see Plate I). The poor foundation it gives for the roadway also causes some slumping in this section. In the Clifton-Scarborough area the most unstable sections of the road and railway cross this formation (see Plate II, Figures 3 and 4). South of the area mapped in detail to date slides associated with the Wombarra Shale have had serious effects on both of the other main roads connecting Sydney with Wollongong, namely Prince's Highway at Bulli Pass and the Mt. Ousley Road. Its effect can also be seen along the Buttenshaw Drive, which connects Austinmer and Wombarra above and to the west of the railway line.

The Bald Hill Claystone is much more stable than the other formations in this group and because of its location high above the critical sections occupied by the road and railway line in the area mapped in detail, it has relatively little bearing on their stability.

The Stanwell Park Claystone is associated with bad landslides. The slides referred to by Shellshear (1890) between Stanwell Creek and Coal Cliff Railway Station were associated with this formation. It forms the foundation for the railway line between Coal Cliff Station and the Clifton Tunnel. Below the railway line and above Stoney Creek the outcrop of the Scarborough Greywacke is completely obscured by steeply sloping detritus down to the level of the Wombarra Shale, which would underlie the road formation at the Stoney Creek crossing if it had not been eroded away. South of the Clifton Tunnel to the Clifton Fault it again forms the foundation for the railway line in a very unstable area. Many of the slides associated with the Stanwell Park Claystone have other complicating causes and are discussed later.

The shales and claystones of the Illawarra Coal Measures have not been mapped in detail in the Coledale-Austinmer area, but are associated with very unstable zones which have caused serious interruptions to railway traffic.

The Tertiary igneous rocks are relatively unimportant in their effects. South of Wollongong they are much more extensive and flows may occur. In this area they have their effects on drainage and detritus formation and hence on slides. However, they form only scattered outcrops in the area mapped. At one point on the road between Coal Cliff and Clifton a weathered dyke can be seen in the cliff face above the road. The roadway has been subject to settlement at this point on a number of occasions, but to what extent the presence of the dyke is a contributing factor it is not possible to determine without exploratory work. It probably contributed its quota of weathered clayey material to the slope on which the road was formed and to the fill used ; it could also affect the underground water flow and may increase seepage. However, at this point, with road on the the poor foundation formed by the Wombarra Shale, the steep slope below, and being adjacent to the Harbour Fault, settlement would still be likely if the dyke were absent.

The rock units not only affect the stability of an area because of the nature of the foundation they provide, but also have their effects because they are the parent material from which the detritus in any area is derived, so governing its properties, and they and the detritus formed from them also form the raw material used as fill in many railway and roadway embankments.

Structural Geology

The structural geology has what may be termed direct and indirect effects on the landslide problem. The direct effects occur in areas such as faults zones, where water movement can give rise to major problems ; the indirect effects may be due to the structural pattern causing certain beds, which may form unstable foundations, to occur at road and railway levels.

The best example of the direct effects is the area of the Clifton Fault. At this point the roadway has been completely cut and remained so for long periods (see Plate 2, Figures 5 and 6). The road from the north is rising through a cutting in the Scarborough Greywacke until the fault zone is reached. South of the fault the movement has brought the basal portion of the Wombarra Shale against the fault at road level. At rail level the northern and southern faces of the fault zone are occupied by the Stanwell Park Claystone and Wombarra Shale respectively. The fault-zone acts as a drainage channel. Weathering and erosion along it have resulted in a thicker detritus cover than nearby areas, the detritus being derived from the weathering of the Wombarra Shale and Stanwell Park Claystone. The fault acts as a feeder for underground water and even after prolonged dry spells water is still running from the area. The net result is that a relatively small rainfall can thoroughly saturate the detritus in the fault zone, where it is already in a highly unstable position. An indirect effect of the fault is that although the road level has risen almost 100 feet in about 10 chains instead of being on an horizon near the top of the Scarborough Greywacke, it is again within the upper portion of the Wombarra Shale.

A good example of the indirect effects, in this case the influence of minor folding on the stability, is in the vicinity of Scarborough Railway Station. Here there is a minor anticlinal fold, as the result of which the top of the Wombarra Shale rises above rail-level about 10 chains north of the centre of the railway station. At the station itself the Otford Greywacke Member occurs in the cutting, and south of the station the base of the member has risen above rail level. Corresponding to this we find that beyond about 10 chains north of the station, although material from the Stanwell Park Claystone above the cutting in the Scarborough Greywacke may slide onto the line, the foundations of the line are stable ; between this point and the railway station serious settlements occur ; the railway station itself, being on the Otford Greywacke, appears to be stable ; and south of the station settlements take place.

Causes of Instability.

Instability is affected by the normal processes of weathering and erosion. Superimposed on this are the the effects of construction works in the area. The amount of water in the detritus has a critical bearing on its stability and this is in turn affected by the weather, so that abnormal weather conditions may be considered as another variant. It is proposed to discuss this problem under three headings :-

(a) Normal erosion,
(b) Construction works,
(c) Effect of variable water content.

(a) *Normal Erosion.*

Erosion in the near South Coast District follows an irregular pattern with maxima associated generally with periods of peak rainfall. The shale and claystone formations weather to yield clayey detritus, while the sandstones and greywackes yield blocks, both large and small. This results from weathering and erosion of the softer formations leading to undercutting of the more resistant ones with resultant rockfalls, when segments break off along the well-marked system of vertical jointing (see Plate I, Figures 2, 3 and 4).

As remarked previously the erosional function of the streams in the area is mainly the removal of material which has been brought into their channels by landslides. Much of the detritus never reaches stream channels but is moved by successive slides and creep until it reaches the waterfront, where it is removed by wave action.

The rainfall in the area in normal years would lie between 40 and 50 inches, and although slight variations occur between registrations in different parts of the area, the general pattern is similar. In dry years the rainfall falls below 30 inches and in the record wet year of 1950 the registration at Stanwell Park was more than 120 inches. It was associated with this record rainfall that the road was cut completely near Clifton for some months, the road badly affected near Scarborough, the railway line between Austinmer and Coledale and the embankment at Wombarra severely damaged, to mention only some of the major effects.

The role of water in producing these effects is considered later, but there can be no doubt the periods of high rainfall are the times when a high incidence of landslides can be anticipated.

It should be realized that landslides would have taken place in the area in periods of peak rainfall, even had there been no human habitation with its consequent construction of roads, railways and buildings. This is well illustrated by landslides in the Camden-Picton area. Here, although excessive clearing of the ground has contributed to the erosion, the bulk of the slides has taken place on hillslopes away from the roads and can not have been caused by any construction works. The road over the Razorback was badly affected by landslides and, although the road construction probably aggravated conditions, the area would have been subject to slides even if the road had not been constructed there.

The area within the South Coast District where the forces of normal erosion cause spectacular rockfalls is along the Lawrence Hargrave Drive, between Coal Cliff and Clifton (see Plate I, Figures 2, 3 and 4). Here coastal erosion by the sea undermines the Coal Cliff Greywacke leading to rockfalls. This in turn leads to slides from the overlying Wombarra Shale and consequent undermining of and rockfalls from the Scarborough Greywacke. As a result slides take place from the overlying Stanwell Park Claystone and in turn lead to undermining and rockfalls from the Bulgo Greywacke. Ultimately slides from the Bald Hill Claystone and undermining of the Hawkesbury Sandstone would lead to rockfalls from the escarpment. The road is subject to both rockfalls from above and slumping of the foundation which rests on the Wombarra Shale.

Water erosion of rock formations along creeks in the area are of minor importance but in the case of Hargraves Creek, erosion of the Stanwell Park Claystone could ultimately undermine the railway embankment.

(b) *Construction Works.*

In this section the effects of any construction undertaken to ameliorate the landslides is not considered, but only the construction normally carried out to satisfy the needs of transport, housing and industry.

It is often difficult to determine to what extent landslides have been caused by construction works. In most cases where cuttings have slumped, the movements have taken place not during construction, when the cause could be directly attributed to the formation of the cutting, but some time subsequently, generally during a period of high rainfall, so that the latter might be suspected as the major cause. However in most cases it is considered that although the excessive rainfall may have been the trigger which initiated the slide, the removal of support from the toe of the potential slide area by the construction of the cutting was the fundamental cause of the trouble. Long periods of time between the construction and the slope failure still do not preclude the formation of the cutting being the primary cause. Deterioration of the material above the cutting with time can ultimately result in the decrease of the shearing resistance until it passes the critical point for failure, without the complication of other abnormal conditions. A classic example is a railway cutting between London and Folkestone, which failed in fair weather during 1939, about 70 years after the cut was constructed.

One of the main effects of construction work is in the removal of lateral support on a slope due to the excavation for cuttings. Many examples could be given of slopes above cuttings being affected by landslides, while below they have remained stable (*e.g.* between Austinmer and Coledale), others where the faces of cuttings have failed in heavy rain soon after they have been constructed (*e.g.* access road to South Clifton Colliery). On the South Coast the removal of lateral support has caused slope movements to take place in detritus and no examples are known where rocks dipping towards the cutting have been involved in rockslides. Such types do occur in other parts of the State, the best known being on Lapstone Hill, where beds of the Hawkesbury Sandstone dip at about 20° towards the road and have been involved in rockslides.

In an area as inherently unstable as the near South Coast very little additional load on an area may increase the shearing stresses beyond the critical point where shear failure would take place. In many places embankments, or fill sections where cut and fill methods of construction are employed, have been founded on detritus with a basement of weathered incompetent rock. Excellent examples occur in the Clifton-Scarborough-Wombarra area where the incompetent basement is the Wombarra Shale.

Although many of the houses in the district are built on detritus it does not appear that the weight of the buildings has been the main cause of any movements which have taken place. Numerous houses located on slide areas have been damaged or completely destroyed, but in all cases examined there have been other more obvious causes for the slides, although the houses probably made some contribution to the instability.

Embankments and fill may alter the natural drainage of the area and could cause trouble for this reason. In some instances they may act as a relatively porous area for the collection of surface water which could result in a considerable increase in the weight of the superincumbent mass, as well as feeding water into the underlying detritus or rock foundation. The former acts to increase the shearing stresses, the latter to reduce the shearing resistance. Alteration of the natural drainage need not have injurious effects. It could be deliberately designed in such a way that conditions were improved.

Several dams have been constructed in the area. Provided they were watertight the only effect would be the increase in weight, although when full this may be considerable. However, if they should leak they form an almost constant source of water percolation into the foundations. They are often located in areas where water is concentrated, and in two particular instances are along or close to major fault zones. In such situations any percolation from them must aggravate conditions.

(c) *Effect of Variable Water Content.*

Variation in water content of the detritus has a marked effect on its shearing resistance and hence of its stability. The presence of some water may increase the cohesion as against perfectly dry material (*e.g.* compare the angle of repose of damp as against that of dry sand). However, under natural conditions it is doubtful whether the detritus could ever become perfectly dry in this area and sufficient moisture is present to develop the maximum cohesion. The effect of increasing the water content has been discussed by Terzaghi (1950) and many others. It acts in several ways, including

(a) decreasing cohesion due to filling voids with water and expelling the air,
(b) increasing the weight and hence shearing stresses,
(c) possibly dissolving cementing material,
(d) causing rise in piezometric surface, involving increase of pore-water pressure and decrease of shearing resistance.

It is quite obvious from studying the rainfall figures and periods of prevalence of landslides that the most unstable periods are those when the rainfall is the highest. In any area the water may fall directly on it during rainfall, be brought to it by surface drainage, or be derived from underground sources. It is where these sources are combined that the maximum effects are felt, a good example being along the zone of the Clifton Fault, which has been described previously.

CONTROL OF INSTABILITY

The question of controlling the incidence of landslides raises two main problems. In the first place care needs to be excised to ensure that any action taken does not increase the natural instability of the area, and in the second place some sections are so unstable that special action is required to improve the stability in order to make any construction undertaken reasonably safe.

The stability of any area is relative and governed by conditions at the time under consideration. An area may be fairly stable during years of average rainfall, subject to serious landslides in years with double the average rainfall, but could become uninhabitable until the topography became adjusted to the new conditions if the rainfall were, say, ten times the average. The aim of control measures should be to ensure that the area will *probably* be stable in the worst weather conditions which could reasonably be anticipated.

Measures to be taken fall into three main groups :

(a) Avoidance of any action during construction operations which would aggravate existing conditions and increase the instability.
(b) Construction works to support bad ground or restrict erosion.
(c) Drainage, both to restrict ingress of water to affected areas and assist in removal of water from them.

(a) *Avoidance of Aggravating Conditions.*

This factor only applies to new constructions but has often been neglected in the past. In many places the road and railway had to be constructed over areas where the surface detritus was potentially unstable and was resting on one of the incompetent formations as a foundation. In some cases complete removal of the detritus and its replacement by suitable fill would have been warranted if it were considered that effective drainage could not be otherwise designed.

The usual causes which aggravate instability during construction operations are removal of lateral support to rock or detritus in making cuttings, overloading due to weight of embankments of buildings, and detrimental interference with existing drainage. These factors have been discussed previously and examples quoted.

It is often advisable to re-route transport arteries in order to avoid bad ground. However, in the South Coast the section available for the road and railway is restricted because of the topography, so that it is not possible to avoid completely the unstable areas. It has been proposed to re-route the railway line between Stanwell Park and Wombarra by constructing two tunnels, one between the southern side of the viaduct over Stanwell Creek and the vicinity of Coal Cliff Colliery siding and the other between the latter area and Wombarra. This would avoid most of the bad areas where troubles are experienced at present, but involves problems of its own. For much of their lengths the tunnels would be driven in either the Stanwell Park Claystone or Wombarra Shale and would cross the Coal Cliff Fault and possibly others. The worst feature however is that for a considerable length of the more southerly tunnel its course lies over old worked ground in collieries which have worked the underlying Bulli Seam. Some of these old workings have probably collapsed or are likely to do so in the future. The problems involved are not insuperable but the project would not be a simple tunnelling operation.

(b) *Use of Retaining Walls, etc.*

The value of retaining walls, sheet piling, cribbing, etc. have been discussed fully in literature, for example by Ladd (1928, 1935). Several examples are to be found in the South Coast area.

Their value differs greatly according to local circumstances. If they have been built merely to prevent loose material rolling down onto railways or roads they often serve their purpose very well. However, if they are required to hold back large bodies of detritus they are of somewhat doubtful efficacy. Where they can be successfully keyed into a firm foundation they can achieve their objective. A successful wall of this type was constructed at Port Kembla No. 2 Colliery, on the slopes of Mt. Kembla to the south of Wollongong. The wall was of re-inforced concrete with a triangular cross-section. The weight of the detritus pushing against the sloping back of the wall appears to press it firmly on its foundation, which is rock *in situ*, thus minimising any tendency for an outward movement of the base, or for rotation about its front edge. Conventional walls, even when securely attached to a firm foundation have been known to fail because the weight of the saturated detritus or fill has caused the wall to rotate about its base and topple over.

Where it is not possible to secure the wall to a firm foundation, any attempt to hold large, or even medium sized areas of detritus by means of a retaining wall or sheet piling is often useless. Should the detritus reach an unstable condition the wall is merely incorporated in the slide and, if anything, could increase its destructive effect.

Concrete and stone walls have been used for another purpose along the Lawrence Hargrave Drive, between Coal Cliff and Clifton (see Plate I, Figures

2, 3 and 4). Here the object is to prevent the weathering and fretting of the Wombarra Shale, which causes undermining of the overlying Scarborough Greywacke. How efficiently these walls are achieving their purpose it is not possible to say. Although they prevent obvious deterioration, what action is taking place behind them is a matter for conjecture. It could well be that moisture present may have ideal conditions for chemical weathering of the shales to produce clayey decomposition products.

(c) *Drainage.*

Efficient drainage is the key to the solution of the problem of landslide prevention and control. There are two separate considerations in connection with drainage of any area. These are minimising the entry of water to the area and aiding the removal of water from it.

Water may reach an area by three main methods :

(a) Direct precipitation,
(b) Flowing on to it or seeping through soil and detritus from higher levels,
(c) Percolation from underground sources.

It is impossible to prevent completely the access of water but much can be done to reduce it. Minimum absorption of rain falling on the surface requires maximum run-off. The presence of vegetation assists in that it helps control surface erosion. Smoothing irregularities prevents the accumulation of water in hollows and infiltration along surface cracks.

Water flowing from higher levels needs to be diverted from critical areas. Drains have often been constructed above areas of detritus with this aim in view. However, in many cases these are only open drains dug in the soil. These may serve their purpose for some time but ultimately erosion along them, cracking open during dry periods, and concentration of water along them, converts them into lines of excessive seepage and could result in the formation of a surface of sliding, thus initiating a landslide.

Water from underground sources can be controlled where the source is localized and known. Generally speaking, where seepage is from fault zones which have collected water from widely separated and diverse sources, control of ingress is not possible. In such cases control must be directed towards adequate and efficient removal of the water from the danger area.

In many cases rapid removal of water can be achieved by drains built within areas of detritus or fill. This can prevent the build-up in the water content of the material and keep its shearing resistance above the critical value at which failure occurs. The importance of drainage to the stability of filled areas has been well demonstrated at Wombarra, immediately south of the area mapped in detail. Here, early in the rainy season of 1950, the embankment south of Wombarra Railway Station partly subsided carrying with it portion of the platform on the " down " line. Drains were dug in the toe of the embankment under the direction of the Railway Department's engineers and were so successful in achieving their purpose that no further serious movement took place during the very heavy rains later in the 1950 season, although very serious landslides occurred in other parts of the Illawarra District. As long ago as 1890 Shellshear (1890) constructed a series of drains to control movement in an embankment on the old railway line (now the Lawrence Hargrave Drive) between Stanwell Park and Coal Cliff. They proved successful at the time of their installation and although they cannot be found now they may still be working to some extent because this is not a particularly bad section of the roadway at the present time.

It can be seen that drains are required to fulfil two needs which are often contradictory. Some drains around or through areas of detritus require to be impervious so that water in them will not gain access to the detritus. Others need to be constructed of porous material so as to permit the collection of water by them from the detritus. While it may be possible to combine these functions in drains by constructing them with an impervious base to prevent seepage from them and a porous upper section to permit seepage into them, it is felt that in general it may be better to build two sets of drains, one impervious to collect water above the area and carry it around or though it, and the other porous to collect water from within the fill or detritus, thus keeping down the water content of the material and hence increasing its shearing resistance. In both cases it is necessary to construct the outlets so as to prevent surface erosion at the foot of the detritus or embankment, which would in turn affect the stability of the slope.

It is not sufficient to construct the necessary drains; they must also be maintained. Gradual accumulation of small amounts of debris can cause blockages. Such blockages along road drains can result in the diverted water eroding and removing the bitumen seal with ultimate destruction of the roadway. It is also not sufficient to construct drains along the edges of roads and leave porous areas where water can enter between the sealed roadway and the drain or between the drain and the rocks at the roadside.

Summary and Conclusions.

The Stanwell Park-Scarborough area, because of its topography, has landslides as a normal phenomenon of the erosion cycle. Periods of high rainfall are the times when a high incidence of landslides can be anticipated. Local interest and demands for remedial measures have waxed and waned with the incidence of the landslides and can be expected to continue to do so in the future.

The geological investigation has been able to relate the landslide areas to the underlying geological formations and this information can be used as a basis for planning construction and remedial measures. The construction of roads, railways and buildings will increase the likelihood of landslides taking place *unless special precautions are taken.*

Control methods must be based on the provision of adequate drainage. This should be designed both to prevent ingress of water to the area where possible, and to remove water from it in order to keep the moisture content below the critical level when failure would take place. In some places material from cuts may be unsuitable for use as fill, and detritus under foundations may need to be removed and replaced by suitable fill. It is possible under present conditions that landslides could occur in wet seasons which would completely cut direct surface communications between Sydney and Wollongong and normal transport may take weeks or even months to restore.

After slumping has taken place and movement has ceased, the addition of fill to restore the original level may make a road or railway trafficable once more, but does nothing to prevent a recurrence of slumping. The additional load may make it more likely to recur. It should be borne in mind that remedial measures can be carried out much more economically and efficiently during dry periods than during wet seasons, when landslides are imminent or have just taken place. Areas which could be successfully treated when stable may be quite impossible to treat satisfactorily while movement is taking place.

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Explanation of Plates.

Plate I.

Figure 1.—Stanwell Park and Coal Cliff from Hargrave's Lookout. Stanwell Park in the foreground, Coal Cliff between hills in middle distance. Hawkesbury Sandstone crops out on crests of hills ; wooded slopes in Bald Hill Claystone and Bulgo Greywacke ; grassed section at Stanwell Park and corresponding area at Coal Cliff in Stanwell Park Claystone ; cliffs north and south of Stanwell Park in Scarborough Greywacke ; houses at Coal Cliff on Wombarra Shale ; rock platform at Coal Cliff in Coal Cliff Greywacke ; beyond Coal Cliff the Illawarra Coal Measures crop near sea level. Cuttings and embankments or railway (above) and roadway (below) cross face of near hill on Stanwell Park Claystone.

Figure 2.—Coal Cliff-Clifton Road. Stanwell Park Claystone is the highest outcrop ; Scarborough Greywacke vertically faced massive band ; Wombarra Shale above and below road level with Otford Greywacke Member immediately above road ; Coal Cliff Greywacke steep outcrop below sloping Wombarra Shale ; Illawarra Coal Measures at sea level with Bulli Coal Seam at top. Concrete and rock retaining walls cover part of Wombarra Shale immediately below the Scarborough Greywacke.

Figure 3.—Coal Cliff-Clifton Road. Closer view of section shown in Figure 2. Also shows stonewall below road.

Figure 4.—Coal Cliff-Clifton Road. Similar to Figure 3. Illustrates the absence of seal between the edge of the bitumen and the gutter, and the gutter and the cliff face.

Figures 5 and 6.—Cutting between Stanwell Park and Coal Cliff. Completely through old landslide. Broken nature of rock shown in Figure 5 and steep dips in the right side of Figure 6.

Plate II.

Figure 1.—Coledale-Austinmer Area. Top of slide which affected the railway line. Shows break between higher unaffected ground and slide area.

Figure 2.—Coledale-Austinmer Area. The toe of the slide shown in Figure 1 was located on slip surface between the railway line (down-line) and wheel tracks (originally occupied by the up-line). Area occupied by the up-line rose several feet during 1950 wet season. This picture taken after excavation made during remedial operations.

Figure 3.—Scarborough Road. Section of road based on detritus with foundation of Wombarra Shale. Former position of road shown to the left of the present road.

Figure 4.—East of Scarborough Road. Slope below road shown in Figure 3. Shows broken nature of detritus cover over Wombarra Shale. Remains of drain in foreground.

Figure 5.—Clifton Road. Off-setting of central yellow line on road is due to sideways movement of the road.

Figure 6.—Clifton Road. View looking uphill towards Clifton. Detritus, soil and vegetation from the overlying Stanwell Park Claystone has been washed over the solid outcrop of the Scarborough Greywacke in the face of the cutting. Foundation of the road is almost completely washed away.

OCCULTATIONS OBSERVED AT SYDNEY OBSERVATORY DURING 1957.

By K. P. Sims, B.Sc.

(Communicated by the Government Astronomer.)

Manuscript received, February 25, 1958. Read, April 2, 1958.

The following observations of occultations were made at Sydney Observatory with the 11½-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the Occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. The necessary data were taken from the *Nautical Almanac* for 1957, the Moon's right ascension and declination (hourly table) and parallax (semi-diurnal table) being interpolated therefrom. No correction was applied to the observed times for personal effect but a correction of $-0 \cdot 00152$ hour was applied before entering the ephemeris of the Moon. This corresponds to a correction of $-3'' \cdot 0$ to the Moon's mean longitude.

Table I.

Serial No.	N.Z.C. No.	Mag.	Date.	U.T.	Observer.
				h m s	
350	1158	5·2	Feb. 12	13 43 38·9	R
351	766	6·0	Mar. 9	9 46 05·1	W
352	935	6·9	Mar. 10	11 55 41·8	W
353	1271	5·9	May 6	8 30 24·7	S
354	1364	6·5	June 3	7 29 00·7	R
355	1971	5·8	June 8	11 02 57·9	W
356	2074	7·1	July 6	13 03 09·6	W
357	2034	7·2	Aug. 2	11 17 50·0	S
358	2880	5·1	Aug. 8	14 33 23·5	S
359	2830	6·9	Sept. 4	10 29 44·1	S
360	2497	6·6	Sept. 29	10 27 05·7	W
361	2640	6·6	Sept. 30	10 52 02·0	S
362	2649	6·7	Sept. 30	11 40 51·6	S
363	——	9·0	Sept. 30	11 48 04·5	S
364	——	8·5	Sept. 30	11 48 35·6	S
365	2653	6·4	Sept. 30	12 15 25·9	W
366	——	8·6	Sept. 30	12 16 06·2	W
367	2789	7·3	Oct. 1	10 06 55·4	R
368	3054	6·4	Oct. 3	14 20 55·2	W
369	2573	7·3	Oct. 27	9 00 37·9	W
370	2578	6·4	Oct. 27	10 59 53·1	W

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1957). The observers were H. W. Wood (W), W. H. Robertson (R) and K. P. Sims (S). In all cases the phase observed was disappearance at the dark limb. Table II gives the results of the reductions which were carried out in duplicate. The N.Z.C. numbers given are those of the *Catalog of* 3539 *Zodiacal Stars for the Equinox* 1950·0 (Robertson, 1940), as recorded in the *Nautical Almanac*.

TABLE II.

Serial No.	Luna-tion.	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of $\Delta\alpha$	Coefficient of $\Delta\delta$
350	422	+ 84	—54	71	—45	29	+1·5	+1·3	—0·8	+10·1	—0·71
351	423	+ 45	+89	20	+40	80	—0·7	—0·3	—0·6	+ 6·0	+0·90
352	423	+ 89	+45	80	+40	20	—0·7	—0·6	—0·3	+13·0	+0·37
353	425	+ 50	—87	25	—43	75	—0·1	0·0	+0·1	+ 3·8	—0·97
354	426	+ 97	+24	94	+23	6	—1·3	—1·3	—0·3	+14·7	—0·05
355	426	+ 71	+70	51	+50	49	—1·2	—0·9	—0·8	+12·9	+0·48
356	427	+ 87	+49	76	+43	24	—2·9	—2·5	—1·4	+13·9	+0·27
357	428	+ 37	+93	14	+34	86	—1·8	—0·7	—1·7	+ 8·5	+0·81
358	428	+ 89	+46	79	+41	21	—2·9	—2·6	—1·3	+11·2	+0·62
359	429	+ 88	—47	78	—41	22	—1·2	—1·1	+0·6	+13·6	—0·31
360	430	+ 79	+61	63	+48	37	—3·1	—2·4	—1·9	+11·2	+0·61
361	430	+ 24	+97	6	+23	94	—2·0	—0·5	—1·9	+ 2·1	+0·99
362	430	+100	+ 6	100	+ 6	0	—2·5	—2·5	—0·2	+14·0	+0·14
363	430	+ 99	+15	98	+15	2	0·0	0·0	0·0	+13·8	+0·23
364	430	+ 92	+39	85	+36	15	—2·0	—1·8	—0·8	+12·5	+0·46
365	430	+ 85	+53	72	+45	28	—2·5	—2·1	—1·3	+11·3	+0·60
366	430	+ 84	+54	71	+45	29	—2·7	—2·3	—1·5	+11·2	+0·61
367	430	+ 39	+92	15	+36	85	—2·2	—0·9	—2·0	+ 3·5	+0·97
368	430	+ 94	—33	89	—31	11	—1·3	—1·2	+0·4	+14·6	—0·06
369	431	+ 98	+22	95	+22	5	—2·3	—2·3	—0·5	+13·7	+0·26
370	431	+ 64	+77	41	+49	59	—3·5	—2·2	—2·7	+ 8·4	+0·80

The stars involved in occultations 363, 364 and 366 were not in the *Nautical Almanac* list; they are Yale *12* II 7607, 7605 and 7614. The apparent place of 7607 was R.A. $18^h\ 15^m\ 34^s{\cdot}92$, Dec. $-18°\ 46'\ 38''{\cdot}6$; that of 7605 was R.A. $18^h\ 15^m\ 30^s{\cdot}10$, Dec. $-18°\ 43'\ 02''{\cdot}3$, and that of 7614 was R.A. $18^h\ 16^m\ 16^s{\cdot}00$, Dec. $-18°\ 37'\ 56''{\cdot}3$.

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Sims, K. P., 1957. THIS JOURNAL, **91**, 55; *Sydney Observatory Papers*, No. 29.

PRECISE OBSERVATIONS OF MINOR PLANETS AT SYDNEY OBSERVATORY DURING 1955 AND 1956

By W. H. Robertson.

Manuscript received, May 5, 1958. Read, June 4, 1958.

These photographic observations of positions of minor planets, which have been selected for purposes of fundamental astronomy, including correction of the proposed Catalogue of Faint Stars, are published under the heading " precise " to indicate that they have been made and reduced with rather more attention to detail than is necessary for general measures of positions of minor planets.

The plates were taken with the 8-inch wide angle camera of Yale University Observatory (Y), scale 100″ to the millimetre, which was mounted here from 1954 July to 1956 September, the 13-inch standard astrograph (A), and the 9-inch camera made by Taylor, Taylor and Hobson, scale 116″ to the millimetre (T). On each plate were taken four exposures separated in declination by approximately $0'\cdot 5$. Guiding was performed on the planet in right ascension only, when the planet was bright enough. When the planet was too faint the guiding mechanism (Wood, 1954) was set at the appropriate speed in right ascension only and the guiding done on a star. The beginnings and endings of the exposures were recorded on a chronograph. The exposure times ranged from 40 seconds to 240 seconds.

Rectangular coordinates of each image of the minor planet and six reference stars were measured on a long screw measuring machine in direct and reversed positions of the plate. The proper motions in the catalogues were used to bring the star positions to the epoch of the plate but no corrections have been applied to alter the system of the catalogues. The stars were divided into two groups and the planet's position was measured before and after the three stars of each group in each position of the plate. The measures of the first two and the last two exposures were averaged and the reduction was then performed four times, twice with each group of stars. The usual three star dependence reduction was used, including to third order terms in the differences of the equatorial coordinates. No correction which could affect the result by as much as $0''\cdot 01$ has been neglected.

The tabulated results give means for all four images for the separate groups of stars at the mean of the times. The differences between the results average $0^s\cdot 024 \sec\delta$ in right ascension and $0''\cdot 32$ in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^s\cdot 010 \sec\delta$ and $0''\cdot 14$. In the case of those planets, Ceres and Juno, which have ephemerides in the Nautical Almanac the result from the first two exposures was compared with that from the last two by adding the movement computed from the ephemeris. The means of the differences so obtained were $0^s\cdot 017 \sec\delta$ in right ascension and $0''\cdot 14$ in declination. In this comparison the star places are used in the same way for each position and the seeming improvement in the probable errors illustrates the extent to which the results are influenced by errors in the star places.

TABLE I.

No.		R.A. (1950·0.) h m s	Dec. (1950·0.) ° ′ ″	Parallax Factors. s	″	
	1 Ceres 1955 U.T.					
1	May 4·77528	19 48 20·942	—24 25 15·79	—0·047	—1·43	W, Y
2	May 4·77528	19 48 20·933	—24 25 15·94			
3	May 16·75833	19 51 53·406	—25 02 17·31	—0·002	—1·32	R, Y
4	May 16·75833	19 51 53·454	—25 02 16·81			
5	June 1·71661	19 50 57·674	—26 11 14·86	—0·001	—1·15	W, Y
6	June 1·71661	19 50 57·658	—26 11 14·68			
7	June 15·68998	19 44 43·740	—27 26 15·17	+0·062	—0·98	S, Y
8	June 15·68998	19 44 43·748	—27 26 15·32			
9	June 23·64509	19 39 08·094	—28 11 37·74	—0·004	—0·84	W, Y
10	June 23·64509	19 39 08·072	—28 11 37·31			
11	June 27·63739	19 35 52·460	—28 34 09·42	+0·015	—0·79	R, Y
12	June 27·63739	19 35 52·523	—28 34 09·46			
13	July 4·61644	19 29 38·560	—29 12 00·45	+0·024	—0·69	S, Y
14	July 4·61644	19 29 38·592	—29 12 00·52			
15	July 7·60626	19 26 49·676	—29 27 17·10	+0·037	—0·65	S, Y
16	July 7·60626	19 26 49·680	—29 27 17·64			
17	July 25·55552	19 09 52·492	—30 41 00·69	+0·060	—0·49	S, Y
18	July 25·55552	19 09 52·552	—30 41 01·66			
19	Aug. 4·49656	19 01 56·438	—31 05 57·02	—0·033	—0·40	R, Y
20	Aug. 4·49656	19 01 56·348	—31 05 56·93			
21	Aug. 10·48827	18 58 06·734	—31 15 34·33	+0·005	—0·37	R, Y
22	Aug. 10·48827	18 58 06·654	—31 15 35·54			
23	Aug. 18·45839	18 54 22·520	—31 22 47·58	—0·014	—0·36	R, Y
24	Aug. 18·45839	18 54 22·480	—31 22 47·24			
25	Aug. 25·44091	18 52 29·728	—31 24 32·10	—0·003	—0·35	R, Y
26	Aug. 25·44091	18 52 29·750	—31 24 32·93			
27	Sep. 7·39984	18 52 32·568	—31 18 52·02	—0·024	—0·37	R, Y
28	Sep. 7·39984	18 52 32·549	—31 18 51·72			
29	Sep. 12·38303	18 53 44·497	—31 14 09·40	—0·038	—0·38	R, A
30	Sep. 12·38303	18 53 44·457	—31 14 09·20			
	1 Ceres 1956 U.T.					
31	July 26·78566	1 31 07·350	— 3 34 14·55	—0·037	—4·42	W, A
32	July 26·78566	1 31 07·316	— 3 34 14·52			
33	Aug. 7·77027	1 35 50·422	— 3 49 56·16	+0·006	—4·38	S, A
34	Aug. 7·77027	1 35 50·406	— 3 49 56·16			
35	Aug. 9·78590	1 36 21·250	— 3 54 19·53	+0·070	—4·38	S, Y
36	Aug. 9·78590	1 36 21·242	— 3 54 19·30			
37	Aug. 15·74809	1 37 22·239	— 4 10 07·30	—0·020	—4·34	W, Y
38	Aug. 15·74809	1 37 22·278	— 4 10 07·64			
39	Aug. 23·72590	1 37 30·340	— 4 37 32·59	0·000	—4·27	S, Y
40	Aug. 23·72590	1 37 30·337	— 4 37 32·13			
41	Aug. 27·70344	1 37 01·844	— 4 53 39·30	—0·034	—4·26	R, Y
42	Aug. 27·70344	1 37 01·864	— 4 53 39·17			
43	Sep. 10·66570	1 32 28·094	— 6 00 04·33	—0·023	—4·09	R, Y
44	Sep. 10·66570	1 32 28·128	— 6 00 04·54			
45	Sep. 24·65126	1 23 49·784	— 7 12 35·02	+0·069	—3·93	S, A
46	Sep. 24·65126	1 23 49·770	— 7 12 35·30			
47	Oct. 11·58230	1 09 56·526	— 8 26 12·14	+0·029	—3·76	R, T
48	Oct. 11·58230	1 09 56·530	— 8 26 11·89			
49	Oct. 23·54199	0 59 54·556	— 8 54 51·56	+0·027	—3·69	W, T
50	Oct. 23·54199	0 59 54·559	— 8 54 52·11			
51	Nov. 21·43726	0 43 53·385	— 8 15 48·62	—0·018	—3·78	R, T
52	Nov. 21·43726	0 43 53·373	— 8 15 48·54			
53	Nov. 26·43497	0 42 54·908	— 7 54 13·26	+0·020	—3·83	S, T
54	Nov. 26·43497	0 42 54·888	— 7 54 13·04			
55	Dec. 4·41618	0 42 33·630	— 7 12 10·50	+0·030	—3·93	W, T
56	Dec. 4·41618	0 42 33·658	— 7 12 10·59			

TABLE I.—*Continued.*

No.		R.A. (1950·0.) h m s	Dec. (1950·0.) ° ′ ″	Parallax Factors. s ″	
	3 Juno 1956 U.T.				
57	Apr. 23·79666	19 22 14·820	— 7 31 34·40	—0·007 —3·88	S, A
58	Apr. 23·79666	19 22 14·789	— 7 31 34·36		
59	Apr. 26·79387	19 23 20·064	— 7 17 27·66	+0·007 —3·91	S, A
60	Apr. 26·79387	19 23 20·091	— 7 17 27·64		
61	May 23·72024	19 24 56·742	— 5 26 12·20	+0·004 —4·16	W, A
62	May 23·72024	19 24 56·712	— 5 26 11·66		
63	May 28·70402	19 23 32·084	— 5 10 53·06	—0·001 —4·20	R, A
64	May 28·70402	19 23 32·068	— 5 10 53·03		
65	June 6·68310	19 19 38·948	— 4 49 38·44	+0·019 —4·24	S, A
66	June 6·68310	19 19 38·950	— 4 49 38·17		
67	June 13·65646	19 15 30·892	— 4 39 45·68	+0·004 —4·27	W, A
68	June 13·65646	19 15 30·904	— 4 39 45·22		
69	June 19·63493	19 11 18·142	— 4 36 27·97	—0·003 —4·27	R, A
70	June 19·63493	19 11 18·145	— 4 36 28·00		
71	June 28·60654	19 04 05·227	— 4 41 08·06	+0·001 —4·26	S, A
72	June 28·60654	19 04 05·206	— 4 41 07·56		
73	July 3·59754	18 59 45·602	— 4 48 51·96	+0·024 —4·25	W, A
74	July 3·59754	18 59 45·618	— 4 48 51·72		
75	July 18·52956	18 46 38·470	— 5 33 04·87	—0·029 —4·15	S, A
76	July 18·52956	18 46 38·436	— 5 33 05·50		
77	July 24·53402	18 41 45·464	— 5 58 41·23	+0·044 —4·09	W, A
78	July 24·53402	18 41 45·451	— 5 58 41·36		
79	Aug. 7·48630	18 32 28·528	— 7 10 51·03	+0·034 —3·93	S, A
80	Aug. 7·48630	18 32 28·526	— 7 10 50·62		
81	Aug. 14·46061	18 29 17·588	— 7 51 19·14	+0·021 —3·83	W, Y
82	Aug. 14·46061	18 29 17·633	— 7 51 19·70		
83	Aug. 21·44030	18 27 14·814	— 8 33 11·52	+0·022 —3·73	W, Y
84	Aug. 21·44030	18 27 14·820	— 8 33 11·72		
85	Aug. 27·44498	18 26 26·078	— 9 09 32·00	+0·089 —3·67	S, Y
86	Aug. 27·44498	18 26 26·076	— 9 09 31·34		
87	Aug. 30·42921	18 26 21·713	— 9 27 29·44	+0·066 —3·62	W, Y
88	Aug. 30·42921	18 26 21·728	— 9 27 30·49		
89	Sep. 3·40737	18 26 36·426	— 9 51 13·12	+0·031 —3·55	S, Y
90	Sep. 3·40737	18 26 36·456	— 9 51 13·84		
	40 Harmonia 1956 U.T.				
91	June 21·80043	23 21 44·246	— 8 23 32·08	—0·010 —3·76	R, A
92	June 21·80043	23 21 44·261	— 8 23 32·24		
93	July 4·78265	23 32 23·910	— 7 56 08·58	+0·022 —3·82	W, A
94	July 4·78265	23 32 23·868	— 7 56 08·30		
95	July 17·75817	23 39 07·783	— 7 57 32·38	+0·041 —3·82	S, A
96	July 17·75817	23 39 07·820	— 7 57 32·02		
97	July 26·74466	23 41 07·076	— 8 17 07·56	+0·071 —3·79	W, A
98	July 26·74466	23 41 07·094	— 8 17 07·58		
99	Aug. 7·70361	23 39 59·854	— 9 07 07·60	+0·048 —3·66	S, A
100	Aug. 7·70361	23 39 59·908	— 9 07 07·44		
101	Aug. 15·66472	23 36 49·598	— 9 53 42·86	+0·002 —3·55	W, Y
102	Aug. 15·66472	23 36 49·596	— 9 53 43·03		
103	Aug. 29·62821	23 27 14·000	—11 30 54·22	+0·028 —3·32	R, Y
104	Aug. 29·62821	23 27 14·022	—11 30 54·36		
105	Sep. 6·60832	23 20 09·266	—12 27 39·22	+0·050 —3·18	W, Y
106	Sep. 6·60832	23 20 09·316	—12 27 38·90		
107	Sep. 10·58340	23 16 26·842	—12 54 05·31	+0·014 —3·12	R, Y
108	Sep. 10·58340	23 16 26·870	—12 54 04·76		
109	Oct. 11·48024	22 53 54·417	—14 39 29·87	+0·005 —2·87	R, T
110	Oct. 11·48024	22 53 54·414	—14 39 30·05		
111	Oct. 18·47199	22 52 09·102	—14 32 57·09	+0·043 —2·89	W, T
112	Oct. 18·47199	22 52 09·168	—14 32 56·76		
113	Oct. 31·42269	22 52 57·076	—13 53 22·78	—0·013 —2·96	R, T
114	Oct. 31·42269	22 52 57·086	—13 53 21·91		

TABLE II.

No.	Comparison Stars.	Dependences.		
1	Yale *14* 13806, 13825, 13837	0·217984	0·353774	0·428242
2	Yale *14* 13803, 13826, 13842	0·195380	0·499357	0·305264
3	Yale *14* 13841, 13872, 13898	0·443722	0·224008	0·332270
4	Yale *14* 13848, 13858, 13896	0·236106	0·450480	0·313414
5	Yale *14* 13814, 13877, 13898	0·435917	0·323452	0·240632
6	Yale *14* 13817, 13848, 13894	0·274608	0·368326	0·357066
7	Yale *13* II 12942, 12979, 13022	0·310658	0·329876	0·359466
8	Yale *13* II 12953, 12986, 13032	0·299440	0·481054	0·219506
9	Yale *13* II 12896, 12908, 12942	0·357696	0·342231	0·300072
10	Yale *13* II 12865, 12874, 12983	0·199228	0·419668	0·381105
11	Yale *13* II 12838, 12888, 12913	0·391046	0·339932	0·269022
12	Yale *13* II 12834, 12874, 12926	0·350216	0·364774	0·285010
13	Yale *13* II 12769, 12794, 12817	0·272284	0·290868	0·436848
14	Yale *13* II 12771, 12786, 12834	0·373348	0·341017	0·285635
15	Yale *13* II 12718, 12780, 12793	0·439843	0·223952	0·336205
16	Yale *13* II 12745, 12746, 12779	0·302189	0·305828	0·391982
17	Cape *17* 10422, 10479, 10482	0·315636	0·254652	0·429712
18	Cape *17* 10416, 10476, 10502	0·330885	0·423700	0·245415
19	Cape *17* 10345, 10384, 10397	0·338120	0·317830	0·344050
20	Cape *17* 10348, 10355, 10417	0·331738	0·322431	0·345831
21	Cape *17* 10301, 10322, 10369	0·363812	0·215956	0·420232
22	Cape *17* 10306, 10342, 10345	0·211524	0·419414	0·369062
23	Cape *17* 10278, 10286, 10345	0·359137	0·397798	0·243065
24	Cape *17* 10265, 10301, 10322	0·249569	0·550872	0·199558
25	Cape *17* 10235, 10278, 10313	0·269826	0·404366	0·325809
26	Cape *17* 10230, 10301, 10304	0·385982	0·356518	0·257501
27	Cape *17* 10230, 10285, 10301	0·281444	0·346498	0·372057
28	Cape *17* 10235, 10278, 10306	0·327794	0·230748	0·441458
29	Cape *17* 10263, 10299, 10313	0·336794	0·234575	0·428630
30	Cape *17* 10269, 10301, 10303	0·340882	0·340466	0·318652
31	Yale *17* 350, 353, 365	0·318710	0·177672	0·503617
32	Yale *17* 340, 361, 369	0·399870	0·049736	0·550395
33	Yale *17* 369, 373, 395	0·418222	0·287688	0·294090
34	Yale *17* 370, 375, 391	0·490935	0·203543	0·305522
35	Yale *17* 373, 375, 395	0·493524	0·191786	0·314690
36	Yale *17* 371, 379, 391	0·415972	0·276470	0·307558
37	Yale *17* 373, 383, 398	0·395122	0·249188	0·355690
38	Yale *17* 371, 387, 395	0·320130	0·463652	0·216218
39	Yale *17* 370, 393, 395	0·390124	0·398186	0·211690
40	Yale *17* 373, 379, 398	0·373762	0·164541	0·461696
41	Yale *17* 370, 389, 398	0·444358	0·297324	0·258318
42	Yale *17* 367, 373, 401	0·260084	0·331246	0·408670
43	Yale *17* 344, *16* 312, 336	0·282954	0·233184	0·483863
44	Yale *16* 309, 329, *17* 367	0·285534	0·317903	0·396562
45	Yale *16* 286, 293, 299	0·509376	0·097177	0·393448
46	Yale *16* 280, 295, 296	0·279421	0·255331	0·465248
47	Yale *16* 228, 250, 253	0·282230	0·469243	0·248527
48	Yale *16* 229, 244, 263	0·374182	0·378954	0·246864
49	Yale *16* 203, 228, *11* 202	0·427968	0·260402	0·311630
50	Yale *16* 205, 214, 219	0·435774	0·321266	0·242960
51	Yale *16* 146, 158, 160	0·498910	0·181857	0·319234
52	Yale *16* 139, 155, 168	0·398328	0·252602	0·349070
53	Yale *16* 135, 155, 156	0·234922	0·351444	0·413634
54	Yale *16* 142, 150, 160	0·349526	0·398562	0·251912
55	Yale *16* 142, 146, 155	0·189930	0·233738	0·576331
56	Yale *16* 137, 150, 157	0·292777	0·280231	0·426992
57	Yale *16* 6718, 6733, 6754	0·314558	0·474662	0·210779
58	Yale *16* 6717, 6736, 6740	0·291121	0·318000	0·390879
59	Yale *16* 6728, 6736, 6754	0·233130	0·368736	0·398134
60	Yale *16* 6727, 6749, 6764	0·513776	0·188906	0·297318
61	Yale *17* 6638. 6643, 6660	0·271864	0·502732	0·225403

TABLE II.—*Continued.*

No.	Comparison Stars.	Dependences.		
62	Yale *17* 6639, 6647, 6668	0·557455	0·288503	0·154042
63	Yale *17* 6622, 6631, 6653	0·308618	0·341198	0·350184
64	Yale *17* 6619, 6639, 6647	0·315560	0·372950	0·311489
65	Yale *17* 6585, 6609, 6617	0·198198	0·499368	0·302434
66	Yale *17* 6596, 6605, 6615	0·239802	0·344804	0·415394
67	Yale *17* 6544, 6576, 6585	0·332568	0·308894	0·358538
68	Yale *17* 6560, 6581, 6583	0·508666	0·214178	0·277156
69	Yale *17* 6513, 6528, 6537	0·351231	0·146752	0·502016
70	Yale *17* 6517, 6523, 6544	0·200664	0·462736	0·336600
71	Yale *17* 6461, 6482, 6483	0·399946	0·307433	0·292622
72	Yale *17* 6464, 6472, 6494	0·425062	0·361378	0·213560
73	Yale *17* 6421, 6422, 6461	0·272206	0·304282	0·423512
74	Yale *17* 6429, 6448, 6449	0·545714	0·211878	0·242408
75	Yale *17* 6304, 6329, 6330	0·189546	0·413850	0·396604
76	Yale *17* 6316, 6333, *16* 6360	0·380168	0·259936	0·359896
77	Yale *16* 6292, 6323, *17* 6298	0·400854	0·310340	0·288806
78	Yale *16* 6300, 6313, *17* 6304	0·459202	0·286535	0·254264
79	Yale *16* 6209, 6225, 6243	0·188990	0·493472	0·317538
80	Yale *16* 6211, 6215, 6241	0·267328	0·196816	0·535856
81	Yale *16* 6206, 6212, 6225	0·387010	0·322204	0·290787
82	Yale *16* 6191, 6209, 6249	0·349240	0·356578	0·294182
83	Yale *16* 6191, 6213, 6215	0·436270	0·257894	0·305836
84	Yale *16* 6185, 6205, 6224	0·339680	0·336790	0·323530
85	Yale *16* 6195, 6203, 6210	0·415916	0·246896	0·337188
86	Yale *16* 6191, 6212, *11* 6314	0·333942	0·314926	0·351133
87	Yale *16* 6184, 6212, *11* 6314	0·321448	0·360642	0·317910
88	Yale *16* 6183, 6191, 6208	0·302334	0·130654	0·567011
89	Yale *16* 6184, 6208, *11* 6317	0·249679	0·329758	0·420562
90	Yale *11* 6286, 6347, *16* 6205	0·194238	0·220464	0·585297
91	Yale *16* 8295, 8319, 8320	0·581889	0·396830	0·021280
92	Yale *16* 8297, 8313, 8314	0·394230	0·271744	0·334026
93	Yale *16* 8338, 8350, 8357	0·198138	0·572200	0·229663
94	Yale *16* 8344, 8348, 8360	0·388034	0·410406	0·201559
95	Yale *16* 8364, 8376, 8385	0·359902	0·454088	0·186010
96	Yale *16* 8368, 8369, 8382	0·135999	0·542114	0·321886
97	Yale *16* 8368, 8390, 8401	0·356210	0·454564	0·189225
98	Yale *16* 8369, 8379, 8394	0·314782	0·292862	0·392356
99	Yale *16* 8363, 8390, 8391	0·370379	0·402728	0·226894
100	Yale *16* 8372, 8380, 8385	0·502544	0·379036	0·118420
101	Yale *11* 8229, 8244, *16* 8372	0·276725	0·394670	0·328605
102	Yale *11* 8237, 8255, *16* 8363	0·491367	0·230542	0·278091
103	Yale *11* 8182, 8201, 8204	0·341495	0·292022	0·366484
104	Yale *11* 8190, 8198, 8203	0·390330	0·343431	0·266239
105	Yale *11* 8160, 8169, 8180	0·150684	0·441388	0·407928
106	Yale *11* 8164, 8176, 8179	0·311080	0·292430	0·396491
107	Yale *11* 8147, 8160, 8168	0·278399	0·292298	0·429304
108	Yale *11* 8144, 8156, 8175	0·272056	0·342276	0·385668
109	Yale *12* I 8502, 8511, 8519	0·339055	0·263066	0·397878
110	Yale *12* I 8497, 8505, 8530	0·353684	0·359726	0·286590
111	Yale *12* I 8485, 8507, 8511	0·331244	0·422321	0·246434
112	Yale *12* I 8482, 8499, 8519	0·352084	0·269496	0·378420
113	Yale *12* I 8482, 8513, 8518	0·289114	0·499896	9·210990
114	Yale *12* I 8485, 8519, *11* 8058	0·270938	0·273660	0·455402

In a number of cases a second reduction was made by deriving plate constants from the same measures. In all cases the difference of the result from that of the dependence reduction was a small fraction of the probable error so that in future we will use the dependence method which takes rather less than half the time.

No correction has been applied for aberration, light time or parallax, but in Table I are the factors which give the parallax correction when divided by the distance. In the cases where detailed ephemerides were available, the O–C residuals vary smoothly except apparently for small discontinuities in passing between catalogues. The serial numbers identify the reference stars and dependences in Table II. The observers at the telescope were W. H. Robertson (R), K. P. Sims (S) and H. W. Wood (W). I wish to thank Mrs. M. A. Wilson and Mr. Sims for assistance in the measurement and reduction of some of the plates and Mr. Wood for help in initiating this programme.

Reference.

Wood, H., 1954. *Observatory*, **74**, 250.

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The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity, it was resuscitated in 1850, under the name of the "Australian Philosophical Society", by which title it was known until 1856, when the name was changed to the "Philosophical Society of New South Wales"; in 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, it assumed its present title, and was incorporated by Act of the Parliament of New South Wales in 1881.

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LIVERSIDGE RESEARCH LECTURE*

MODERN STRUCTURAL INORGANIC CHEMISTRY.

By A. D. WADSLEY, D.Sc., F.R.A.C.I.

Minerals Utilization Section, Chemical Research Laboratories Commonwealth Scientific and Industrial Research Organization, Melbourne, Australia.

INTRODUCTION.

By any standards, the late Professor Archibald Liversidge was a very great man, who exercised a profound influence upon science in Australia as well as in the United Kingdom. His long association with the Royal Society of New South Wales and the Australian and New Zealand Association for the Advancement of Science, in both of which he held high office, is perpetuated by means of special lectures, and I am very proud of being asked to deliver one of them. In fact it is a challenge of a unique kind. Generalities and reviews are not enough to justify the conditions under which it is offered, but " it will be such as will primarily encourage research, and not by giving instruction in what is already known ". This is no easy task, offering as it does an invitation to evaluate some field with emphasis on what still needs to be done.

In the solid state chemistry is three-dimensional, and structural chemistry is concerned primarily with the arrangements of atoms, their motions relative to one another and the forces which exist between them. It deals with organization rather than with transient phenomena. Two ideas represent turning points in the history of chemistry, and it is significant that in each the third dimension was introduced. Organic chemistry became a science after van't Hoff and le Bel introduced the concept of the tetrahedral carbon atom, and subsequently the architecture of molecules could, in principle, be established by chemical means. The first major advances in the systematic study of salts were due to Werner's theory of coordination number, the ligands to a metal atom being disposed in a definite geometrical pattern. Various chemists experimented with chemical models which were based upon the repetitious packing of spheres, but it was not until the introduction of X-ray diffraction analysis that these matters could be proved and extended. The chief triumphs of this most elegant discipline attended the introduction of the mathematical techniques of Fourier analysis in which, systematically if laboriously, the centres of scattering matter could be accurately deduced and the configuration of even the most complicated of molecular or ionic systems established. It is still, however, an impossible task to find direct evidence of chemical bonds, and as solid state chemistry is based ultimately upon the bond-forming characteristics of atoms one must still, in the best traditions of science, rely upon speculations and theory. As data accumulate and laboratory techniques improve, the laws of chemistry undergo continuous revision. Theory must give way before facts, which may be regarded as the experimental verification of ideas. This method of successive approximation is the essence of research work and it is seldom that any problem, no matter how trivial it might appear, could not be expected to throw a shadow of uncertainty upon chemical principles.

At the present time, structural inorganic chemistry may in one sense be regarded as very well documented. We have only to turn to books such as

* Delivered before the Royal Society of N.S.W., 29th July, 1958.

W. L. Bragg's " The Atomic Structures of Minerals ", A. F. Wells' " Structural Inorganic Chemistry " and " The Nature of the Chemical Bond " by L. Pauling to realize the extent of facts which are known. As a field of research work, one might well take the view of bringing these volumes up to date by filling in the gaps or by the inclusion of newer or refined data. But this would not be in the spirit of the Liversidge lecture. Rather, different avenues of experimental chemistry must be sought, and this could be done in several ways.

One could explore a new field of solid-state chemistry if the experimental methods by which simultaneous high pressures and temperatures are achieved were made available. The synthesis of diamond, cubic boron nitride and a high-density form of silica (coesite) is known. But many ionic substances, not in the most compact form under ordinary conditions, could be expected to have other structures which are the most stable at high pressures. If these revert rapidly to the normal forms on the release of pressure, techniques of X-ray analysis at high pressure could be developed. The valency states which exist at high pressure must also be the subject of future studies.

Alternatively, one may expect much new research work in structural chemistry in another direction. Reaction between solids is initiated by heating, which supplies the necessary energy. Heat may often change the total chemical composition, particularly if hydrogen, fluorine, the alkali metals or some other volatile component is present. Will other forms of energy, such as fast neutrons, be capable of inducing chemical changes at low temperatures? Or can they bring about transformations into disordered or polymorphic forms?

Possibilities such as these are a matter for conjecture with the present state of knowledge. Tonight, instead, I propose to examine a path in which, at the present, ideas of structure are slowly developing, and which may lead ultimately to the reassessment of much of the data at present taken for granted in certain chemical systems.

Solid-state chemistry is a name now largely used to describe compounds of the metals with the non-metals of the first, second, third and fourth periods of the periodic table. It also includes compounds formed between these elements. It embraces many of the disciplines of mineralogy, metallurgy and solid-state physics as well as of chemistry. Compounds in this definition are regarded as ionic, although in many cases covalent bonds are formed. The structures are formed by networks of atoms coordinated together which terminate only at the boundaries of the crystal or at some other discontinuity. If the metal ion can adopt two different valency states in the one phase, there is no reason why the compounds it forms should conform to the earliest quantitative laws taught in chemistry, the laws of constant and of multiple proportions. A *non-stoichiometric compound*, in J. S. Anderson's definition (1946), is a homogeneous phase with a range of composition, and in which the maxima or minima of properties—melting point, conductivity, lattice order—do not coincide with a rational atomic ratio of the components.

The reasons for variation of composition are threefold:

(*a*) Ions of either sort or both simultaneously may be absent from the network of atoms.

(*b*) Additional ions may occupy positions which are normally vacant.

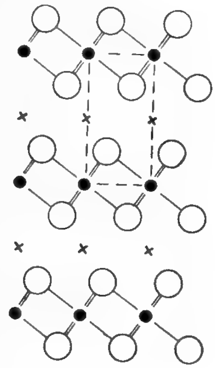
(*c*) The grouping of ions in certain crystallographic planes may alter so as effectively to reduce the numbers of one kind.

It is difficult, except in the briefest way, to discuss all of these matters in the time which is available, and I propose to limit my remarks to the first and third of these mechanisms. The second has been dealt with elsewhere (Wadsley, 1957*a*).

Phase Systems where Metal Vacancies Occur.

In a classic investigation Hägg (1935) showed that Fe_3O_4 and γFe_2O_3 represented the limits of one particular non-stoichiometric phase with the spinel structure. Based upon the crystallographic data, γFe_2O_3 more properly had the formula $Fe_{2\frac{2}{3}}O_4$. Variability of composition was proved to be due to the removal of iron atoms from Fe_3O_4 in which they were all present, and charge deficiencies were adjusted by changes of valency of the metal ions remaining. It should therefore be written $Fe_{2\frac{2}{3}}\,vac_{\frac{1}{3}}\,O_4$. The structure was a continuous variable giving rise to the term " subtractive solid solution ".

It has been shown by subsequent studies that in different preparations of γFe_2O_3 having substantially the spinel lattice, the vacancies could be ordered (Braun, 1952 ; David and Welch, 1956). This takes the form of weak additional lines in an X-ray diffraction pattern due to a superlattice, which is a repeat unit indicating the loss of some of the elements of symmetry. γFe_2O_3 could



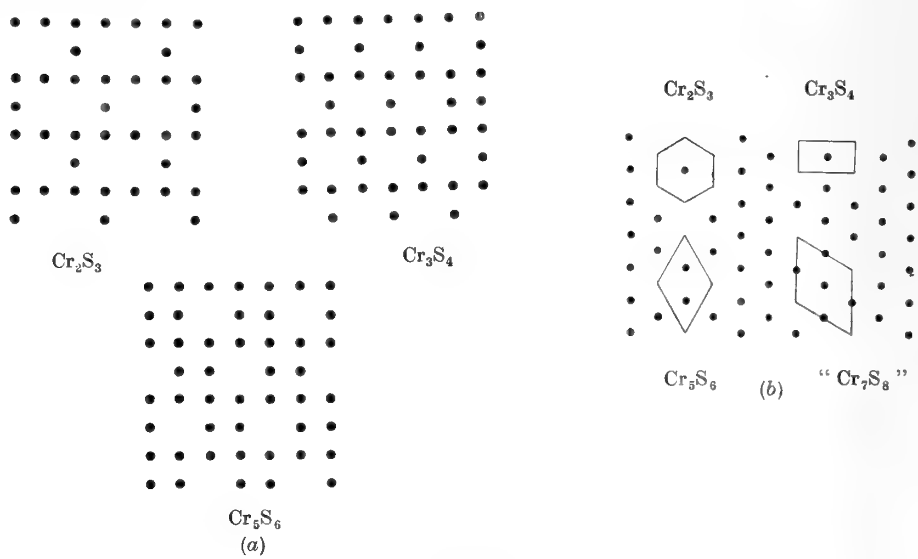
Text-fig. 1.

In the NiAs-like grouping, the metal atoms (drawn both as small black circles and as crosses) are each bonded to the non-metals (large open circles) ; the removal of the metals marked by crosses results in the CdI_2-type arrangement (in projection). The unit cell for both is drawn in broken lines.

vary between the limits $Fe_8[H_4Fe_{12}]O_{32}$ to $Fe_8[(Fe_{1\frac{1}{3}}\,vac_{2\frac{2}{3}})Fe_{12}]O_{32}$ for any one unit cell. The hydrogen ions replace iron atoms and vacancies which together form a set of octahedral sites strictly defined by the diffraction data. More recently still there is evidence (van Oosterhout *et al.*, 1958) of another superlattice three times larger than the spinel unit cell, in which the formula is $Fe_{24}[(Fe_4vac_8)Fe_{36}]O_{96}$.

It now appears that there are at least three possible arrangements for this one substance in which the vacancies are randomly distributed, partly ordered, or fully ordered over a limited number of the metal positions. Only one end member of a system in which the iron content is variable has been considered, and it is by now evident, if vacancies (or hydrogen atoms) adopt a definite structural role as they appear to do, that the system is no longer a two- but a three-component one. The term " solid solution " has little meaning. Classical methods of phase analysis are difficult to apply in cases such as this, the evidence having been collected by and large as the results of chance experiments. Methods of systematic study need to be developed, and hydrothermal techniques will undoubtedly assume great importance, particularly where hydrogen plays a structural role. The pH potential phase diagrams used by Pourbaix (1949) in the field of metal corrosion have been used effectively in geochemical studies of uranium and vanadium (Garrels, 1955; Evans and Garrels, 1958). By introducing the temperature variable as well, with its associated hydrothermal pressure, this would develop into a most powerful tool.

Until not very long ago, the system chromium-sulphur was regarded as homogeneous within the range CrS–Cr_2S_3. This was suppposedly due to the random removal of metal atoms from CrS which had an atomic arrangement usually referred to as the NiAs type. This is widely believed to be a very common mechanism for the sulphides, selenides and tellurides of the transition metals, and in favourable cases the complete removal of half the cations results in the CdI_2-like structure (Fig. 1). Often this elegant transition is found only within limited ranges.



Text-fig. 2.

(*a*) The structures of Cr_2S_3, Cr_3S_4 and Cr_5S_6 drawn in projection, the sulphur atoms being omitted for clarity. In each case the vacancies are confined to alternate metal atom layers and form a regular sequence, both in each sheet and between " defective " sheets.

(*b*) A single sheet of metal atoms. The geometrical figures show how the vacancies form regular patterns of different kinds. For a particular phase the appropriate pattern is regularly distributed over the whole of each defective sheet. " Cr_7S_8 " is modelled upon Fe_7S_8 (Bertaut, 1953).

Jellinek (1957) has shown quite conclusively that this is an oversimplification, and that there are six recognizable compounds which exist within the limits given above. These are CrS, Cr_7S_8, Cr_5S_6, Cr_3S_4 and Cr_2S_3 in two forms. All are distinct phases with no range of composition and with no solid solution between them; they are strictly stoichiometric. In Figures 2 (*a*) and 2 (*b*) the structures are shown diagrammatically, the metal atoms alone being drawn. In each case vacancies which occur are confined to each alternate layer of metal atoms. Different arrangements of the vacancies are characteristic of the different phases. In Cr_7S_8 they are random, and the structure is therefore only partly ordered; in Fe_7S_8 they are ordered (Bertaut, 1953), and the grouping of vacancies is included in Figure 2 (*b*) for comparison. This system may again be considered a ternary one in which a vacancy assumes the role of a lattice component.

The possibility exists that there are additional phases within the range Cr_7S_8–CrS. If based upon the scheme elucidated by Jellinek, their structures would be based upon other methods of arranging hexagonal or rectangular networks of holes. If these are too far apart, it is likely that the holes or vacancies are clustered together as in the defective layers of the Cr_2S_3 or Cr_3S_4 kind, and these groups, regular in themselves, are disordered in any one layer. This, with the evidence of a two-phase region, seems unlikely. But additional experimental variables have not been studied systematically—temperature of formation or temperature of annealing. Furthermore, since the segregation of structural units is a rate-controlled process, the time of heat treatment must also be considered. The examination of the phase system by X-ray diffraction was made at normal temperature and pressure (N.T.P.) which, on an absolute scale, is a purely arbitrary point and as a reference has little meaning.

In the simplest case the continuous structural variation between CrS and Cr_2S_3 could be expected to occur as a high temperature sequence, and this could be examined either by using high temperature diffraction techniques or by " quenching in " the high temperature structure. If it exists it is then a special idealized case. What could one expect to find in the structures of layer lattices of this kind as a consequence of controlling these sundry variables ?

Polymorphous forms may arise as the result of different stacking sequences in the non-metal layers. This is found for Ti_2S_3 (Wadsley, 1957*b*) and Zr_2Se_3 (McTaggart and Wadsley, 1958).

For the vacancies in the metal positions there are several methods of distribution :

(*a*) Randomly distributed over all the octahedral positions and not confined to every second layer.
(*b*) Randomly distributed in every second (or third, etc.) layer.
(*c*) Ordered in alternate layers but with no three-dimensional ordering.
(*d*) Confined to layers, either ordered or disordered, but with these having no regular sequence.
(*e*) Ordered layers of two or more kinds.

The list of possibilities is immense, but there is good reason to suppose that they will eventually be found, if not by X-rays, then by electron diffraction. The literature on the crystal chemistry of layer silicates, clays, the lamellar compounds of graphite, on the polymorphism of silicon carbide and zinc sulphide, the bismuth oxyhalides (Wadsley, 1955) provide much evidence in support. The systematic examination of order-disorder transitions in sulphides or oxides has been limited to one or two examples (Frueh, 1950). No relationships between transition temperature and structure, or some other parameter, have been established. The literature contains much conflicting evidence which arises from an inadequate appreciation of these matters. There are little or no thermodynamic data despite the obvious need for a measurement of an *order* term.

If we accept the abundant evidence that vacancies do exist and that, energetically and structurally, it is most probable that they tend to a system of order, one may well ask why they are present in the first instance. Schottky and Wagner (1930) worked out the conditions of equilibrium for lattice defects in a real crystal, and this has been useful in the subsequent application to problems of solid state physics. But when the concentration of defects, of one kind or another, is large, a different approach is required in which the emphasis is upon energetics rather than upon statistical methods.

Each metal atom, in all the chromium sulphides which were previously discussed, has seven or eight nearest neighbours, six being sulphur atoms in an octahedral grouping ; the others are metal atoms close enough to be regarded as forming a metallic type bond. Can solids of this kind be called intermetallic compounds? Many of them have some of the properties of metals—lustre, electrical conductivity or semi-conductivity, and ductility. The electron theory of metals, or some modification of it, could be expected to play an important part (Frueh, 1954), not only in terms of rate processes on the surface, but in the study of the solid itself which is our immediate objective. The Brillouin zones represent locations of discontinuities in the energy states which are permissible to free electrons in the periodic field of a crystal structure. A recent determination of the zones for AgCuS (the mineral stromeyerite) proved that a fractional number of silver ions gave a better electron-to-atom ratio than a whole number (Frueh, 1955). Any electrons in addition to these would need to be at a considerably higher energy level. Rather than attempt to accommodate these, some atoms were omitted. This is according to fact. Stromeyerite always has a deficit of oxygen; careful preparations of the composition AgCuS always contained free silver, and it was proved that the stable phase had the composition $Ag_{0 \cdot 9}CuS$.

This approach, properly applied and extended, could give reasons why non-stoichiometric compounds may exist, and could, with refinement, give composition limits. Yet this is the only example in which it has been tried. Properties such as low temperature heat capacity, thermal and electrical conductivity, Hall effect, will also be fruitful sources of information when they are more widely accepted by the chemist and the geologist.

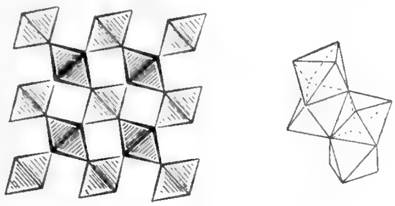
Systems in which Changes of Polyhedral Grouping, or Shears, Occur.

Originally it was supposed that the oxides a metal could form were based upon the valency of ions in the dissolved state. Since Ti^{4+}, Ti^{3+} and Ti^{2+} were believed known, it was assumed that titanium could form three oxides, TiO_2 (three polymorphous forms of which were known in mineralogy), Ti_2O_3 and TiO. These were proved to exist by preparation and by chemical analysis. A tensimetric X-ray study later showed that more phases than these could be formed (Ehrlich, 1939, 1941); moreover, they were non-stoichiometric and could be represented as single-phase regions by the formulae TiO_2–$TiO_{1 \cdot 9}$; $TiO_{1 \cdot 8}$–$TiO_{1 \cdot 7}$; $TiO_{1 \cdot 56}$–$TiO_{1 \cdot 46}$; and $TiO_{1 \cdot 35}$–$TiO_{0 \cdot 6}$. This particular phase system was confirmed in most respects by several workers, and a "not impossible" phase diagram was constructed to summarize the work up to 1954 (De Vries and Roy, 1954). Very recently, however, the same system has again been examined with great attention to detail, and at least seven previously unnoticed phases were found to exist within the range $TiO_{1 \cdot 75}$–$TiO_{1 \cdot 9}$. It was shown that they could all be represented by a general formula Ti_nO_{2n-1}, n having whole number values between 4 and 10 (Andersson *et al.*, 1957). Each of these substances is strictly stoichiometric and was prepared by melting, and then annealing, mixtures of titanium metal and the dioxide in the appropriate proportions. They should therefore have been found in the previous phase studies. Can these two sets of careful work be reconciled?

The crystal structure of Ti_5O_9 has now been worked out in detail (Andersson, MS. 1958).* It consists of the rutile structure in the form of blocks which are separated by regular discontinuities. At the junction of the blocks (in which the octahedra which constitute the structure share edges and corners) some octahedra share faces as well as edges (Fig. 3). The net result is the loss of oxygen in the unit cell, which now has a complex formula. It is to be expected that other members of the series Ti_nO_{2n-1} will have structures of a closely related kind.

* The author is grateful to Dr. Sten Andersson, University of Stockholm, Sweden, for allowing him to quote this work prior to its publication.

A series of oxides is known which has the general formula (Mo, W)$_n$O$_{3n-1}$, n having values between 8 and 14 inclusive. The structure of each is based upon that of WO_3, which consists of W–O octahedra sharing all six corners with



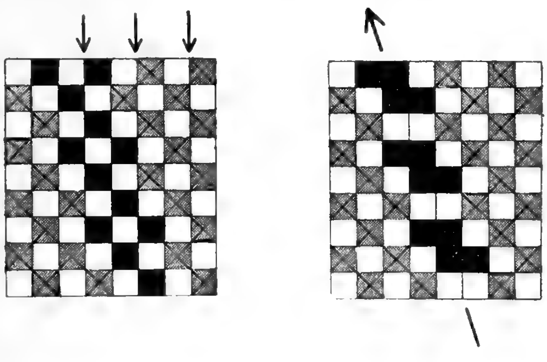
(a) (b)

Text-fig. 3.

(a) The structure of TiO_2 (rutile) represented as octahedra viewed in projection down the edges. The octahedra share corners, as well as edges above and below the plane of the paper.

(b) Discontinuity in Ti_5O_9 (drawn in perspective) which joins blocks of the normal rutile structure. Faces as well as edges are now shared.

similar ones (Fig. 4 (*a*)). In the series, blocks of this structure are separated by discontinuities or shears in which the octahedra of adjacent blocks share edges with one another, again resulting in a loss of oxygen (Fig. 4 (*b*)). Differences between individual members of the series are restricted only to the widths of the



(a) (b)

Text-fig. 4.

(a) The structure of WO_3 (idealized) in projection, the squares representing octahedra. The black squares are those which adopt a new configuration if blocks of the structure are moved by a hypothetical force applied in the direction of the arrows.

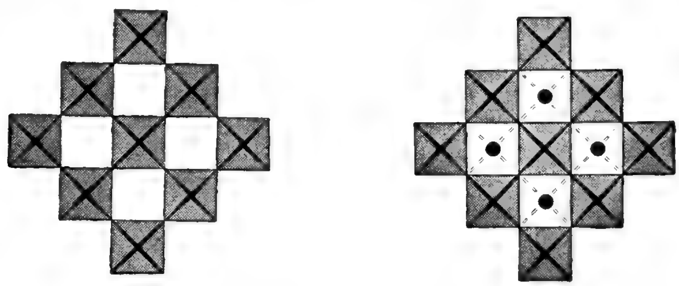
(b) The direction of the discontinuity or shear is indicated by the arrow. The black octahedra now share edges with each other, and corners with unchanged blocks of the normal WO_3 structure. This type of shear is common to all members of the homologous series (Mo, W)$_n$O$_{3n-1}$.

unchanged WO_3-type blocks, the discontinuity for all members being identical. The numeral n in the general formula can be used as a measure of the distances between the discontinuities (Hägg and Magnéli, 1954).

The existence of these series is not in itself remarkable. The members are quite stable and can be crystallized; they form structures which are perfectly rational, and the only difficulty which is presented is that of the valency of the metal ions. But in many diverse chemical systems it is now becoming clear that compounds with mixed or fractional valencies may contain free electrons which are raised in energy level to the conduction band. With their high mobility they give the solid to which they are bound many of the properties of a metal. These oxides are no exception.

What is remarkable about them, from the structural point of view, is that the discontinuities are regular; perhaps the chosen experimental conditions of annealing and of heat treatment favoured the development of these particular phases. But it is possible to devise other structures of a similar kind.

Consider a finite number of regular blocks (let us say seven) separated by a discontinuity designated by the stroke /; the structure can now be represented as –7/7/7/7–. Other kinds of sequence –4/10/4/10– or –5/9/5/9–, etc., can be visualized and, in these, blocks of two (or more) different widths alternate with one another. These represent new phases, each of which would have the same chemical formula and density as one another and the original, differing only in the length of one axis and in one angle of the unit cell. Again, perhaps, two



Text-fig. 5.—The relationship between the structures of WO_3 (left) and of the perovskite type (right). The squares are octahedra viewed down a corner, the small black circles additional metal ions which change the formula from BX_3 to ABX_3.

(or more) widths of block –6/6/8/6/8/8– would form in no ordered way; or segregate in disordered block "clusters" of one or more kinds –6/6/6/8/8/8/8/8/6/6–. This could well be identified as a two-phase region even although there is every reason to suppose it could exist in one single crystal.

As in the chromium sulphides, these speculations serve to introduce order-disorder which, as a variable, is seldom studied systematically in solid-state chemistry.

The series of titanium oxides ceases with the member $Ti_{10}O_{19}$; there is some evidence that higher homologues do exist (Andersson *et al.*, 1957), but equilibrium conditions are not readily achieved in the region $TiO_{1\cdot 9}$–TiO_2. If discontinuities of structure similar to those found in Ti_5O_9 do occur, they are probably disordered. But they should at the same time give diffuse X-ray reflexions and these are often difficult to observe. The limiting case is represented by a single shear; this may well be related to the dislocation twin of the solid-state physicist.

Homologous series could well be expected in many of the simple types of lattice—the NaCl-type, wurtzite, and so on. Cerium (Bevan, 1955) and praseodymium oxides (Ferguson *et al.*, 1954) of complex formulae are known, and whilst the structures are based upon the fluorite lattice, it is uncertain whether they contain shears of a new type or ordered omissions of oxygen atoms. Preliminary work (Wadsley, MS. 1958) has demonstrated shear structures formed by mixed oxides of titanium and niobium, a model based upon a comparison of

V_2O_5 and V_6O_{13} having previously been proposed (Wadsley, 1957*c*). The $(W, Mo)_nO_{3n-1}$ system, already mentioned, is perhaps the easiest of all to demonstrate, but it is based upon a lattice type which is rare. However, the structure is closely related to that of perovskite (ABO_3 type) for which there are numerous examples (Fig. 5). Recent work has shown that $SrTiO_3$ has the perovskite structure which persists over a range of composition to $SrTiO_{2\cdot5}$. (Kestigian *et al.*, 1957). Could a ternary series $Sr_{n-1}Ti_nO_{3n-1}$, closely related in every way, be formed? So far there is no evidence either for or against it, as annealing experiments have not as yet been made.

The shear or discontinuity mechanism will undoubtedly be recognized in future studies as a common one. Experiments could be devised, as they have been, to find evidence for it in different structural types. In the most favourable circumstances a closely related homologous series is found, but the experimental conditions, unless carefully chosen, may lead only to the observation of a solid solution which, again, must be regarded as a special case.

Phase Rule.

What has been discussed in this lecture may perhaps be described as speculations based upon experimental observations, and with questions posed by techniques and theories drawn from diverse disciplines. The classical approach to problems of this kind is based ultimately upon the Phase Rule which, in turn, is concerned with the relationship between phases in equilibrium with one another. But in these solid systems order-disorder phenomena are common, or could be expected to occur. The degree of order is a function of temperature and can be a continuous variable. The attainment of equilibrium at a particular temperature is a rate-controlled process which, in practice, may never be achieved. Ubbelohde (1957), in a review of thermal transformations in solids, discusses these and other matters in terms of a modified equation

$$F=C+2+\Sigma\pi-P$$

where $\Sigma\pi$ are additional " degrees of freedom ", the other symbols having their usual meaning.

Indeed, at the present level of understanding a *phase* itself cannot be rigorously defined (Brindley *et al.*, 1958).

Chemical Bonds

Little emphasis has so far been placed in this lecture upon the role of the chemical bond in solid inorganic substances. To the structural crystallographer, bonds exist between an atom and its nearest neighbours, and in practice this works out quite well. The nature of a bond, tetrahedral, octahedral or the like, is well established, but its character leaves room for speculation as the bond " lengths " and the " angles " between them are seldom ideal and rarely equal to one another. There is much current work, in chemical theory on the one hand and in coordination chemistry on the other, which has as its object the elucidation of the character of a chemical bond, and the help of the crystallographer is sought when anomalies arise or when precision is required. But the crystallographer has his own particular problem which, for want of a better term, can be called a structure-determining property of an ion, or perhaps a second-order bond effect.

In inorganic chemistry there are certain well-known groups of elements which, from the viewpoint of crystal chemistry, have identical characteristics—ionic radius, number of stable valency states and types of primary bond. Yet the compounds formed by the elements of any one group are not always alike, as one might well expect. As an example, the chemistry of zirconium and hafnium is virtually identical. Yet the crystal structures of the sulphides differ. ZrS has the NaCl structure, and the unit cell contains equal numbers of vacancies of both Zr and S. It has an extended homogeneity range to Zr_2S_3 which still is based upon the same structure. HfS, on the other hand, has a complex unknown structure, probably related to CrS. Hf_2S_3 is hexagonal and is related to Cr_2S_3, not to Zr_2S_3. Both ZrS_2 and HfS_2 have the same structures of the CdI_2 type (McTaggart and Wadsley, 1958).

Examples could be quoted for other pairs of elements, but it is not the function of this lecture to review the literature. In this particular case, both Hf and Zr form an octahedral grouping with the sulphur atoms. The structures they form are based upon the different arrangements of the octahedra, a second-order effect resulting in a cubic packing for the lower sulphides of Zr, a hexagonal for Hf. One could relate this behaviour in a qualitative way with some variable : the ionization potential ; to an empirical measure of the effective shielding of the core of an atom by the electrons remaining after the bonding electrons are removed (Ahrens, 1954) ; or to the polarizability of the ion. But these variables cannot predict those compounds likely to differ in structure, nor why the effect is limited to certain specific compounds.

Trace amounts of foreign ions may also in this way influence the structure of solids. Ti_3O_5 has one type of structure when it is very pure (Åsbrink and Magnéli, 1957). The substitution of iron for titanium even at the limit represented by the formula $Ti_{2 \cdot 9}Fe_{0 \cdot 1}O_3$ involves a complete reorganization to another, the pseudo-brookite arrangement (Zhdanov and Rusakov, 1954). In both the metal atom is in octahedral coordination.

However well based the conception of a new solid might be, and however well the choice of composition is made, the chemist is faced with the possibility of failure because these unknown or unforeseen matters cannot be assessed. It is still a matter of experimental trial and error, and therefore a subject for systematic research.

Conclusions.

In the terms of his bequest, the late Professor Liversidge suggested that this particular lecture would " stimulate the lecturer and the public to acquire new knowledge by research ". This I have attempted to do by showing that as more is learned about the way in which solids are built, fresh avenues for study and for thought are revealed.

This branch of inorganic chemistry had its origins in mineralogy, and still continues to draw upon minerals as the raw material for study, as themselves or as chemical models. Whilst a complete phase study from this point of view is impractical, in an individual mineral the element of time as a degree of freedom can be eliminated.

At present, inorganic compounds, many of which are suggested by the chemical constitution of mineral analogues, are the subject for intensive research work in diverse fields of solid-state physics in which the objectives are the complex interrelationships between composition, structure and properties. The current need for high temperature technological materials is also an urgent matter in which solid-state chemistry plays a vital role. These and other needs have already led to a great deal of research which will undoubtedly expand in many ways. But, as is often the case, much of that which is basic to the subject has been by-passed or overlooked. May I say how highly I value the opportunity to discuss some of these matters with you, through the wisdom and generosity of a very remarkable man.

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FLEXURE OF A SLAB ON AN ELASTIC FOUNDATION.

By Geoffrey Bosson.

Manuscript received, June 4, 1958. Read, August 6, 1958.

Summary.

This paper is concerned with the bending of a loaded stratum which is resting on an elastic foundation. Expressions, in the form of rapidly convergent series, are obtained for the displacement and pressure at the interface between stratum and foundation.

Problems concerned with the flexure of beams which are in contact with an elastic foundation are usually dealt with by adopting the Westergaard hypothesis, which assumes that the supporting force exerted by the foundation upon the beam, at any point of the interface, is proportional to the amount by which the foundation is depressed at that point. In a much earlier paper, the author has shown—by an heuristic rather than a rigorous method—that, if the depth of the foundation is small, there is reason to believe that this hypothesis (even if the foundation has isotropic elastic properties) will give approximately correct results. It was shown, however, that the hypothesis would cease to be valid in the case of an elastic foundation of significant depth (Bosson, 1939). It is fairly evident that the Westergaard hypothesis would hold strictly only in the case of a foundation having zero modulus of rigidity. One might, for instance, expect it to give reasonably good results if applied to a reinforced concrete road laid upon soil, but not to a similar road laid upon rock. For a foundation of non-zero rigidity, it is physically intuitive that the pressure exerted by the foundation would be a "functional", rather than a function, of the depression.

In the present paper we consider an infinite slab of elastic material having Young's modulus E and Poisson's ratio σ_1, bounded by the planes $y=0$ and $y=b$. This slab, or stratum, is assumed to be—and to remain—in contact with the semi-infinite foundation $y \leqslant 0$, the foundation having modulus of rigidity μ and Poisson's ratio σ. The quantity b will be assumed to be "small", which will be taken to mean that, when the stratum is subjected to bending, the curvature of the plane $y=\frac{1}{2}b$, at the point $(x, \frac{1}{2}b, z)$, is substantially the same as that of the plane $y=0$ at the point $(x, 0, z)$. This curvature will be assumed to be small enough for the elementary theory of bending to apply. Contact between stratum and foundation is regarded as smooth, *i.e.* the shearing stress across the plane $y=0$ is taken to be zero.

It will be convenient to use the terms "length", "thickness" (or, in the case of the foundation, "depth") and "breadth", when referring to dimensions measured respectively in the directions of the x, y and z axes of cartesian co-ordinates.

The components of the stress tensor at the point (x, y, z) are denoted by $p_{xx}, \ldots, p_{yz}, \ldots$, and the components of the displacement vector at the same point are denoted by u, v, w. We assume that the stratum and the foundation are in a state of plane strain parallel to the plane $z=0$, *i.e.* that $w=0$ and that u and v are functions of x and y only. Subject to these assumptions, the state of stress in the foundation, when in equilibrium and when body forces can be neglected, is given in terms of an Airy stress function, $\chi(x, y)$, by the equations

$$p_{xx}=\frac{\partial^2\chi}{\partial y^2}, \qquad p_{yz}=p_{zx}=0,$$

$$p_{yy}=\frac{\partial^2\chi}{\partial x^2}, \qquad p_{xy}=-\frac{\partial^2\chi}{\partial x\partial y},$$

$$p_{zz}=\sigma\nabla_1^2, \text{ where } \nabla_1^4\chi=0$$

$$\text{and } \nabla_1^2\equiv\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}.$$

Further, the displacements are given by the equations

$$2\mu u=(1-\sigma)\frac{\partial\psi}{\partial y}-\frac{\partial\chi}{\partial x},$$

$$2\mu v=(1-\sigma)\frac{\partial\psi}{\partial x}-\frac{\partial\chi}{\partial y},$$

where $\psi(x, y)$ is the " displacement function " defined by the equations

$$\frac{\partial^2\psi}{\partial x\partial y}=\nabla_1^2\chi,$$

$$\nabla_1^2\psi=0.$$

Suppose that, on the face $y=b$, of the stratum, we have the boundary conditions $p_{xy}=p_{yz}=0$, $p_{yy}=-W(x)$ and that, on the face $y=0$, we have $p_{xy}=p_{yz}=0$, $p_{yy}=-P(x)$. Then, if $V(x)$ denote the displacement in the y-direction of the point $(x, 0, z)$ of the stratum, the usual elementary theory of bending gives the equation

$$\frac{\bar{E}b^3}{12}\frac{d^4V}{dx^4}+W-P=0, \qquad \dots\dots\dots\dots \quad (1)$$

where $\bar{E}=E/(1-\sigma_1^2)$.

The load function, $W(x)$, being known, this equation may be solved for V once an expression for P has been determined. (The Westergaard hypothesis, of course, takes $P=-KV$, where K is some constant.)

Since we have assumed that the load on the stratum is such as to keep the latter in contact with the foundation and that the contact is " smooth ", it follows that the conditions on the face $y=0$ of the foundation are

$$p_{yy}=-P(x), \ p_{xy}=0 \text{ and } v=V(x).$$

The stress function corresponding to these conditions and giving stresses which tend to zero as the more remote portions of the foundation are approached is easily shown to be

$$\chi=\frac{1}{\pi}\int_{-\infty}^{\infty}P(\xi)(x-\xi)\arctan[(x-\xi)/y]d\xi. \qquad \dots\dots\dots\dots \quad (2)$$

The corresponding displacement function is

$$\psi=\frac{1}{\pi}\int_{-\infty}^{\infty}P(\xi)[2y\arctan\{(x-\xi)/y\}+(x-\xi)\ln\{(x-\xi)^2+y^2\}]d\xi. \qquad (3)$$

From these expressions we obtain

$$2\mu v=\frac{1}{\pi}\int_{-\infty}^{\infty}P(\xi)\left[3-2\sigma+(1-\sigma)\ln\{(x-\xi)^2+y^2\}-\frac{y^2}{(x-\xi)^2+y^2}\right]d\xi.$$

$$\dots\dots\dots\dots \quad (4)$$

From (4), on putting $y=0$, we have

$$2\mu V(x)=\frac{1}{\pi}\int_{-\infty}^{\infty} P(\xi)[3-2\sigma+(1-\sigma)\ln(x-\xi)^2]d\xi. \quad \ldots\ldots\ldots\ldots\ldots\ldots (5)$$

In practice, $P(\xi)$ would be sufficiently well behaved to permit differentiation under the integral sign. Thus we have

$$\mu V'(x)=-\frac{1-\sigma}{\pi}\int_{-\infty}^{\infty}\frac{P(\xi)}{\xi-x}d\xi, \quad \ldots\ldots\ldots\ldots (6)$$

and so, from the theory of Hilbert transforms, we obtain

$$P(x)=\frac{\mu}{\pi(1-\sigma)}\int_{-\infty}^{\infty}\frac{V'(\xi)}{\xi-x}d\xi, \quad \ldots\ldots\ldots\ldots (7)$$

the integrals in (6) and (7) being taken in the sense of Cauchy principal values. It is this relation which, so far as this paper is concerned, replaces the Westergaard hypothesis.

When we eliminate P between equations (1) and (7), we obtain the integro-differential equation

$$\frac{\bar{E}b^3}{12}\frac{d^4V}{dx^4}+W-\frac{\mu}{\pi(1-\sigma)}\int_{-\infty}^{\infty}\frac{V'(\xi)}{\xi-x}d\xi=0. \quad \ldots\ldots (8)$$

Now let $F(t)$ be the Fourier transform of $V'(x)$, so that

$$V'(x)=(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty} F(t)e^{-ixt}dt \quad \ldots\ldots\ldots\ldots\ldots (9)$$

and

$$V^{(iv)}(x)=i(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty} t^3F(t)e^{-ixt}dt. \quad \ldots\ldots\ldots\ldots (10)$$

Further

$$\int_{-\infty}^{\infty}\frac{V'(\xi)}{\xi-x}d\xi=(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty}\frac{d\xi}{\xi-x}\int_{-\infty}^{\infty}F(t)e^{-i\xi t}dt$$

$$=(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty}F(t)dt\int_{-\infty}^{\infty}\frac{e^{-i\xi t}}{\xi-x}d\xi.$$

$$=-\mathrm{i}(\tfrac{1}{2}\pi)^{\frac{1}{2}}\int_{-\infty}^{\infty}e^{-ixt}\operatorname{sgn} t\,.\,F(t)dt, \quad \ldots\ldots (11)$$

assuming that the order of the integrations may be changed.
From the last four equations we now obtain

$$W(x)=-\mathrm{i}(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty}\left[\frac{\bar{E}b^3t^3}{12}+\frac{\mu}{1-\sigma}\operatorname{sgn} t\right]e^{-ixt}F(t)dt, \quad \ldots\ldots (12)$$

whence, from the theory of Fourier transforms, we have

$$F(t)=\frac{i}{(2\pi)^{\frac{1}{2}}\left[\frac{\bar{E}b^3t^3}{12}+\frac{\mu}{1-\sigma}\operatorname{sgn} t\right]}\int_{-\infty}^{\infty}W(\alpha)e^{i\alpha t}d\alpha$$

$$=\frac{12i}{\bar{E}b^3(2\pi)^{\frac{1}{2}}(t^3+\lambda^3\operatorname{sgn} t)}\int_{-\infty}^{\infty}W(\alpha)e^{i\alpha t}d\alpha, \quad \ldots\ldots\ldots\ldots (13)$$

where

$$\lambda^3=\frac{12\mu}{\bar{E}b^3(1-\sigma)}. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Use of equation (9) now gives

$$V'(x)=\frac{6i}{\pi \bar{E}b^3}\int_{-\infty}^{\infty}\frac{e^{-ixt}dt}{t^3+\lambda^3 \operatorname{sgn} t}\int_{-\infty}^{\infty}W(\alpha)e^{i\alpha t}d\alpha, \quad \ldots\ldots\ldots\ldots \quad (15)$$

which, on integration and taking $V(0)=0$, gives

$$V(x)=\frac{6}{\pi \bar{E}b^3}\int_{-\infty}^{\infty}\frac{(1-e^{-ixt})dt}{t(t^3+\lambda^3 \operatorname{sgn} t)}\int_{-\infty}^{\infty}W(\alpha)e^{i\alpha t}d\alpha \quad \ldots\ldots\ldots\ldots \quad (16)$$

as the expression for the deflection of the interface.

W being known, $V(x)$ can be calculated from (16), though numerical integration would be necessary in most cases. Suppose, however, that a concentrated line load of unit intensity per unit breadth is applied to the slab along the line $x=0$, $y=b$. In this case we shall have $W(x)=\delta(x)$, where $\delta(x)$ is the Dirac delta function. Let $V_1(x)$ be the value of V calculated from (16) for this value of W. It then follows from the superposition principle that, if $W(x)$ behaves suitably at infinity, the value of $V(x)$ in the general case will be given by

$$V(x)=\int_{-\infty}^{\infty}W(\xi)V_1(x-\xi)d\xi. \quad \ldots\ldots\ldots\ldots \quad (17)$$

Thus, provided an explicit expression can be found for $V_1(x)$, the deflection in the general case can be found from (17) by a relatively simple integration. For this reason, we shall confine our attention to the task of obtaining an expression for $V_1(x)$.

The Case when $W(x)=L\delta(x)$.

In order to preserve dimensions, we take the intensity of the line load to be L instead of unity.

With $W(x)=L\delta(x)$, (16) becomes

$$V_1(x)=\frac{6L}{\pi \bar{E}b^3}\int_{-\infty}^{\infty}\frac{(1-e^{-ixt})dt}{t(t^3+\lambda^3 \operatorname{sgn} t)},$$

i.e.

$$V_1(x)=\frac{12L}{\pi \bar{E}b^3}\int_{-\infty}^{\infty}\frac{(1-\cos xt)dt}{t(t^3+\lambda^3)} \quad \ldots\ldots\ldots\ldots \quad (18)$$

This integral does not appear to be readily expressible in closed form. However, it may easily be expressed in terms of rapidly convergent series.

To obtain a series for $V_1(x)$, we let $V^*(p)$ be the Laplace transform of $V_1(x)$, so that

$$V^*(p)\equiv \mathbf{L}\{V_1(x)\}=\int_0^{\infty}e^{-px}V_1(x)dx. \quad (\text{Re } p>0).$$

On applying the Laplace transformation to (18), we find that

$$\frac{\pi \bar{E}b^3p}{12L}V^*(p)=\int_0^{\infty}\frac{tdt}{(t^3+\lambda^3)(t^2+p^2)}$$

$$=\frac{1}{\lambda^6+p^6}\left[\frac{2p^2\lambda\pi}{3\sqrt{3}}+\frac{2p^4\pi}{3\lambda\sqrt{3}}+\lambda^3\ln\lambda-\lambda^3\ln p-\frac{\pi p^3}{2}\right]. \quad (19)$$

We now follow the usual Heaviside technique by expanding the right-hand member of (19) in descending powers of p.

Thus

$$\frac{\pi\bar{E}b^3p}{12L}V^*(p)=\frac{2\lambda\pi}{3\sqrt{3}}\left[\frac{1}{p^4}-\frac{\lambda^6}{p^{10}}+\frac{\lambda^{12}}{p^{16}}-\ldots\right]$$
$$+\frac{2\pi}{3\sqrt{3}}\left[\frac{1}{p^2}-\frac{\lambda^6}{p^8}+\frac{\lambda^{12}}{p^{14}}-\ldots\right]$$
$$+\lambda^3\ln\lambda\left[\frac{1}{p^6}-\frac{\lambda^6}{p^{12}}+\frac{\lambda^{12}}{p^{18}}-\ldots\right]$$
$$+\lambda^3\left[\frac{1}{p^6}-\frac{\lambda^6}{p^{12}}+\frac{\lambda^{12}}{p^{18}}-\ldots\right]\ln(1/p)$$
$$-\frac{\pi}{2}\left[\frac{1}{p^3}-\frac{\lambda^6}{p^9}+\frac{\lambda^{12}}{p^{15}}-\ldots\right]. \quad \ldots\ldots\ldots\ldots \quad (20)$$

Making use now of the well-known results

$$\mathbf{L}\left\{\frac{x^n}{n!}\right\}=\frac{1}{p^{n+1}}$$

and $\mathbf{L}\left\{\frac{x^n}{n!}\left(\ln x+\gamma-1-\frac{1}{2}-\frac{1}{3}-\ldots-\frac{1}{n}\right)\right\}=\frac{1}{p^{n+1}}\ln\,(1/p)$,

where $x\geqslant 0$ and γ is Euler's constant, we have immediately, for $x\geqslant 0$,

$$\frac{\pi\bar{E}b^3}{12L}V_1(x)=\frac{2\lambda\pi}{3\sqrt{3}}\left[\frac{x^4}{4!}-\frac{\lambda^6x^{10}}{10!}+\frac{\lambda^{12}x^{16}}{16!}-\ldots\right]$$
$$+\frac{2\pi}{3\lambda\sqrt{3}}\left[\frac{x^2}{2!}-\frac{\lambda^6x^8}{8!}+\frac{\lambda^{12}x^{14}}{14!}-\ldots\right]$$
$$+\lambda^3\ln\lambda\left[\frac{x^6}{6!}-\frac{\lambda^6x^{12}}{12!}+\frac{\lambda^{12}x^{18}}{18!}-\ldots\right]$$
$$+\lambda^3\left[\frac{x^6}{6!}\left(\ln x+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{6}\right)\right.$$
$$-\frac{\lambda^6x^{12}}{12!}\left(\ln x+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{12}\right)$$
$$\left.+\frac{\lambda^{12}x^{18}}{18!}\left(\ln x+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{18}\right)-\ldots\right]$$
$$-\frac{\pi}{2}\left[\frac{x^3}{3!}-\frac{\lambda^6x^9}{9!}+\frac{\lambda^{12}x^{15}}{15!}-\ldots\right]. \quad \ldots\ldots\ldots \quad (21)$$

It will be noted that the series is rapidly convergent.

It will be obviously convenient to transform the series (21) into dimensionless terms by means of the substitution

$$X=\lambda x. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (22)$$

When this is done and use is made of equation (14), (21) becomes

$$\frac{\mu V_1}{L(1-\sigma)}=\frac{2}{3\sqrt{3}}\left[\frac{X^2}{2!}+\frac{X^4}{4!}-\frac{X^8}{8!}-\frac{X^{10}}{10!}+\ldots\right]$$
$$+\frac{1}{\pi}\left[\frac{X^6}{6!}\left(\ln X+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{6}\right)\right.$$
$$-\frac{X^{12}}{12!}\left(\ln X+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{12}\right)$$
$$\left.+\frac{X^{18}}{18!}\left(\ln X+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{18}\right)-\ldots\right]$$
$$-\frac{1}{2}\left[\frac{X^3}{3!}-\frac{X^9}{9!}+\frac{X^{15}}{15!}-\ldots\right]. \quad \ldots\ldots\ldots\ldots \quad (23)$$

It is clear from symmetry that (23) remains true for $X<0$ provided X is replaced by $|X|$.

The greater part of the second member of (23) can be expressed in closed form in terms of familiar functions. Thus, if we define a function $G(X)$ by the equation

$$G(X)=\frac{X^{12}}{12!}\left(\frac{1}{7}+\frac{1}{8}+\ldots+\frac{1}{12}\right)-\frac{X^{18}}{18!}\left(\frac{1}{7}+\frac{1}{8}+\ldots+\frac{1}{18}\right)+\ldots, \quad (24)$$

equation (23) may be written as

$$\frac{\mu V_1}{L(1-\sigma)}=\frac{4}{9}\sinh\left(\frac{1}{2}X\sqrt{3}\right)\sin\frac{1}{2}X$$
$$+\frac{1}{\pi}\left(\ln X+\gamma-2{\cdot}45\right)\left[1-\frac{1}{3}\cos X-\frac{2}{3}\cosh\left(\frac{1}{2}X\sqrt{3}\right)\cos\frac{1}{2}X\right]$$
$$-\frac{1}{6}\left[2\cosh\left(\frac{1}{2}X\sqrt{3}\right)\sin\frac{1}{2}X-\sin X\right]+\frac{1}{\pi}G(X). \quad \ldots\ldots \quad (25)$$

For computational purposes, (23) is obviously more convenient for small values of X, while (25) is better for larger values of X.

Behaviour of V_1 at Infinity

It is clear, by the Riemann-Lebesgue lemma, that the value of $V_1'(x)$ obtained by differentiating (18) will be zero at $x=\pm\infty$. On the other hand, it is not hard to show that the value of $V_1(x)$ tends logarithmically to infinity as $x\rightarrow\pm\infty$. Since the smallness of displacements is implicit in the theory which has been used, it follows that the analysis given here would not be applicable for large values of x. This difficulty is endemic in the fields of two-dimensional harmonic and biharmonic analysis and occurs in almost all cases in which plane stress or plane strain theory is applied to non-finite regions. The basic stress-function of equation (2) corresponds to the solution given by Love (1944), who draws attention to this difficulty. However, he states that the solution "may be regarded as giving correctly the local effect of force applied at a point of the boundary". He gives also a reference to the photo-elastic verification of this statement.

For the reasons just stated, it must be emphasized that the present author claims only local validity for the results of this paper.

The Pressure at the Interface

In order to find the value of P, it is most convenient to return to (1). For $W=L\delta(x)$, we should have, when $x\neq 0$,

$$P=\frac{Eb^3}{12}\frac{d^4V_1}{dx^4}=\frac{Eb^3\lambda^4}{12}\cdot\frac{d^4V_1}{dX^4}$$
$$=\frac{\mu\lambda}{1-\sigma}\cdot\frac{d^4V_1}{dX^4}. \quad \ldots\ldots (26)$$

Thus, using (23)

$$\frac{P}{\lambda L}=\frac{2}{3\sqrt{3}}\left[1-\frac{X^4}{4!}-\frac{X^6}{6!}+\frac{X^{10}}{10!}+\frac{X^{12}}{12!}-\frac{X^{16}}{16!}-\ldots\right]$$
$$+\frac{1}{2}\left[\frac{X^5}{5!}-\frac{X^{11}}{11!}+\frac{X^{17}}{17!}-\ldots\right]$$
$$+\frac{1}{\pi}\left[\frac{X^2}{2!}\left(\ln X+\gamma-1-\frac{1}{2}\right)-\frac{X^8}{8!}\left(\ln X+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{8}\right)\right.$$
$$\left.+\frac{X^{14}}{14!}\left(\ln X+\gamma-1-\frac{1}{2}-\ldots-\frac{1}{14}\right)-\ldots\right]. \quad \ldots\ldots (27)$$

Calculation based on (27) indicates that P changes sign between $X=3$ and $X=4$, after which it tends to zero rapidly. This would indicate that, unless there is adhesion between stratum and foundation, contact between them would not be maintained—a violation of one of the assumptions. Further, the supposition that there is adhesion at the interface would, in general, nullify the assumption of "smooth" contact at the interface. However, the negative values of P are very small (never more than about 0·005 of the maximum positive value) and errors due to this phenomenon are not likely to be important.

Note on the Series in Equations (23) and (27).

It is well known (Van de Pol and Bremmer, 1950) that, for $X>0$,

$$e^{-X}\mathrm{Ei}(X)=\ln X+\gamma+\sum_{n=1}^{\infty}(-)^n\left\{\ln X+\gamma-\sum_{m=1}^{n}\frac{1}{m}\right\}\frac{X^n}{n!}. \quad \ldots\ldots (28)$$

It follows that, by suitably defining $e^{-X}\mathrm{Ei}(X)$ for complex X, equations (23) and (28) could be expressed in completely closed form. The advantage of so expressing these equations, however, would be somewhat illusory as, so far as the author has been able to discover, no tables of $\mathrm{Ei}(X)$, for complex X, appear to exist.

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A NOTE ON THE POSSIBLE SEDIMENTARY ORIGIN OF SOME AMPHIBOLITES FROM THE COOMA AREA, N.S.W.

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Abstract.

The petrology and geochemistry of an amphibolite from the Cooma district indicate that it is comparable with hornblende-pyroxene granulites previously described by Joplin. Because of certain chemical similarities with the basalts of the Porphyritic Central Magma type, Joplin suggested that these rocks are ortho-amphibolites. Reconsideration of the geochemical data, however, suggests that an igneous origin is unlikely and it is believed that the rocks in question are para-amphibolites.

Joplin (1942) has described a variety of amphibolites and hornblende-pyroxene-granulites from the metamorphic aureole of the Cooma gneiss. She suggested that they represent metamorphosed basic and ultrabasic volcanics and minor obtrusives, and compared the composition of some of the basic rocks with the Porphyritic Central Magma type of the Scottish Tertiary volcanic province (Joplin, 1942, 171–173). During an investigation of the Murrumbidgee bathylith recently completed by the writer, further samples of the Cooma amphibolites were collected and one specimen was analysed. A separation and partial analysis of its hornblende was also made and trace element determinations on the rock and hornblende were kindly undertaken by Dr. S. R. Nockolds, of the Department of Mineralogy and Petrology, Cambridge.

The analysed specimen was collected in the Parish of York, just off the track which runs south from Murrumbucka Gap to join the Canberra-Cooma road near Pearman's Hill; the locality is $2\frac{1}{4}$ miles 54° W. of N. from the junction of the Murrumbidgee and Umaralla Rivers (see Browne, 1943, Plate 6). The amphibolite has an elongated outcrop and is either an inclusion or a roof pendant in the southern extremity of the Murrumbidgee bathylith. As pointed out by Browne (1943), the granitic rocks of the Murrumbidgee bathylith in this region might " almost be regarded as consisting of a great number of lenses or sills separated by screens of country rock ". It is believed that this mass of amphibolite is one of these screens, but unfortunately the field relations are too obscure to allow a more definite opinion to be formed. In hand specimen the amphibolite is a medium grained slightly lineated rock, the lineation reflecting the preferred orientation of hornblende. In thin section the rock is composed of subequal amounts of hornblende and plagioclase (An_{75}) with minor amounts of magnetite, epidote, quartz and secondary chlorite; the texture is nematoblastic. Geochemical, modal and mineralogical data are given in Table 1. The fabric of the rock is clearly metamorphic and the association of basic plagioclase and aluminous hornblende indicates that metamorphism took place

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under conditions of the amphibolite facies. Further classification of this rock into a subfacies is more difficult. Adjacent pelitic rocks are represented by mottled gneiss (Joplin, 1942), in which an andalusite-cordierite-mica assemblage is going over to a cordierite-sillimanite-orthoclase assemblage ; this complex paragenesis clearly indicates that the mottled gneiss is not in a state of equilibrium. The presence of orthoclase and sillimanite indicates a metamorphic temperature comparable to that of the sillimanite-almandine subfacies but the presence of

TABLE 1.

	1	2	3	4
SiO_2 ..	45·53	42·66	49·50	45·39
TiO_2 ..	1·59	1·66	0·75	1·78
Al_2O_3 ..	17·82	20·48	16·47	8·66
Fe_2O_3 ..	4·76	1·15	0·72	5·32
FeO ..	8·17	10·16	9·10	11·69
MnO ..	0·15	0·15	0·16	0·27
MgO ..	5·44	5·64	7·47	11·30
CaO ..	10·95	16·70	14·79	11·53
Na_2O ..	0·63	0·57	0·47	n.d.
K_2O ..	1·83	0·21	0·32	n.d.
H_2O+ ..	2·24	0·41	0·57	n.d.
H_2O- ..	0·21	0·16	0·03	n.d.
P_2O_5 ..	0·25	n.d.	0·05	n.d.
CO_2 ..	0·02	n.d.	n.d.	n.d.
	99·59	99·95	100·35	—
Sp. Gr. ..	3·02	3·01	3·05	—
Trace Elements in Parts per Million.				
Ga.. ..	25	—	—	25
Cr ..	10	—	—	10
V	120	—	—	450
Li	10	—	—	10
Ni ..	5	—	—	5
Co ..	20	—	—	30
Sc ..	45	—	—	100
Zr ..	80	—	—	80
Y ..	25	—	—	45
Sr	200	—	—	30
Ba.. ..	50	—	—	45

Optical Properties of Hornblende.

α	Pale green
β	Brownish green
γ	Olive green
	1·669 ± (0·003)
—2V.	62° ± 2°
γ∧C.	18°

Mode of Analysed Rock.

Hornblende ..	41·0
Plagioclase ..	48·0
Iron ore	5·7
Quartz	2·1
Chlorite	3·0
Epidote	0·2

1. Analysis of amphibolite, locality as in text. Anal. Rudowski and Unwin, with trace element determination by arrangement with S. R. Nockolds.
2. Hornblende-pyroxene-granulite. Anal. G. A. Joplin. (Joplin, 1942, Table 6, No. 1.)
3. Hornblende-granulite. Anal. G. A. Joplin. (Joplin, 1942, Table 6, No. 11.)
4. Partial analysis of hornblende from amphibolite (this table, No. 1). Anal. N. J. Snelling, with trace element determination by arrangement with S. R. Nockolds.

cordierite to the complete exclusion of almandine precludes classification in this subfacies. Both temperature of metamorphism and the composition of the pelites are such that almandine could be expected to develop. The absence of this mineral suggests low hydrostatic pressure during metamorphism (Halferdahl, 1957). A very thorough discussion of the facies classification of the high grade metamorphic rocks around the Wantabadgery and Green Hills granites and the Cooma gneiss has been given by Vallance (1953), who concludes that they represent a transition between the amphibolite and pyroxene hornfels facies.

The high grade of metamorphism is believed to be due to the adjacent Cooma gneiss, and the amphibolite was in its present metamorphic state before the intrusion of the Murrumbidgee bathylith, the metamorphic effects of which are generally very weak. In this area the thermal effects of the bathylith are slight, but volatiles have played an important role locally and caused greisenization and chloritization of the country rock (Joplin, 1943). It seems possible that the high potash and water contents of the analysed amphibolite, when compared with Joplin's analyses, may be due to the introduction of alkali solutions.

With the exception of potash and water, the composition of this amphibolite is very similar to the two basic granulites analysed by Joplin (1942, Table 6). The low magnesia and silica and high lime and alumina of these rocks prompted her to compare them with basalts of the Porphyritic Central Magma type (Bailey and Thomas, 1924); however, they differ in one important respect, namely their low soda content. A review of compilations of rock analyses and of Nockold's (1954) tables of the average chemical compositions of igneous rocks shows that most basalts, dolerites and gabbros have soda contents between 1·5% and 2·5%; basic rocks with soda of the order of 0·5%–1·0% are relatively uncommon. The lime and soda contents of the rocks under discussion would suggest affinities with ultrabasic rather than basic rocks, but alumina is too high and magnesia too low to substantiate such a suggestion. The possibility that these rocks were derived from impure calcareous sediments cannot be ignored, and in this connection it should be noted that the two specimens analysed by Joplin were both distinctly banded rocks. Eckelmann and Poldervaart (1957) have discussed the problem of distinguishing between para- and ortho-amphibolites and conclude that the chemical composition of such rocks is not always a reliable indicator of their origin, and they prefer to rely on field criteria, para-amphibolites showing banding and interlayering with other metasediments. Although banded, the specimens originally described by Joplin were not found *in situ*, and hence their relations with adjacent metasediments could not be determined; however, Dr. Joplin has recently informed the writer of the discovery of similar rocks *in situ* (in Cooma Creek, below the Showground) and she considers that the field evidence definitely indicates a sedimentary origin. The specimen described by the writer showed no signs of banding, and although *in situ*, the exposure was not good enough to determine the relationship with adjacent metasediments. While the low soda content of this specimen is insufficient evidence on which to base any conclusions as to its origin, particularly as there is the possibility that the rock may have been subjected to some metasomatism, there are in addition the trace elements to be considered. Of particular significance are the contents of Ni, Co and Cr; these are all low compared with the usual values determined for basic igneous rocks (Rankama and Sahama, 1950). Although individual analyses of basic rocks may show comparable values for one or other of these constituents, there are very few rocks in which all these elements are as low as in the analysed specimen, and the writer knows of no basic rocks which combine low Ni, Co and Cr with low soda (see Nockolds and Allen, 1953, 1954 and 1956). It is the writer's opinion that the field and geochemical evidence is sufficient to warrant the suggestion that the three rocks which form the subject of this note are more likely to be para-amphibolites than ortho-amphibolites. However, it is not intended that this interpretation should be extended to include all the other amphibolites which occur in the Cooma area and whose chemical composition, in many cases, is far more in keeping with an igneous origin.

This investigation was made during the tenure of a Research Scholarship at the Australian National University, Canberra. I would like to express my gratitude to Dr. G. A. Joplin for her help and encouragement during my stay at Canberra; to the staff of the Department of Radiochemistry for making the rock analysis; and to Dr. S. R. Nockolds, who arranged for the trace element determinations.

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ON THE GENETIC AND STRUCTURAL RELATIONS BETWEEN CONTACT METAMORPHIC MINERALIZATION AND A HYDRO-THERMAL VEIN AT WALANG, N.S.W.

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With Plate III and one Text-figure.

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Abstract.

The extraction, in its entirety, of a small quartz-scheelite-galena vein wholly contained within contact metamorphosed limestone near Bathurst, N.S.W., has facilitated a close study of the vein and its terminations. Structural and mineralogical features commencing with contact metamorphism and concluding with the flow of hydrothermal solutions are discussed.

Introduction.

A small deposit of scheelite recently discovered about a mile north-east of the village of Walang, 15 miles east of Bathurst, furnishes an interesting study of the genetic and structural relations between contact metamorphism and the formation of hydrothermal fissure veins.

The requisite degree of surface erosion, together with mining operations, has completely bared the extremity of a shear fissure vein and portion of a contact metamorphic zone within which the vein was wholly contained. An opportunity was thus afforded to study, in detail, the structure and origin of the vein, its downward passage into the contact zone, and the mineralogical changes that occurred from the contact-zone to the vein over a distance of less than 40 feet. As C. S. Ross states, " small size and compact relations are often an advantage and facilitate study " (U.S.G.S. Prof. Paper 179, 1935).

Some Previous References.

That ore deposits of contact metamorphic or metasomatic origin formed under favourable structural conditions tend to develop outwards from centres of metamorphism is clearly indicated by the numerous examples of pipes, lenses, veins and segregations associated with metamorphic aureoles. Most of the references to contact metamorphic veins, however, appear to be contained in early literature.

The deposition of ore minerals often takes place late in the metamorphic sequence, though there are instances of the mergence or telescoping of meta-somatic ore with the products of other processes which normally operate earlier or later than the period of ore formation.

The tungsten deposits of Oreana, Nevada, regarded by Kerr (1930) as unique, are of the nature of scheelite-bearing pegmatites within a sill-like mass of epidiorite, lying above a thick bed of limestone which is penetrated at depth by granite. The pegmatites, composed of oligoclase, albite, quartz, beryl and scheelite, with traces of garnet and epidote, are connected to the underlying limestone by narrow channels containing small amounts of scheelite. Kerr considers that these deposits disclose a direct link between processes of contact metamorphism and the development of pegmatites.

An even closer relationship between contact metamorphism and the injection of pegmatitic fluids is indicated by the " pegmatites " of Gold Hill, Utah (Butler, 1920 ; Nolan, 1935), where pipe-like ore bodies occur along intersecting joints within contact metamorphosed limestone and cordierite hornfels. The pipes contain grossular, epidote, calcite, quartz, orthoclase and actinolite with scheelite and chalcopyrite.

Fissuring, with flow at elevated metamorphic grade, is indicated by the presence of wollastonite with garnet, quartz, sphalerite and chalcopyrite at Zacatecas, Mexico (Bergeat, 1909), where fissures commence in calc-silicate rock and pass outwards into unaltered limestone. Wollastonite also occurs with sulphides in some of the veins of Tepezala, Mexico (Wandke and Moore, 1935).

Diopside accompanies garnet, vesuvianite, fluorite, calcite, quartz and scheelite in veins at Pine Creek near Bishop, California (Hess and Larsen, 1921). Associated with these ore bodies, within the same contact zone, are numerous quartz lenses rich in scheelite alone.

At Haitcha, New Mexico, veins of galena, pyrite, sphalerite and calcite with garnet traverse metamorphosed limestone containing disseminated sulphides. According to Lindgren *et al.* (1910) some of the deposits of this region " appear to form connecting links between contact metamorphism and vein deposits ".

Sphalerite, galena, chalcopyrite and pyrite occur along a fracture in metamorphosed limestone in the Santa Maria Range of Verlardena, Mexico (Spurr and Garretty, 1908). In other parts of the same district veins containing sphalerite and galena with quartz, calcite and garnet are wholly contained within metamorphosed limestone.

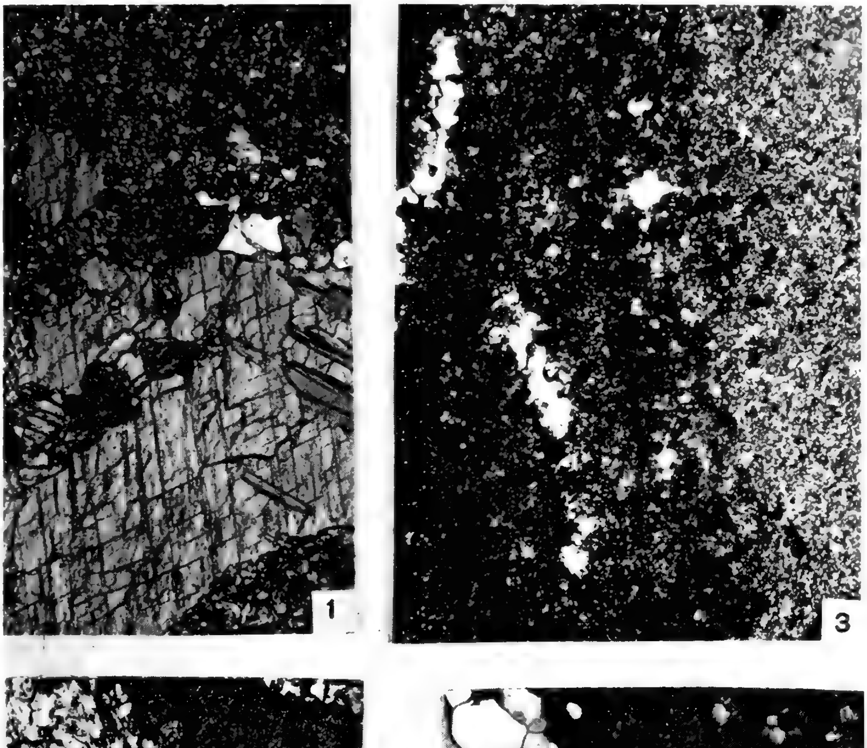
Hedenbergite-andradite veins with iron oxides and copper sulphides in the Oslo region (Goldschmidt, 1911) follow fault-planes in the skarn for considerable distances away from the centre of metamorphism.

At Campiglia Marittima, Italy (Beck, 1905 ; Knopf, 1942), the galena veins contain manganiferous pyroxene, ilvaite, epidote, calcite, quartz and fluorite and appear to be related to a nearby bed of metamorphosed limestone. Because of the prominence of hydrous silicates the veins were classified as hydrothermal.

Narrow quartz veins containing scheelite and minor amounts of pyroxene, actinolite, andradite, biotite, epidote, zoisite, calcite, sphene, pyrite and chalcopyrite transgress the bedding of the scheelite-bearing skarn at King Island, Australia (Edwards *et al.*, 1956). The following sequence of events has been established : (1) Contact metamorphism of calcareous beds ; (2) metasomatism yielding scheelite-bearing skarn ; (3) formation of veins, confined to the area of metasomatism.

The ore bodies of the Wilson Consolidated Mine, Utah (Nolan, 1935), afford an example of epimetamorphic mineralization ; scheelite, gold and bismuthinite occurring in lenses within calc-silicate rock bordered by sandstone. Hess and Larsen (1921) have described similar deposits at Golconda, Nevada, where quartz and scheelite form irregular patches and lenses in scheelite-bearing " tactite ".

At various localities around the Berggiesshübel bathylith in Saxony (Beck, 1905), where it invades Silurian limestones and tuffs, as at Nenntmannsdorf, veins of magnetite and haematite with small amounts of chalcopyrite and bornite pass outwards through the contact zone into unaltered limestone. The contact metamorphosed limestone carries iron oxides and sulphides of metasomatic origin. According to Beck, a second generation of sulphide-bearing veinlets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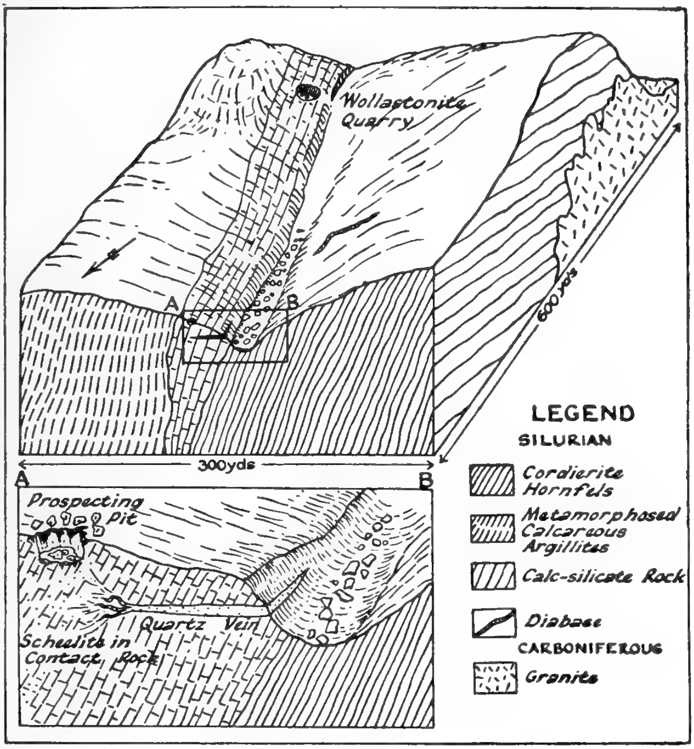
which are confined to the contact zone " seem to have been formed as primary veinlets during the metamorphic process, since they occasionally carry garnet ".

Two sets of veins have been recognized at the Yavapai mine at Clifton-Morenci, Arizona (Emmons *et al.*, 1913). The more prominent set contains magnetite and sulphides, has contact metamorphosed limestone walls, and is believed to be connected directly to intrusive porphyry at depth ; the second set carries the same ore minerals and is wholly contained within the contact rock. Emmons (1913) notes that " the mineralogical trend of the hydrothermal processes at Morenci undoubtedly connects it in some way with contact metamorphism ".



Text-fig. 1.—Block diagram illustrating the occurrence of scheelite at Walang, near Bathurst, N.S.W. (Lower diagram is an enlargement of portion of upper diagram.) Note.—In Legend, Calc-silicate Rock should have Limestone hatching.

Geology of the Walang Area.

(*a*) *Stratigraphy and Structure.*

The greater part of the Walang area consists of Upper Silurian slates, phyllites, sheared andesitic tuffs and impure limestone in association with strata of an argillaceous-calcareous nature. Intensely sheared dykes of diabase occur in places. Low-grade regional metamorphism appears to have been followed by the intrusion of small stocks of lamprophyre and dykes of felsite. The Silurian strata strike N.N.W.-S.S.E. and, in the region of mineralization, dip toward the north-east at 60° to 75°.

Remnants of Upper Devonian quartzites, shales and conglomerates form steep, heavily-wooded ranges rising 250 feet above the otherwise undulating surface. The Devonian sediments strike due north-south and rest with strong unconformity upon the eroded surface of the Silurian.

Kanimblan tectonics folded the Devonian rocks and facilitated large-scale igneous intrusion.

In general the geological pattern at Walang differs very little from that of other Siluro-Devonian areas in central-eastern New South Wales.

(*b*) *Igneous Intrusion.*

The main igneous rock of the area is a coarse-grained, sphene-bearing, biotite granite of the " Hartley " type (Joplin, 1931). This granite (Text-fig. 1) may be continuous at no great depth with the large Bathurst bathylith, which is exposed a few miles to the west.

The granite is veined by narrow pegmatites of simple mineralogy and by equally narrow veins of aplite of similar composition. Possibly related to the granite is a small intrusion of quartz-orthoclase porphyry which has suffered strong deuteric alteration.

Contact Metamorphism.

Contact metamorphism, to a greater or less degree, is discernible for a distance of some 500 yards from the visible margin of the granite. The phyllites and the limestone lens exhibit more pronounced thermal metamorphism than the associated rocks.

The phyllites have been changed to cordierite-hornfelses, some of which contain narrow bands of quartzite developed by either metamorphic diffusion or the metamorphism of intercalated layers of sandstone. In places there is a rapid change in the size of the cordierite porphyroblasts from 2 mm. to 7 or 8 mm., presumably reflecting particle-size variation in the original sediment. Two varieties of cordierite-hornfels may be distinguished in thin section. The coarse-grained rock contains large ill-defined patches of distinctly pleochroic cordierite containing a host of inclusions of quartz and sericite ; these two minerals, together with scattered magnetite, make up the remainder of the rock. Where the sericite is in larger flakes (muscovite), a decussate texture is exhibited. The absence of biotite is an interesting and unusual feature of this rock. In the finer-grained hornfels the cordierite is smaller, non-pleochroic and contains fewer inclusions, quartz, biotite and accessory magnetite being the other constituents. The cordierite grains in some of the outcrops display a lineation inherited from the original bedding of the sediments, and strikes and dips have been obtained locally from this crystal alignment.

The limestone is exposed for a distance of 300 yards, and possibly continues for a further 200 yards beneath thick soil cover to the margin of the granite. It thins out to the north-west, has an exposed vertical extent of about 75 feet, and is bordered on the south by cordierite-hornfels and on the north by calcareous argillites.

The metamorphic minerals of this limestone lens are disposed both in bands, where their distribution is related either to slight compositional changes in the original sediment, or to metamorphic diffusion, and in composite masses. Wollastonite up to two inches in length, greenish diopside, grossular crystals up to half an inch across, and granular calcite are conspicuous.

Thin sections of composite masses taken from a small wollastonite quarry less than 300 yards from the granite outcrop show an unusual mineral assemblage consisting of diopside, grossular, wollastonite, calcite and quartz (Plate III, Fig. 1). Wollastonite is preferentially distributed along cleavage-planes in the calcite and often completely replaces that mineral. Euhedral crystals of grossular as small as 1 mm. occur embedded in quartz or as lenticular patches of larger subhedral crystals showing segmental twinning and weak anisotropism. Granular patches and minute euhedral crystals of diopside are scattered along the quartz-calcite grain boundaries, whence they gradually spread outwards. The calcite is apparently magnesium-bearing, as indicated by the profuse development of granular diopside along many of the calcite-quartz grain boundaries. Quartz, ranging in size up to 0·5 mm., is spread throughout the rock ; its junction with calcite generally results in the formation of wollastonite, but there are instances of sharp non-reactive boundaries where quartz and calcite are in juxtaposition.

The percentage mineral distribution within the composite portions is as follows : wollastonite, 20% ; diopside, 30% ; grossular, 10% ; calcite, 25% ; quartz, 10% ; epidote, 5% or less.

Within 100 yards to the south of the wollastonite quarry the composition of the calc-silicate rock changes, for wollastonite is no longer present and the garnet shows evidence of substantial replacement by epidote, quartz and sericite. Diopside is still a principal constituent and tremolite appears in places, together with quartz, calcite and epidote.

Where the rock contains pieces of scheelite over an inch in size, the proportions of the various silicates again change. Tremolite, ferriferous in part, then becomes the major component either as confused fibrous aggregates or as larger (up to 1 mm.) subhedral grains. Diopside, next in abundance, occurs as granular aggregates and small euhedral crystals. Quartz, with mutual boundaries against other mineral grains or as narrow (0·25 mm.) replacement veinlets, is accompanied by minor amounts of calcite (Plate III, Fig. 2). Locally, however, calcite is conspicuous megascopically in association with large areas of epidote. The percentage mineral composition of this rock (omitting scheelite) is as follows : tremolite, 40% ; diopside, 30% ; quartz, 15% ; calcite, 5% ; epidote, 5% ; chloritized biotite, 5%. Small fragments of argillite incorporated in the rock have been converted to very fine-grained cordierite-hornfels.

An interesting feature of the lower-grade calc-silicate rock is the presence of small (up to 1 mm.) elliptical patches (Plate III, Fig. 3), sometimes bordered by tremolite, epidote and calcite. These patches represent cavities filled with quartz which shows extreme undulose extinction as though its entry and subsequent crystallization had been resisted by the enclosing rock. Minute grains of epidote and a mineral believed to be scheelite are occasionally included within the quartz fillings. Narrow zones of silicification (Plate III, Fig. 3) from 0·5 to 1 mm. wide, traverse parts of the rock, especially in the vicinity of the quartz-filled cavities, and it certainly appears that quartz has been introduced into the rock during the closing stages of metamorphism.

Mineralization.

The appearance of tremolite with much epidote and additive quartz indicates a fall in temperature, a movement away from conditions of predominantly dry metamorphism and the imminence of a stage of hydrothermal activity.

Several pieces of tungsten ore were collected at the surface and from a small prospecting pit in this vicinity. One of these consisted of calc-silicate rock rich in epidote, including a coarse-bladed patch five inches across within which was a mass of scheelite some six square inches in area. It appeared that the scheelite had truncated part of the epidote aggregate indicating a sequence : (1) calc-silicate rock, with fine-grained epidote ; (2) epidote, possibly of a later generation than that in (1) above ; (3) scheelite.

Small grains of pyrrhotite and larger (up to half an inch) patches of galena occur in this part of the contact zone. The galena is a totally additive product

(Pb and S), but the iron of the pyrrhotite, which occurs principally in the hornfels fragments, may have been derived by reaction between magmatic H_2S and biotite. It would appear that the scheelite was formed by reaction between tungsten-bearing fluids expelled from the granite at depth and small patches of calcite that remained in excess of the requirements of metamorphism. Occasional patches of calcite still persist in the rock.

Vein Formation.

At the point shown in Text-figure 1 an outcropping quartz vein dipped into the contact zone at 3° to 5° to the north. The vein was nine to ten inches in maximum thickness, tapered at either side, and was moulded on to the wall rock with strongly slickensided margins. The length of the remaining portion of the vein was 25 feet and its outcrop width six feet.

Table 1.

Trace Element Comparison of Galena and Scheelite from Contact Rock and Quartz Vein Respectively.

Element.	Scheelite from Contact Rock. (Per cent.)	Scheelite from Quartz Vein. (Per cent.)	Galena from Contact Rock. (Per cent.)	Galena from Quartz Vein. (Per cent.)
Fe	0·01–0·1	0·01–0·1	0·15–1·5	0·03–0·3
Mg	0·01–0·1	0·01–0·1	0·05–0·5	0·01–0·1
Ca	—	—	0·3–3	0·03–0·3
Al	0·015–0·15	0·003–0·03	0·03–0·3	0·003–0·03
Ti	—	—	0·002–0·02	0·001–0·01
As	—	—	0·01	0·03–0·3
Sb	—	—	0·01–0·1	0·01–0·1
Bi	—	—	0·1–1	0·1–1
Sn	—	—	0·003–0·03	0·003–0·03
Ag	0·0015–0·015	0·0003–0·003	$>0{\cdot}1$	$<0{\cdot}1$
Pb	0·003–0·03	0·003–0·03	—	—
Yt	0·03–0·3	0·03–0·3	—	—
Yb	0·03–0·3	0·03–0·3	—	—

The vein was followed in by means of a shallow drive and at a distance of 20 feet from the portal it turned towards the north-east and split into three veinlets each about half an inch wide and joined by a number of narrow feeders. Scheelite was visible right down to the ends of the feeders, which were wholly contained in calc-silicate rock. Numerous small grains of scheelite were present in the wall rock in the immediate vicinity of the feeding channels.

From a careful study of the vein, especially at its extremity, and of the distribution of scheelite in the adjacent contact rock, it can be stated with conviction that the vein originated within and was fed *via* the zone of metamorphism and metasomatism. The vein was not directly connected to the granite and dipped away from the granite margin at a very low angle (Text-fig. 1).

The greater part of the vein consisted of high-grade ore with scheelite crystals up to an inch long embedded in the vein-quartz (Plate III, Fig. 4). The scheelite was associated with minor amounts of galena. Thin-section study of the vein failed to reveal the presence of any gangue minerals other than quartz, metamorphic silicates being notably absent.

The mechanism of fissuring may be related to stresses induced by differential volume changes consequent upon metamorphism. It has been shown (Barrell, 1902) that metamorphism of shales to cordierite-hornfels causes volume reduction, while the conversion of limestone to calc-silicate rock results in volume expansion (Maxwell and Verrall, 1953). It is significant in this regard that fracturing occurred at the junction of the cordierite-hornfels and the calc-silicate rock.

Trace Element Determination.

With the aid of a large quartz Hilger spectrograph, the trace element assemblages of galena and of scheelite from the contact rock were compared with those of the same minerals from the vein. In each instance some 20 trace elements were detected; only those considered significant* are listed on p. 52. Close agreement was obtained from the respective pairs of minerals. None of the trace elements present in galena or scheelite from one environment was missing from the corresponding mineral in the other, contrary to what might be expected had the vein minerals been formed other than in the contact zone.

Conclusions.

Two metamorphic grades may be identified within the limestone lens: grossular-diopside-wollastonite-quartz-calcite (omitting minor amounts of epidote) near the exposed granite and diopside-grossular-tremolite-quartz-calcite-epidote further away.

The intimate association of wollastonite with both quartz and calcite indicates that metamorphism ceased at a temperature little in excess of the quartz-calcite stability point. If Danielsson's (1950) thermodynamic assessment of the most likely temperature for the wollastonite reaction be applied to metamorphism at Walang, a temperature of the order of 550° C. is indicated (*cf.* Edwards *et al.*, 1956).

Somewhat lower temperatures, in accordance with greater distance from the granite margin and the disappearance of wollastonite, may be postulated for the metamorphism in the vicinity of the scheelite mineralization.

The absence of metamorphic silicates in the quartz vein shows that contact metamorphism had been completed prior to the flow of aqueo-siliceous solutions into the fissure and points to a further fall in temperature, though perhaps only slight. A similar time-lag between metamorphism and scheelite mineralization has been noted at King Island.

The narrow bands of silicification in the scheelite-bearing contact rock (Plate III, Fig. 3) are interpreted as indicating the subsequent rise through the rocks of a hydrothermal "front". Whether the scheelite of the contact rock was formed by a gas-solid or a liquid-solid reaction is debatable. If by the former then aqueo-siliceous solutions must also have been available near the sites of reaction between expelled volatiles and excess calcite within the contact rock. At the moment of reaction some of the scheelite, as well as galena, was taken into solution (or suspension) and carried, *via* the narrow feeders, into the shear fissure under strictly hydrothermal conditions.

By virtue of its close proximity to a contact metasomatic source, the vein might well be classified as hypothermal, corresponding to the temperature range 300–500° C. of Lindgren's classification.

There seems to be a case for identifying three possible stages in the formation of ore deposits of contact metasomatic origin:

(1) *Contact metamorphism-metasomatism*, giving rise to more or less disseminated ore within the contact aureole at high temperatures.

* Dr. J. R. Butler (Imperial College). Personal communication.

(2) Early fissuring yielding *contact metamorphic-metasomatic veins*, containing metamorphic silicates of various grades as well as ore minerals, formed at slightly lower temperatures than (1) above.

(3) Late fissuring yielding *hydrothermal veins of contact-metasomatic origin*, like the vein at Walang, containing contact metasomatic ore minerals but no contact metamorphic silicates, and having hypothermal, mesothermal and perhaps epithermal mineral assemblages.

The temperature at which the vein minerals form would depend, *inter alia*, on the time lag between metamorphism and the ascent of metallizing agents, the stage in the metamorphic sequence at which fissuring, faulting, etc., occurred, and the distance travelled by the ore-bearing fluids from the focus of metamorphism.

In some respects the processes of mineralization attending contact metamorphism seem to recapitulate the ore-forming processes proceeding directly from an orthomagma.

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Mr. T. Mathews, of Bathurst, N.S.W., owner of the Walang lease, supplied the author with selected specimens during the working of the deposit. Thanks are due also to Professor F. J. Turner, of the University of California, who visited the area with the author in 1956, and Professor D. Williams, of the Imperial College, for reading the manuscript.

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Explanation of Plate III.

Fig. 1.—Calc-silicate rock containing granular diopside, calcite with wollastonite inclusions diagonal to cleavage, quartz (white) and a portion of a grossular grain (upper right). Note quartz abutting against calcite with non-reactive border. Nicols half crossed. ×25.

Fig. 2.—Calc-silicate rock containing diopside, tremolite, quartz and calcite in granoblastic arrangement with metasomatic scheelite (dark area on upper right). Crossed Nicols. ×25.

Fig. 3.—Fine-grained aggregate of diopside, tremolite, calcite, epidote and quartz with quartz-filled cavities and zones of fine-grained (additive) quartz (centre and right half of photo). Crossed Nicols. ×25.

Fig. 4.—Thin section of scheelite-bearing quartz vein. Upper right portion scheelite with quartz inclusions; lower left portion quartz. Crossed Nicols. ×25.

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A

MINOR PLANETS OBSERVED AT SYDNEY OBSERVATORY DURING 1957.

By W. H. Robertson.

Manuscript received, August 25, 1958. Read, December 3, 1958.

The following observations on minor planets were made photographically at Sydney Observatory with the 13-inch standard astrograph. Observations were confined to those with southern declinations in the *Ephemerides of Minor Planets* published by the Institute of Theoretical Astronomy at Leningrad.

On each plate two exposures, separated in declination by approximately 0′·5, were taken with an interval of about 20 minutes between them. The beginnings and endings of the exposures were recorded on a chronograph with a tapping key.

Rectangular coordinates of both images of the minor planet and three reference stars were measured in direct and reversed positions of the plate on a long screw measuring machine. The usual three star dependence reduction retaining second order terms in the differences of the equatorial coordinates was used. Proper motions, when they were available, were applied to bring the star positions to the epoch of the plate. Each exposure was reduced separately in order to provide a check by comparing the difference between the two positions with the motion derived from the ephemeris. The tabulated results are means of the two positions at the average time except in cases 451, 461, 468, 495, 519, 591, 620 where each result is from only one image, due to a defect in the other exposure or a failure in timing it. No correction has been applied for aberration, light time or parallax but in Table I are given the factors which give the parallax correction when divided by the distance. The serial numbers follow on from those of a previous paper (Robertson, 1957). The observers named in Table II are W. H. Robertson (R), K. P. Sims (S) and H. W. Wood (W). The measurements were made by Mrs. M. Wilson who also assisted in the computation.

Table I.

1957 U.T.	Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors
		h m s	° ′ ″	s ″
451 July 10·55113	28 Bellona	18 53 56·14	—13 56 52·8	—0·05 —3·0
452 Aug. 2·46986	28 Bellona	18 36 51·15	—15 21 05·8	—0·07 —2·8
453 June 25·65860	29 Amphitrite	19 41 35·58	—30 38 29·7	+0·06 —0·5
454 July 3·67615	29 Amphitrite	19 33 53·16	—30 57 49·8	+0·07 —0·5
455 May 6·69648	38 Leda	16 50 01·97	—30 15 28·1	+0·13 —0·6
456 May 21·62930	38 Leda	16 37 18·50	—29 51 22·0	+0·07 —0·6
457 June 6·63420	77 Frigga	18 24 49·44	—26 57 20·5	—0·02 —1·0
458 June 13·59074	78 Diana	16 37 45·57	—35 10 44·2	+0·16 +0·1
459 June 24·53294	78 Diana	16 27 25·65	—34 26 44·2	+0·09 +0·1
460 July 10·61087	118 Peitho	20 17 28·37	—31 21 01·9	—0·05 —0·4
461 Oct. 8·55259	121 Hermione	0 59 11·63	— 4 27 57·0	—0·07 —4·3
462 May 21·56896	127 Johanna	14 05 57·52	—15 37 27·0	+0·20 —2·9
463 May 24·52374	127 Johanna	14 03 58·73	—15 33 50·0	+0·09 —2·8

TABLE I—*Continued.*

1957 U.T.			Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
464	Aug.	20·55938	129 Antigone	21 26 10·68	—16 55 54·2	—0·01	—2·5
465	Sep.	3·52977	129 Antigone	21 16 52·92	—18 41 15·8	+0·04	—2·3
466	Sep.	12·49110	129 Antigone	21 12 45·86	—19 33 21·2	+0·01	—2·2
467	Mar.	11·59723	132 Aethra	11 14 12·56	—53 07 36·5	+0·09	+2·9
468	Mar.	21·54672	132 Aethra	11 08 53·02	—52 27 11·8	—0·01	+2·8
469	Oct.	31·56269	146 Lucina	2 22 34·12	— 1 55 28·9	—0·02	—4·6
470	June	24·56024	178 Belisana	17 50 25·95	—25 31 54·8	—0·02	—1·3
471	July	16·49310	178 Belisana	17 31 30·36	—25 31 31·2	0·00	—1·2
472	Apr.	9·66070	179 Klytæmnestra	14 51 34·04	—22 47 21·0	+0·03	—1·7
473	May	15·54526	179 Klytæmnestra	14 24 31·71	—19 54 54·5	+0·04	—2·1
474	June	6·63420	196 Philomela	18 26 08·77	—26 20 14·1	—0·02	—1·1
475	June	19·60896	196 Philomela	18 15 35·52	—26 54 31·9	+0·04	—1·1
476	July	4·61416	214 Aschera	18 54 38·96	—27 40 21·4	+0·10	—1·0
477	June	26·61196	228 Agathe	19 00 55·96	—26 00 47·4	+0·01	—1·2
478	Oct.	23·67336	234 Barbara	2 56 29·01	—12 23 05·0	+0·18	—3·3
479	Nov.	6·60278	234 Barbara	2 43 57·59	—13 38 27·8	+0·11	—3·1
480	Nov.	13·56617	234 Barbara	2 37 58·85	—13 44 41·5	+0·07	—3·0
481	May	24·46928	241 Germania	13 44 20·83	—17 09 16·9	—0·04	—2·5
482	July	10·67571	250 Bettina	21 18 31·08	—33 58 33·0	+0·03	0·0
483	Aug.	13·58452	250 Bettina	20 49 57·61	—35 45 49·1	+0·11	+0·2
484	May	24·46928	266 Aline	13 37 10·76	—16 07 09·5	—0·02	—2·7
485	June	25·69729	278 Paulina	20 04 22·01	—29 21 04·6	+0·14	—0·8
486	Sep.	5·63828	346 Hermentaria	0 21 05·71	—13 01 55·8	0·00	—3·1
487	Sep.	12·66068	346 Hermentaria	0 16 15·69	—13 49 00·8	+0·14	—3·1
488	Oct.	3·59384	346 Hermentaria	23 59 36·13	—15 33 04·0	+0·15	—2·8
489	June	6·59374	380 Fiducia	17 03 54·84	—19 30 02·6	+0·03	—2·2
490	June	19·57060	380 Fiducia	16 51 32·43	—19 44 16·2	+0·10	—2·2
491	May	8·55838	394 Arduina	14 23 01·60	— 9 40 17·8	+0·02	—3·6
492	Apr.	4·58266	407 Arachne	12 11 35·85	—13 32 42·5	+0·09	—3·1
493	Apr.	24·51478	407 Arachne	11 57 14·61	—11 40 02·3	+0·08	—3·3
494	July	4·63914	416 Vaticana	19 53 53·82	—39 03 36·8	+0·11	+0·8
495	Aug.	9·47579	416 Vaticana	19 21 59·80	—41 15 32·8	—0·10	+1·1
496	Aug.	20·47980	416 Vaticana	19 17 58·14	—40 50 51·4	+0·03	+1·1
497	June	19·53208	417 Suevia	15 39 49·24	—11 47 00·0	+0·13	—3·3
498	June	27·48414	417 Suevia	15 36 54·94	—11 40 10·1	+0·06	—3·3
499	Oct.	3·52312	451 Patientia	22 53 19·82	—29 24 39·1	+0·08	—0·7
500	Oct.	8·58012	455 Bruchsalia	1 14 33·40	—16 10 29·9	—0·02	—2·7
501	Oct.	31·52732	455 Bruchsalia	0 56 19·30	—14 01 57·9	+0·06	—3·0
502	Nov.	6·54585	455 Bruchsalia	0 53 30·59	—13 01 20·6	+0·17	—3·2
503	Oct.	1·59934	458 Hercynia	1 10 47·41	—11 46 54·0	—0·01	—3·3
504	May	8·62216	460 Scania	15 58 41·34	—16 48 42·4	+0·01	—2·6
505	Sep.	17·65808	486 Cremona	1 16 02·75	—10 39 35·0	+0·05	—3·5
506	Sep.	30·64616	486 Cremona	1 04 39·00	—12 05 27·9	+0·14	—3·3
507	Oct.	3·55770	492 Gismonda	23 48 11·27	— 3 19 57·2	+0·06	—4·4
508	Oct.	16·51976	492 Gismonda	23 40 37·05	— 3 56 55·6	+0·07	—4·4
509	May	6·59304	506 Marion	15 07 26·77	—42 13 05·0	+0·02	+1·3
510	May	29·55064	506 Marion	14 46 00·80	—40 25 27·6	+0·16	+0·9
511	Aug.	8·67208	521 Brixia	23 00 30·37	—22 50 55·7	+0·04	—1·5
512	Sep.	18·55440	521 Brixia	22 29 23·26	—27 51 42·8	+0·10	—1·0
513	Sep.	30·50886	521 Brixia	22 22 12·30	—28 00 10·0	+0·07	—0·9
514	July	4·66820	524 Fidelio	20 43 31·27	—24 37 48·4	+0·03	—1·4
515	Aug.	29·46520	524 Fidelio	19 54 22·23	—24 27 24·2	—0·02	—1·4
516	June	27·52694	530 Turandot	17 25 14·65	—14 15 37·5	—0·05	—2·9
517	July	15·46565	530 Turandot	17 13 20·13	—15 05 14·5	—0·06	—2·8
518	June	6·67168	536 Merapi	18 55 56·84	—38 06 55·0	+0·04	+0·7
519	June	13·68079	536 Merapi	18 50 52·24	—38 52 38·8	+0·16	+0·6
520	Mar.	26·57426	544 Jetta	12 21 25·14	—16 22 50·4	—0·03	—2·6
521	Apr.	29·70734	546 Herodias	16 19 33·24	—35 13 18·1	+0·19	0·0
522	May	2·65670	550 Senta	15 55 13·89	—30 45 05·8	+0·09	—0·5
523	May	23·57800	550 Senta	15 35 41·40	—28 45 32·2	+0·06	—0·5

TABLE I—*Continued.*

1957 U.T.			Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
524	June	6·50592	550 Senta	15 22 58·20	—26 49 19·3	—0·03	—1·0
525	May	8·52521	554 Peraga	14 02 15·20	—17 13 54·4	—0·04	—2·5
526	May	23·67688	602 Marianna	17 55 50·65	—43 39 47·0	+0·08	+1·5
527	June	13·61940	602 Marianna	17 35 13·43	—43 57 00·3	+0·14	+1·5
528	Sep.	18·58316	618 Elfriede	0 08 17·24	—24 07 03·6	—0·04	—1·5
529	Sep.	30·57204	618 Elfriede	23 59 38·58	—25 10 35·4	+0·06	—1·3
530	May	2·68526	624 Hektor	16 14 38·31	—43 35 07·8	+0·17	+1·4
531	June	27·56434	638 Moira	18 11 25·72	—21 09 19·9	—0·03	—1·9
532	Sep.	17·57138	644 Cosima	23 31 04·02	— 4 58 20·5	0·00	—4·2
533	Oct.	1·55156	644 Cosima	23 20 18·82	— 6 08 09·2	+0·08	—4·1
534	Mar.	14·60401	654 Zelinda	11 37 33·18	—36 30 20·1	+0·06	+0·4
535	Apr.	9·52724	654 Zelinda	11 14 12·31	—33 29 12·8	+0·10	—0·1
536	July	10·67571	674 Rachele	21 14 42·89	—33 55 43·8	+0·04	0·0
537	Aug.	20·53276	674 Rachele	20 39 21·45	—36 49 54·8	+0·02	+0·5
538	May	9·52701	675 Ludmilla	13 47 05·22	—21 46 20·1	+0·01	—1·8
539	May	15·51226	675 Ludmilla	13 43 00·38	—21 07 01·1	+0·02	—1·9
540	Sep.	3·58322	679 Pax	22 11 58·04	—43 49 44·8	+0·12	+1·5
541	Sep.	18·53100	679 Pax	22 03 38·52	—46 14 59·4	+0·10	+1·8
542	Mar.	21·61388	690 Wratislavia	12 33 46·97	—18 22 44·0	+0·02	—2·3
543	Apr.	9·56310	690 Wratislavia	12 20 25·84	—16 44 52·0	+0·06	—2·6
544	May	24·46928	707 Stelna	13 38 57·88	—16 38 56·7	—0·03	—2·6
545	Feb.	28·56539	712 Boliviana	9 54 39·99	— 8 11 19·3	+0·04	—3·8
546	Mar.	11·56610	712 Boliviana	9 46 26·74	— 6 42 38·6	+0·16	—4·0
547	June	25·56194	738 Alagasta	17 15 40·30	—19 07 37·4	+0·07	—2·5
548	July	4·54243	738 Alagasta	17 09 09·18	—19 10 47·9	+0·10	—2·2
549	June	27·68536	742 Edisona	20 39 27·99	—31 42 21·6	+0·04	—0·3
550	Aug.	20·50307	742 Edisona	19 57 09·85	—35 42 52·9	+0·01	+0·3
551	July	10·64558	762 Pulcova	20 33 25·37	—20 52 09·8	+0·03	—2·0
552	Aug.	20·62929	768 Struveana	22 32 35·85	—34 49 24·4	+0·08	+0·1
553	Sep.	17·53862	768 Struveana	22 07 02·94	—35 01 54·5	+0·10	+0·1
554	May	9·56002	769 Tatjana	14 45 33·39	—17 07 48·8	—0·01	—2·5
555	May	29·48070	769 Tatjana	14 30 10·08	—16 45 19·8	—0·06	—2·6
556	Sep.	18·61198	776 Berbericia	0 35 25·49	—28 44 02·1	0·00	—0·8
557	Oct.	2·61261	776 Berbericia	0 23 03·93	—29 21 59·3	+0·02	—0·6
558	Mar.	11·69948	790 Pretoria	13 05 30·29	—31 34 36·2	+0·15	—0·5
559	Mar.	21·65369	790 Pretoria	12 59 40·50	—31 19 23·8	+0·10	—0·4
560	Apr.	9·60964	790 Pretoria	12 46 07·80	—29 49 11·5	+0·16	—0·7
561	Apr.	29·51668	790 Pretoria	12 33 14·56	—27 06 08·2	+0·06	—1·0
562	May	9·59168	866 Fatme	15 26 55·62	—10 21 24·2	0·00	—3·5
563	May	30·53840	866 Fatme	15 10 35·18	—10 01 04·9	+0·04	—3·5
564	Sep.	5·63828	906 Repsolda	0 23 11·82	—12 22 37·6	0·00	—3·2
565	Sep.	12·66068	906 Repsolda	0 17 34·57	—12 44 48·9	+0·14	—3·2
566	Oct.	1·57496	906 Repsolda	0 00 39·17	—13 18 30·0	+0·07	—3·1
567	Mar.	21·68578	914 Palisana	13 45 29·12	—43 38 38·2	+0·12	+1·4
568	Apr.	24·54992	914 Palisana	13 14 29·54	—40 22 20·0	+0·03	+1·0
569	May	2·50647	914 Palisana	13 07 19·80	—38 27 45·4	—0·04	+0·7
570	June	25·65860	925 Alphonsina	19 34 22·59	—30 33 24·0	+0·08	—0·5
571	May	23·63743	926 Imhilde	16 57 17·43	—32 47 07·4	+0·07	—0·2
572	June	4·58206	926 Imhilde	16 44 26·45	—33 57 16·2	+0·02	0·0
573	June	25·52575	926 Imhilde	16 23 26·95	—35 05 24·7	+0·08	+0·2
574	Oct.	8·60750	931 Whittemora	1 26 08·15	—10 44 53·9	+0·05	—3·4
575	Sep.	3·61878	940 Kordula	23 32 43·25	—13 18 47·2	+0·03	—3·0
576	Oct.	1·52472	940 Kordula	23 13 25·68	—14 50 56·5	+0·01	—2·9
577	Sep.	4·53678	952 Caia	22 14 16·00	—24 16 35·5	—0·05	—1·5
578	Sep.	12·55627	952 Caia	22 07 27·77	—24 04 11·3	+0·10	—1·5
579	Sep.	19·51762	952 Caia	22 02 32·06	—23 42 17·2	+0·05	—1·5
580	June	6·63420	972 Cohnia	18 27 18·60	—26 08 48·4	—0·03	—1·2
581	June	19·60896	972 Cohnia	18 16 19·74	—25 48 59·8	+0·04	—1·2
582	July	4·58058	972 Cohnia	18 02 27·72	—25 16 47·8	+0·11	—1·4
583	June	6·59374	976 Benjamina	17 06 18·83	—20 40 30·4	+0·03	—2·0

TABLE I.—*Continued.*

1957 U.T.			Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
584	June	19·57060	976 Benjamina	16 55 51·12	—19 58 08·8	+0·09	—2·1
585	Sep.	16·69286	977 Philippa	1 00 50·39	—16 22 18·6	+0·18	—2·8
586	Oct.	3·64429	977 Philippa	0 47 54·67	—17 31 13·3	+0·20	—2·6
587	July	10·57663	980 Anacostia	19 23 00·76	—20 46 27·6	—0·03	—2·0
588	Aug.	2·49157	980 Anacostia	19 00 03·85	—18 34 55·0	—0·05	—2·3
589	June	25·60081	1010 Marlene	18 22 02·73	—22 53 21·0	+0·05	—1·7
590	July	18·49898	1010 Marlene	18 02 45·05	—23 26 34·1	—0·04	—1·6
591	May	7·56761	1032 Pafuri	15 10 59·34	—10 13 12·9	—0·06	—3·5
592	June	3·50140	1032 Pafuri	14 50 05·81	—10 24 07·5	+0·01	—3·5
593	June	27·52694	1055 Tynka	17 21 04·10	—13 32 10·5	—0·04	—3·0
594	July	15·46565	1055 Tynka	17 08 14·96	—14 39 27·6	—0·05	—2·9
595	May	29·61364	1158 Luda	16 45 12·20	—45 30 24·0	+0·09	+1·8
596	July	4·49784	1158 Luda	16 06 53·12	—43 05 50·7	+0·12	+1·3
597	Sep.	4·63892	1180 Rita	0 04 27·54	—10 24 09·7	+0·03	—3·5
598	Sep.	17·60268	1180 Rita	23 56 34·50	—11 21 58·8	+0·04	—3·4
599	Oct.	2·57701	1180 Rita	23 47 12·35	—12 13 31·6	+0·11	—3·3
600	June	27·65325	1200 Imperatrix	20 06 58·15	—13 10 29·6	0·00	—3·1
601	Feb.	28·64490	1232 Cortusa	11 40 48·37	—14 31 21·6	+0·05	—2·9
602	Mar.	21·57134	1232 Cortusa	11 25 16·87	—13 16 36·2	+0·04	—3·1
603	Apr.	24·63404	1244 Deira	15 02 53·51	—30 27 19·9	+0·08	—0·5
604	June	3·47094	1244 Deira	14 29 12·95	—25 12 11·6	—0·05	—1·3
605	May	9·63894	1281 Jeanne	16 14 20·61	—14 51 16·7	+0·04	—2·8
606	June	19·53208	1281 Jeanne	15 44 04·65	—10 44 32·1	+0·12	—3·5
607	June	25·45986	1281 Jeanne	15 41 56·57	—10 30 33·6	—0·05	—3·5
608	Mar.	26·53601	1284 Latvia	11 31 42·41	—12 18 29·1	—0·05	—3·2
609	Apr.	4·54144	1284 Latvia	11 24 19·74	—11 33 17·4	+0·07	—3·3
610	June	25·65860	1304 Arosa	19 37 15·33	—30 11 59·6	+0·07	—0·6
611	July	3·67615	1304 Arosa	19 30 38·40	—31 13 08·7	+0·08	—0·4
612	May	2·62030	1332 Marconia	14 55 59·52	—18 41 17·6	+0·10	—2·3
613	May	29·51406	1332 Marconia	14 35 25·89	—17 20 20·2	+0·04	—2·5
614	May	7·61650	1336 Zeelandia	16 01 06·99	—17 20 04·7	—0·02	—2·5
615	June	3·54252	1336 Zeelandia	15 38 09·48	—16 30 35·7	+0·03	—2·6
616	Nov.	13·60248	1346 Gotha	3 20 41·56	— 4 39 16·2	+0·09	—4·3
617	Apr.	29·56323	1420 Radcliffe	14 00 59·27	—16 26 17·3	+0·01	—2·6
618	May	2·56231	1420 Radcliffe	13 58 29·45	—16 10 03·3	+0·04	—2·6
619	Apr.	29·56323	1496 Turku	14 00 42·48	—17 20 46·1	+0·01	—2·5
620	May	2·54886	1496 Turku	13 57 37·83	—17 03 11·3	0·00	—2·5
621	May	6·53749	1496 Turku	13 53 40·08	—16 39 09·4	0·00	—2·6
622	May	21·51990	1496 Turku	13 41 42·72	—15 13 07·8	+0·10	—2·8
623	Sep.	4·59651	1550 1937 WD	23 30 18·64	—24 10 44·8	—0·03	—1·5
624	Sep.	12·60324	1550 1937 WD	23 24 03·34	—24 40 21·8	+0·08	—1·4
625	Sep.	30·54568	1550 1937 WD	23 10 54·60	—24 19 45·1	+0·08	—1·5
626	Oct.	2·53132	1550 1937 WD	23 09 50·80	—24 09 29·2	+0·05	—1·5
627	Oct.	23·63464	1568 Aisleen	2 22 15·26	—34 13 56·9	+0·16	—0·1
628	Nov.	11·53578	1568 Aisleen	2 10 42·95	—34 45 20·6	+0·02	+0·2
629	Sep.	19·54597	1585 Union	23 02 48·21	—20 08 25·6	0·00	—2·1
630	Apr.	29·61628	1957 HA	14 24 36·12	—19 39 01·4	+0·13	—2·2
631	Aug.	13·65713	1957 NA	0 07 39·27	—12 36 14·2	—0·11	—3·2
632	Aug.	13·65751	1957 NA	0 07 39·30	—12 36 15·2	—0·11	—3·2
633	Aug.	20·70610	1957 NA	0 20 24·00	—16 24 09·5	+0·08	—2·6
634	Sep.	3·65190	1957 NA	0 31 04·62	—21 46 08·7	+0·01	—1·8
635	Sep.	16·64990	1957 NA	0 29 59·23	—24 08 12·1	+0·12	—1·6
636	Sep.	30·60196	1957 NA	0 24 52·64	—24 12 18·8	+0·10	—1·5
637	Oct.	23·56970	1957 NA	0 22 31·22	—20 34 03·3	+0·20	—2·2
638	Oct.	31·49893	1957 NA	0 24 51·47	—18 42 58·0	+0·04	—2·3
639	Nov.	11·48832	1957 NA	0 30 44·13	—15 55 47·9	+0·08	—2·7

TABLE II.

Comparison Stars	Dependences			
451 Yale *12* I 6987, 7019, *11* 6528	0·44590	0·16668	0·38742	R
452 Yale *12* I 6855, 6864, 6871	0·14443	0·44159	0·41397	S
453 Cape *17* 10752, 10755, 10764	—0·04497	0·49851	0·54646	S
454 Cape *17* 10679, 10681, 10701	0·48608	0·23707	0·27685	W
455 Cape *17* 8820, 8833, 8850	0·31677	0·13388	0·54935	R
456 Yale *13* II 10401, 10439, 10440	0·20791	0·34677	0·44532	W
457 Yale *14* 12760, 12820, *13* II 11985	0·39471	0·24149	0·36380	S
458 Cape *18* 8235, 8269, *17* 8733	0·61973	0·22888	0·15139	W
459 Cape *17* 8585, 8616, 8617	0·47644	0·31676	0·20680	S
460 Cape *17* 11075, 11083, 11097	0·26741	0·52302	0·20957	R
461 Yale *17* 215, 228, 233	0·39703	0·20919	0·39378	R
462 Yale *12* I 5284, 5286, 5297	0·36733	0·46317	0·16951	W
463 Yale *12* I 5262, 5278, 5286	0·17151	0·64808	0·18040	S
464 Yale *12* I 8077, 8080, 8088	0·32552	0·28172	0·39275	R
465 Yale *12* II 9125, 9144, 9153	0·33869	0·46533	0·19598	S
466 Yale *12* II 9098, *13* I 9102, 9115	0·36436	0·17219	0·46346	W
467 Cape *19* 4261, 4277, 4283	0·39530	0·39820	0·20650	S
468 Cape *19* 4237, 4240, 4245	0·39981	0·39403	0·20616	W
469 Yale *21* 483, *17* 579, 596	0·38817	0·27492	0·33691	R
470 Yale *14* 12228, 12248, 12290	0·53215	0·25817	0·20968	S
471 Yale *14* 12065, 12095, 12097	0·69584	—0·07631	0·38047	W
472 Yale *14* 10678, 10696, 10699	0·41575	0·27679	0·30747	W
473 Yale *12* II 6022, 6034, 6040	0·12664	0·49798	0·37538	S
474 Yale *14* 12786, 12816, 12820	0·32795	0·41086	0·26119	S
475 Yale *14* 12653, *13* II 11836, 11873	0·42889	0·33150	0·23961	R
476 Yale *13* II 12372, 12374, 12398	0·43135	0·21678	0·35187	W
477 Yale *14* 13228, 13233, 13268	0·27398	0·38158	0·34444	S
478 Yale *11* 667, 669, 685	0·47276	0·29255	0·23469	W
479 Yale *12* I 727, 737, *11* 643	0·36127	0·30723	0·33150	S
480 Yale *11* 613, *12* I 700, 721	0·18070	0·38530	0·43400	W
481 Yale *12* I 5174, 5185, 5189	0·16318	0·39392	0·44290	S
482 Cape *17* 11643, 11665, 11669	0·36606	0·24100	0·39294	R
483 Cape *18* 10786, 10808, 10813	0·26253	0·50210	0·23537	W
484 Yale *12* I 5139, 5144, 5152	0·45747	0·22246	0·32007	S
485 Yale *13* II 13207, 13240, 13254	0·49888	0·30299	0·19813	S
486 Yale *11* 59, 66, 77	0·38153	0·44474	0·17374	S
487 Yale *12* I 68, 83, 86	0·47318	—0·02658	0·55340	W
488 Yale *12* I 8810, 8820, 8826	0·33760	0·36363	0·29877	W
489 Yale *12* II 6976, 6980, 6981	0·05217	0·84604	0·10179	S
490 Yale *12* II 6894, 6911, *13* I 6897	0·68394	—0·00070	0·31676	R
491 Yale *16* 5089, 5090, 5104	0·18939	0·45612	0·35449	R
492 Yale *11* 4466, 4470, 4474	0·39383	0·29941	0·30676	S
493 Yale *11* 4409, 4418, 4424	0·39427	0·20077	0·40496	S
494 Cape *18* 10310, 10314, 10358	0·50507	0·21330	0·28163	W
495 Cord. D 14217, 14265, 14276	0·33830	0·26435	0·39735	R
496 Cord. D 14190, 14212, 14217	0·26677	0·45768	0·27555	W
497 Yale *11* 5481, 5482, 5484	0·44791	1·35230	—0·80021	R
498 Yale *11* 5444, 5466, 5471	0·35599	0·29262	0·35138	W
499 Yale *13* II 14713, 14720, 14727	0·05768	0·64084	0·30147	W
500 Yale *12* I 311, 324, 326	0·24511	0·22565	0·52924	R
501 Yale *11* 188, *12* I 244, 250	0·21143	0·51773	0·27084	R
502 Yale *11* 174, 183, 188	0·17567	0·45765	0·36668	S
503 Yale *11* 243, 244, 254	0·48145	0·18073	0·33782	W
504 Yale *12* I 5838, 5839, 5850	0·51393	0·13218	0·35389	R
505 Yale *11* 256, 270, 272	0·38745	0·44018	0·17237	R
506 Yale *11* 212, 224, 233	0·33634	0·14750	0·51616	W
507 Yale *17* 8148, 8149, 8157	0·45298	0·17734	0·36968	W
508 Yale *17* 8117, 8118, 8131	0·22630	0·37974	0·39396	S
509 Cord. D 10356, 10384, 10386	0·54213	0·27954	0·17832	R
510 Cord. D 10016, 10033, 10034	1·00698	0·38438	—0·39136	R
511 Yale *14* 15483, 15507, 15514	0·16859	0·39374	0·43767	S
512 Yale *13* II 14544, 14560, 14582	0·27035	0·37041	0·35924	R
513 Yale *13* II 14499, 14513, 14518	0·19335	0·45125	0·35540	W
514 Yale *14* 14390, 14395, 14420	0·19552	0·23590	0·56858	W

TABLE II.—*Continued.*

Comparison Stars	Dependences			
515 Yale *14* 13866, 13895, 13919	0·36781	0·20678	0·42541	R
516 Yale *12* I 6247, *11* 5950, 5967	0·23954	0·16203	0·59843	S
517 Yale *12* I 6167, 6173, 6194	0·14091	0·31701	0·54208	R
518 Cape *18* 9800, 9820, 9858	0·35981	0·28332	0·35687	S
519 Cape *18* 9751, 9783, 9784	0·24578	0·24961	0·50461	W
520 Yale *12* I 4756, 4762, 4777	0·22641	0·35998	0·41360	R
521 Cape *18* 8092, 8109, *17* 8514	0·09013	0·44808	0·46179	W
522 Cape *17* 8269, 8303, 8304	0·60956	0·20267	0·18777	W
523 Yale *13* II 9771, 9778, 9800	0·28217	0·32470	0·39313	W
524 Yale *14* 10933, 10952, 10977	0·29936	0·33245	0·36819	S
525 Yale *12* I 5255, 5260, 5277	0·33358	0·36275	0·30368	R
526 Cord. D 12992, 13026, 13127	0·16828	0·35874	0·47298	W
527 Cord. D 12623, 12725, 12730	0·30937	0·62252	0·06811	W
528 Yale *14* 27, 51, 61	0·19024	0·59103	0·21874	R
529 Yale *14* 15942, 15962, 15964	0·32382	0·28447	0·39172	W
530 Cord. D 11335, 11349, 11369	0·13278	0·67826	0·18895	W
531 Yale *13* I 7530, 7563, 7577	0·29329	0·16800	0·53871	S
532 Yale *17* 8075, 8076, 8089	—0·45250	0·53170	0·92080	R
533 Yale *16* 8294, 8301, 8308	0·38200	0·26772	0·35028	W
534 Cape *18* 5476, 5479, 5492	0·31208	0·50092	0·18700	S
535 Cape *17* 5530, 5537, 5569	0·40472	0·10559	0·48970	W
536 Cape *17* 11610, 11615, 11643	0·55175	0·18244	0·26582	R
537 Cape *18* 10710, 10715, 10730	0·37787	0·13976	0·48237	R
538 Yale *13* I 5827, 5854, *14* 10103	0·34824	0·41340	0·23836	R
539 Yale *13* I 5808, 5815, 5816	0·34772	0·29318	0·35910	S
540 Cord. D 15799, 15800, 15837	0·27443	0·19146	0·53411	S
541 Cord. D 15717, 15744, 15753	0·24188	0·09167	0·66645	R
542 Yale *12* II 4826, 4832, 4843	0·25453	0·50266	0·24281	W
543 Yale *12* I 4755, 4765, 4767	0·24666	0·45374	0·29960	W
544 Yale *12* I 5144, 5151, 5163	0·27417	0·43443	0·29140	S
545 Yale *16* 3849, 3856, 3861	0·38120	0·61998	—0·00118	W
546 Yale *16* 3794, 3816, 3820	0·38121	0·13835	0·48044	S
547 Yale *12* II 7065, 7078, 7079	0·40151	0·26334	0·33516	S
548 Yale *12* II 7011, 7027, 7033	0·40262	0·14900	0·44838	W
549 Cape *17* 11281, 11298, 11316	0·32633	0·15962	0·51405	S
550 Cape *18* 10335, 10352, 10374	0·27271	0·40368	0·32361	R
551 Yale *13* I 8821, 8830, 8834	0·31498	0·27491	0·41011	R
552 Cape *17* 12231, 12258, *18* 11574	0·23776	0·44194	0·32030	R
553 Cape *18* 11346, *17* 12034, 12066	0·55884	0·05262	0·38854	R
554 Yale *12* I 5452, 5458, 5476	0·32287	0·39630	0·28083	R
555 Yale *12* I 5388, 5399, 5402	0·40207	0·31376	0·28417	S
556 Yale *13* II 198, 217, 223	0·25547	0·45513	0·28940	R
557 Yale *13* II 113, 120, 142	0·28560	0·32942	0·38498	W
558 Cape *17* 6604, 6608, 6627	0·10146	0·39081	0·50774	S
559 Cape *17* 6546, 6568, 6585	0·27700	0·42090	0·30209	W
560 Yale *13* II 8182, 8212, 8220	0·42003	0·24810	0·33186	W
561 Yale *14* 9450, 9471, 9498	0·19516	0·79591	0·00893	W
562 Yale *11* 5390, *16* 5396, 5424	0·29481	0·15907	0·54612	R
563 Yale *16* 5306, 5314, 5326	0·26130	0·47043	0·26827	R
564 Yale *11* 59, 69, 77	—0·00895	0·60978	0·39916	S
565 Yale *11* 46, 52, 59	0·30573	0·32687	0·36740	W
566 Yale *11* 8321, 8333, 8337	0·17532	0·69062	0·13406	W
567 Cord. D 9183, 9228, 9238	0·23499	0·54680	0·21821	W
568 Cape *18* 6341, 6378, Ft. 10849	0·23818	0·41250	0·34932	S
569 Cape *18* 6263, 6282, 6298	0·20745	0·32068	0·47188	W
570 Cape *17* 10679, 10680, 10700	0·28764	0·20285	0·50951	S
571 Cape *17* 8914, 8926, 8932	0·26452	0·11540	0·62008	W
572 Cape *17* 8754, 8762, 8815	0·20852	0·39331	0·39817	S
573 Cape *17* 8557, 8578, *18* 8126	0·25522	0·33696	0·40783	S
574 Yale *11* 309, 310, 321	0·31165	0·34063	0·34773	R
575 Yale *12* I 8693, *11* 8223, 8233	0·32116	0·34650	0·33234	S
576 Yale *12* I 8597, 8600, 8609	0·14952	0·14134	0·70914	W
577 Yale *14* 15155, 15163, 15179	0·44686	0·32584	0·22730	S
578 Yale *14* 15096, 15107, 15128	0·30779	0·26506	0·42714	W

TABLE II—*Continued.*

Comparison Stars	Dependences			
579 Yale *14* 15070, 15071, 15088	0·45877	0·30038	0·24085	R
580 Yale *14* 12786, 12820, 12837	0·22379	0·27082	0·50539	S
581 Yale *14* 12667, 12674, 12690	0·27091	0·33557	0·39351	R
582 Yale *14* 12439, 12456, 12463	0·39170	0·44955	0·15875	W
583 Yale *13* I 6977, 7007, 7015	0·31435	0·43762	0·24803	S
584 Yale *12* II 6911, 6926, *13* I 6939	0·49963	0·16489	0·33548	R
585 Yale *12* I 248, 259, 266	0·24749	0·35248	0·40002	R
586 Yale *12* II 193, 217, 227	0·29373	0·53714	0·16913	W
587 Yale *13* I 8285, 8308, 8315	0·49050	0·22436	0·28514	R
588 Yale *12* II 8046, 8058, 8072	0·60366	0·16053	0·23580	S
589 Yale *14* 12757, 12771, 12779	0·88781	0·37626	—0·26407	S
590 Yale *14* 12445, 12447, 12484	0·34118	0·34614	0·31267	W
591 Yale *16* 5306, 5325, 5326	0·42643	0·27108	0·30249	R
592 Yale *11* 5205, 5220, *16* 5216	0·27428	0·45301	0·27271	S
593 Yale *11* 5936, 5945, 5950	0·34466	0·50825	0·14709	S
594 Yale *12* I 6131, 6144, 6160	0·26594	0·45160	0·28246	R
595 Cord. D 11735, 11759, 11817	0·50759	0·16412	0·32829	R
596 Cord. D 11267, 11286, 11311	0·24974	0·51113	0·23912	W
597 Yale *11* 4, 5, 14	0·35176	0·34561	0·30263	S
598 Yale *11* 8304, 8319, 8322	0·32174	0·39966	0·27860	R
599 Yale *11* 8264, 8281, 8282	0·25577	0·49544	0·24879	W
600 Yale *11* 7085, 7095, 7099	0·16600	0·69300	0·14100	S
601 Yale *12* I 4576, *11* 4348, 4356	0·52192	0·15065	0·32743	W
602 Yale *11* 4284, 4288, 4293	0·37659	0·28323	0·34018	W
603 Cape *17* 7800, 7813, 7822	0·40773	0·24104	0·35123	S
604 Yale *14* 10449, 10480, 10496	0·24656	0·46069	0·29275	R
605 Yale *12* I 5903, 5913, 5923	0·34420	0·41661	0·23918	R
606 Yale *11* 5481, 5488, 5496	0·41910	0·19966	0·38124	R
607 Yale *11* 5473, 5481, 5488	0·30610	0·38444	0·30946	W
608 Yale *11* 4303, 4309, 4320	0·32309	0·41696	0·25995	R
609 Yale *11* 4275, 4278, 4291	0·42441	0·08034	0·49525	S
610 Cape *17* 10714, 10719, 10731	0·43365	0·34267	0·22367	S
611 Cape *17* 10631, 10651, 10681	0·32087	0·28906	0·39008	W
612 Yale *12* II 6196, 6215, 6220	0·35765	0·31222	0·33012	W
613 Yale *12* I 5407, 5421, 5428	0·46076	0·21625	0·32298	R
614 Yale *12* I 5847, 5850, 5864	0·22335	0·58222	0·19443	R
615 Yale *12* I 5733, 5740, 5753	0·39542	0·32030	0·28428	S
616 Yale *17* 801, 806, 823	0·27487	0·31591	0·40922	W
617 Yale *12* I 5243, 5261, 5262	0·25873	0·58153	0·15974	W
618 Yale *12* I 5232, 5248, 5260	0·34746	0·57663	0·07591	W
619 Yale *12* I 5249, 5251, 5272	0·04650	0·84492	0·10858	W
620 Yale *12* I 5232, 5246, 5260	0·56428	0·22980	0·20592	W
621 Yale *12* I 5215, 5225, 5232	0·35251	0·26101	0·38648	R
622 Yale *12* I 5158, 5165, 5182	0·25714	0·43392	0·30893	W
623 Yale *14* 15736, 15744, 15757	0·17993	0·40358	0·41649	S
624 Yale *14* 15671, 15686, 15709	0·13486	0·25709	0·60805	W
625 Yale *14* 15586, 15598, 15604	0·41080	0·38776	0·20144	W
626 Yale *14* 15581, 15586, 15598	0·37402	0·36466	0·26132	W
627 Cape *17* 839, 863, 870	0·30155	0·32373	0·37472	W
628 Cape *17* 782, 800, *18* 677	0·50823	0·23500	0·25678	W
629 Yale *13* I 9700, 9703, 9713	0·25734	0·15786	0·58480	R
630 Yale *12* II 6022, 6039, 6052	0·32379	0·51520	0·16101	W
631 Yale *11* 13, 23, 32	0·68004	0·28041	0·03955	W
632 Yale *11* 6, 23, 26	0·30476	0·39849	0·29675	W
633 Yale *12* I 87, 94, 101	0·17592	0·45862	0·36546	R
634 Yale *14* 197, 236, 244	0·10143	0·65416	0·24441	S
635 Yale *14* 216, 218, 239	0·30465	0·43671	0·25864	R
636 Yale *14* 158, 178, 199	0·27546	0·38976	0·33478	W
637 Yale *13* I 83, 85, 100	0·29614	0·41867	0·28519	W
638 Yale *12* II 87, 101, 112	0·35251	0·31001	0·33747	R
639 Yale *12* I 135, 142, 152	0·24590	0·33338	0·42072	W

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SEISMIC TRAVEL-TIMES IN AUSTRALIA

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Abstract.

The travel-times of phases from nine Australian mainland earthquakes are examined. A comparison is made with travel-times found from the 1956 atomic explosions at Maralinga. This indicates that the Maralinga times apply within a few seconds over other parts of Australia.

The *Lg* phase is generally well recorded and travels with a surface velocity near 3·50 km/sec.

1. Introduction

Recent summaries of Australian earthquakes by Burke-Gaffney (1952), Gutenberg and Richter (1954), and Jaeger and Browne (1958), illustrate that the Australian continent is an area of relatively minor seismicity.

While this is the main explanation for the scarcity of seismic information on the Australian crust, there are two special difficulties which have hindered precision in studies of Australian earthquakes. First, until recently, there were few seismological stations on the Australian continent and in the adjacent area. For example, the Central Australian earthquake of 1941 June 27, to which

Table I.

Details of Australian Seismological Stations, 1901–1950.

Station.	Instrument.	Component.	Commenced recording.	Suspended recording.
Adelaide	Milne	E.—W.	1909	1941
	Milne-Shaw	N.—S.	1924	1950
Brisbane	Milne-Shaw	N.—S.	Sept. 1937	
	Milne-Shaw	E.—W.	Sept. 1937	
	Benioff	Z.	Sept. 1943	
	Benioff	N.—S.	Feb. 1944	
Melbourne	Milne	E.—W.	1901	1916
	Milne-Shaw	E.—W.	1931	March 1940
	Milne-Shaw (recommenced)		Jan. 1949	Dec. 1949
Perth	Milne	E.—W.	Sept. 1901	Dec. 1937
	Milne-Shaw	N.—S.	Jan. 1923	
Riverview	Wiechert	N.—S.	March 1909	
	Wiechert	E.—W.		
	Wiechert	Z.		
	Mainka	N.—S.	1910	
	Mainka	E.—W.		
	Galitzin	N.—S.	1941	
	Galitzin	E.—W.		
	Galitzin	Z.		
Sydney	Milne	E.—W.	May 1906	1948

Gutenberg and Richter (*loc. cit.*) have assigned a magnitude of 6½, was recorded at only 6 stations within 20°. It follows that, in studies of such earthquakes, assessment of the reliabilities of near stations is particularly important. In Table I the types and times of operation, ignoring minor suspensions, of the seismographs at the Australian stations between 1901 and 1950 are listed.

It is of historical interest that Sydney Observatory possessed a seismic recorder as early as 1888. Mr. Harley Wood, the New South Wales Government Astronomer, has informed me that in April, 1888, H. C. Russell mentioned installing a Ewing seismograph, although Mr. Wood has never been able to find any records of work produced from it.

The second difficulty is that observations beyond 20° are restricted mainly to northerly azimuths. This difficulty is somewhat offset by *PKP* observations at reliable European and North American stations which allow an almost independent estimate of origin-time t_0.

In spite of these obstacles it has proved possible to make some provisional inferences on Australian travel-times.

2. Revision of Epicentres and Origin-Times.

In all, the nine earthquakes shown in Table II have been examined. Earthquakes I–VIII are listed in the *International Seismological Summary**, but II and V only as undetermined shocks. The Central Australian series are

Table II.
Earthquakes Examined.

Earthquake	Date	Provisional epicentre		Source	Location
I	1929 August 16	16°·3 S	122°·4 E	I.S.S.	N–W Australia
II	1937 October 28	29°·0 S	132°·5 E	B.–G.†	South Australia
III	1937 December 20	25°·8 S	137°·0 E	I.S.S.	Central Australia
IV	1938 April 17	25°·8 S	137°·0 E	I.S.S.	Central Australia
V	1939 March 26	31°·2 S	138°·0 E	G. & R.‡	South Australia
VI	1941 April 29	26°·9 S	116°·3 E	I.S.S.	West Australia
VII	1941 May 4	25°·8 S	137°·0 E	I.S.S.	Central Australia
VIII	1941 June 27	26°·2 S	137°·5 E	I.S.S.	Central Australia
IX	1954 March 1	35°·6 S	138°·5 E	B.C.I.B.S.§	Adelaide

† Burke-Gaffney (1952).
‡ Gutenberg and Richter (1954).
§ Bulletin of the Central International Bureau of Seismology.

interesting. Several were felt in the neighbourhood of the Finke River (de Jersey, 1946) and may indicate tectonic weakness towards the edge of the Pre-Cambrian Shield. The latitudes in Table II are geographic but the geocentric latitudes were used to calculate angular distances $\triangle$.

Revision for all earthquakes except II and III was from the P_n arrival-times, using the Jeffreys-Bullen travel-times||, with ellipticity corrections where needed. Let x° and y° denote the north and east angular corrections needed to the epicentre and Y sec. the increase needed to t_0. Then, for an observation at distance $\triangle^\circ$ and azimuth α° from the trial epicentre of a shallow focus earthquake,

$$Y-(dt/d\triangle)(x\cos\alpha+y\sin\alpha)=\mu, \quad \ldots\ldots\ldots\ldots \quad (1)$$

where t is the P_n travel-time, and μ is the P_n residual.

* Abbreviated hereafter to I.S.S.

|| Referred to hereafter as the J.-B. tables.

For groups of observations with small variation in $dt/d\triangle$ and α, mean values of $dt/d\triangle$, α and μ were taken after dropping large unsupported residuals. Details of the solutions for V and IX have already been published (Bullen and Bolt, 1956; Bolt, 1956) and these illustrate the general method followed.

The corrections to the provisional solutions are given in Table III. n is the total number of reported P_n observations available and n' is the number used in forming the equations of condition.

TABLE III.

Revision of epicentres and origin-times.

Earth-quake	n	n'	Corrections		Revised origin-time			Magni-tude*
			$x°$	$y°$	h	m	s	
I	15	11	—0·66±0·06	—1·49±0·13	21	28	22·2±0·8	6¼
II	10	—	—2·85	+4·00	9	34	43	—
III	9	—	+0·35	—0·50	22	35	2	5½±
IV	24	18	+0·30±0·10	+0·22±0·08	8	56	21·6±0·3	6
V	14	9	—0·79	—0·03	3	56	5	5½
VI	54	32	+0·09±0·05	—0·17±0·07	1	35	40·9±0·6	6¾
VII	13	13	—0·50±0·09	—0·13±0·15	22	7	29·8±0·7	5·3—5·9
VIII	48	38	+0·48±0·15	+0·32±0·15	7	55	50·7±0·4	6½
IX	12	8	+0·75	+0·16	18	9	52	—

* As given by Gutenberg and Richter (1954).

Formal standard errors are given for the larger shocks I, IV, VI, VII and VIII to allow comparison between the revisions. However, because of the difficulties mentioned in Section 1 and the likelihood of significant deviations of Australian travel-times from the assumed J.–B. times (*cf.* Section 4) these errors are underestimates.

Revised residuals for reported S_n phases were also calculated. In general they showed considerable scatter about zero for all epicentral distances, but in every case gave some support for the revision. Additional notes on five earthquakes with special features are given in the following sections.

2. 1 *The* 1937 *October* 28 *earthquake.* No solution for this earthquake is given by the I.S.S. or Gutenberg and Richter; Burke-Gaffney (*loc. cit.*), from data at Adelaide, Brisbane and Riverview, places the epicentre near the central west of South Australia. However, the similarity in appearance between the Riverview and Adelaide records of this shock and those of the Finke River shocks IV, VII and VIII suggests that it also occurred in the Finke region.

Trial calculations showed that a solution giving agreement with all nine onsets identified in the I.S.S. as P_n is impossible. Subsequent examination indicated that the P_n identifications on the Perth and Melbourne records were very doubtful. Ignoring these readings, an assumed epicentre at 26°·0S, 136°·5E (geocentric latitude) and an origin-time of 9h 34m 43s agreed well with the P_n and S_n arrival-times at Adelaide and Amboina as well as the impetus P onsets at the North American stations. Residuals using the new solution are shown in Table IV. (The adopted S_n phase at Perth is given in the I.S.S. as SSS.) There is other support for the suggested easterly shift of epicentre. The vertical component Wiechert record at Riverview has an *emersio* onset at 9h 38m 17s as large as that reported at 9h 40m 36s and the corresponding residual, shown in brackets, agrees well with P_n. Also, while Mr. Spigl, at Perth Observatory,

TABLE IV.

P, PKP and S residuals, assuming solution as 26°·0 *S*, 136°·5 *E*, t_0=9*h* 34*m* 43*s*.

Station.		Observed P or PKP		O.—C.	Observed S		O.—C.
		m.	s.	s.	m.	s.	s.
Adelaide	8°·88	*i* 2	15	+2	3	51	—4
Melbourne	13°·66	—	—	—	5	45	—5
Brisbane	14°·80	—	—	—	6	29	+11
Riverview	14°·82	. (3	34)	(+2)	6	28	+9
Perth	18°·94	—	—	—	7	44	+10
Amboina	23°·71	5	11	—3	9	29	+2
Ksara	112°·38	*e* 14	23	—18	—	—	—
Pasadena	116°·22	*i* 18	43	—2	—	—	—
Mount Wilson ..	116°·31	*i* 18	44	—2	—	—	—
Riverside	116°·93	*i* 18	45	—2	—	—	—
Williamstown.. ..	150°·66	*i* 19	51	+3	—	—	—
Oak Ridge	151°·84	*i* 19	54	+4	—	—	—
Weston	152°·04	*e* 19	50	0	—	—	—

informed me that he could " find no macroseismic data on the earthquake amongst our cuttings ", a report in the *Adelaide Advertiser* (30th October, 1937) suggests that " the tremor occurred about 700 miles from Adelaide, possibly in New South Wales ".

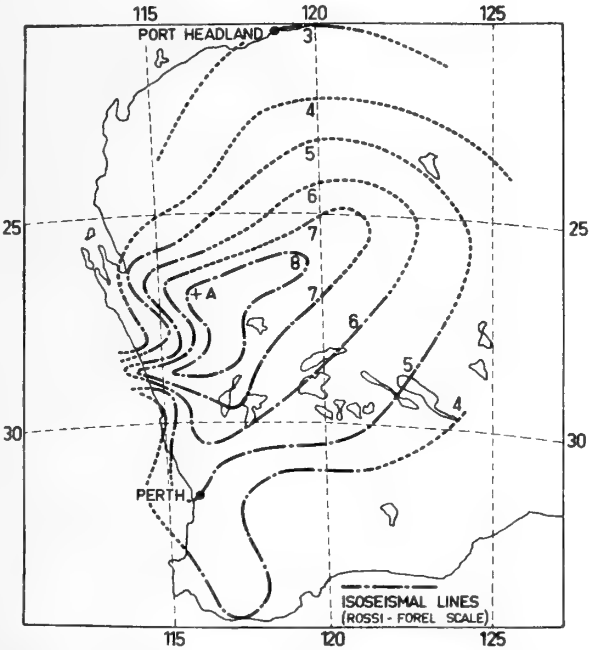

Figure 1.—Isoseismal map of the 1941 April 29 earthquake.

2. 2 *The* 1937 *December* 20 *earthquake.* *P* phases were recorded at only 6 stations and *PKP* at only 3. The shock was not recorded at Brisbane or Perth, but the Riverview and Adelaide P_n onsets are clear. When the epicentre

adopted for II and an origin-time of 22h 35m 2s, were tried as a solution, the P_n residuals gave $\sigma=0\cdot81$ sec. as the standard error for one observation, compared with $\sigma=1\cdot98$ sec. for the I.S.S. solution. Again the uncertainties are underestimated but the formal reduction in σ is taken to be genuine.

2. 3 *The* 1941 *April* 29 *earthquake.* This has special interest as the only recorded inland Australian earthquake with appreciable focal depth. It was widely felt in Western Australia, and Mr. Spigl has kindly supplied an isoseismal map (Figure 1), drawn at the Dominion Observatory, Wellington, from data collected in 1941.

A surface focus was assumed in the I.S.S. solution, but there are the usual characteristics of depth, namely *pP* phases, negative *PKP* and *SKS* residuals, and dependence of P_n residuals on distance. Therefore, in the revision, equation (1) was modified by including a term $z(dt/dz)$ on the left, where $6338z$ km is the required increase in focal depth ; the J.–B. tables for depth 0·00 were used.

An equation of condition for *PKP* was included with those for *P*, and the least squares solution was

$x=+0°\cdot09\pm0\cdot05$, $y=-0°\cdot17\pm0\cdot07$, $z=-0\cdot00013\pm0\cdot0007$,
$t_0=$1h 35m $40\cdot9\pm0\cdot6$s, and $\sigma=1\cdot08$ sec.

This solution, which corresponds to point A on Figure 1, gives a rounded P_n residual at Perth ($\triangle=5°\cdot13$) of 0 sec. compared with +3 sec. in the I.S.S. solution. The focal depth corresponds to $32\cdot2\pm4\cdot2$ km and is supported by a mean *SKS* residual of $+0\cdot7\pm1\cdot00$ sec. from 10 observations.

The revised residuals of the recorded *pP* and *sP* phases are listed in Table V.

TABLE V.

pP and sP residuals, assuming epicentre A.

Station.	△	O (*pP*) m.	O (*pP*) s.	O.—C. s.	O (*sP*) m. s.	O.—C. s.
Adelaide	20°·90	4	56	+5	(4 56)	+1
Riverview	30°·97	*i* 6	29	+3	(6 29)	—1
Medan	34°·60	6	57	—1	—	—
Manila	41°·44	*i* 7	54	—1	7 57	—2
Christchurch	48°·21	8	53	+4	(8 53)	0
Wellington	49°·84	9	04	+2	(9 04)	—2
Tuai	51°·84	9	22	+5	(9 22)	+1
Kodaikanal	52°·55	*e* 9	22	0	—	—
Calcutta	55°·94	9	48	+1	—	—
Bombay	61°·86	10	28	0	—	—
Vladivostok	71°·14	11	25	—2	—	—
Sapporo	73°·35	11	39	—1	—	—
Samarkand	80°·43	12	21	+1	—	—
Tashkent	80°·48	*i* 12	19	—1	—	—
Baku	90°·80	—	—	—	*e* 13 18	+3

Geographically the stations fall into two groups : Group I consists of Adelaide, Riverview and the three New Zealand stations, Group II of the remaining stations to the north-west. If the phases for both groups (except Baku) are interpreted as *pP*, the group mean residuals are $+3\cdot8\pm1\cdot4$ sec. and $-0\cdot4\pm0\cdot9$ sec., respectively. The difference, $4\cdot2\pm1\cdot1$ sec., which appears significant, may be possibly explained in terms of a probable greater crustal thickness under Australia than under the Indian Ocean. Alternatively, if the phases in Group I are *sP* the mean residual becomes $-0\cdot20\pm1\cdot2$ sec. and the difference with the Group II mean is not significant.

2. 4 ***The* 1954 *March* 1 *earthquake.*** This earthquake occurred within a few miles of Adelaide (Bolt, 1956) and detailed macroseismic data obtained by Kerr-Grant (1956) give some check on the epicentral position. Travel-times for phases recorded from it may have probably higher precision than those from other earthquakes studied here. Some additional data have lately become available. First, work by Burke-Gaffney and Bullen (1957) in another context has drawn my attention to a phase recorded at Kimberley on March 1 at 18h 22m 57s. The corresponding values of $\triangle$ and the P_n residual from the revised solution are $91°\cdot03$ and -2 sec ; the latter gives some support from an azimuth previously not available.

Secondly, the Melbourne Wood-Anderson and Milne-Shaw seismograms are reproduced in Kerr-Grant's paper. An examination verifies the times of onsets at Melbourne used in the revision and shows also a clear onset (where the traces become discontinuous) at 18h 12m 56s. This will be referred to in Section 4.

2. 5 *The* 1941 *May* 4 *earthquake.* The Adelaide record of this earthquake shows three aftershocks. The third, of almost equal magnitude to the main shock, was also recorded at Riverview and Brisbane where onset times after 23h from the station bulletins are :

Riverview	(1) 27m 29s (*e*),	(2) 30m 6s (*i*),
	(3) 30m 22s (*i*),	(4) 31m 32s (*i*).
Brisbane	(1) 27m 51s (*eN*),	(2) 29m 54s (*iN*).

Assuming this aftershock to have the same epicentre as the main shock and an origin-time of 23h 23m 57s (which makes the Adelaide P_n residual zero), these onsets can be associated with the following particular phases, residuals against the J.–B. Tables being also given :

Riverview $\triangle=14°\cdot48$ (1) P_n+4s, (2) S_n-6s, (3) $SS-2$s.

Brisbane $\triangle=14°\cdot48$ (2) S_n-14s.

The Riverview *impetus* onset (4) corresponds to a wave with a surface velocity of $3\cdot53$ km/sec (*cf.* Section 3). These results suggest that the third aftershock may have had nearly the same epicentre as the main shock.

3. *Lg* and *Rg* Phases.

An important consequence of the above revisions was that they revealed the existance of *Lg* and *Rg* phases on records of Australian earthquakes. The *Lg* phase was clear on the Riverview records of all earthquakes in Table II except 1929 August 16, a marginal earthquake off the north-west coast, but the *Rg* phase was clear only for 1941 May 4 and 1954 March 1. Tracings of the Riverview Galitzin records for 1954 March 1 are shown in Figure 2. It may be seen that the *Rg* displacement is in the vertical plane. (For Riverview $\alpha\approx85°$.)

Excluding shock II, 20 observations at Riverview from the remaining earthquakes on both vertical and horizontal components give a mean *Lg* velocity of $3\cdot50\pm0\cdot07$ km/sec. The mean *Rg* group velocity is $3\cdot03\pm0\cdot07$ km/sec from three observations (Bolt, 1957).

Shock II was excluded because of the degree of uncertainty of its epicentre. However, on the revised solution, the arrival-times at Riverview, Brisbane and Melbourne, quoted in the I.S.S. as 9h 42m 31s (*iSN*), 42m 30s (*iSEN*), 41m 55s (*S*), correspond to surface velocities of $3\cdot52$, $3\cdot50$ and $3\cdot52$ km/sec, respectively. Other examples may be found in the I.S.S. where the more energetic *Lg* phase has been identified at Australian Stations as *S* on records of Australian earthquakes.

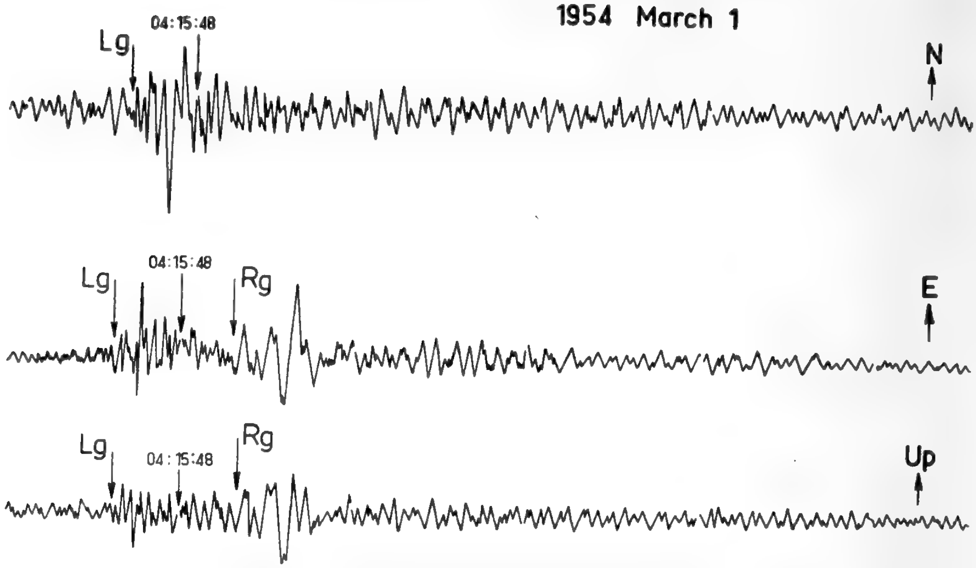

Figure 2.—Riverview Galitzin records showing *Lg* and *Rg* phases from the Adelaide earthquake 1954 March 1. The interval between the time-breaks is 1 min.

4. Phases from Australian Earthquakes.

The Adelaide seismograms ($\triangle \approx 9°$) of the Finke River earthquakes III, IV, VII and VII (aftershock) give some information on near-earthquake phases. [The epicentral determination of II is relatively too uncertain for this earthquake to be used and the Adelaide seismogram of VIII is not available. V($\triangle \approx 3°$) has already been discussed (Bullen and Bolt, *loc. cit.*)]. No great precision is claimed for the following results since, in addition to the uncertainties in the epicentral determinations, the Milne-Shaw instrument's slow drum rate ($<$8mm/mn) makes the reading of near-earthquake phases difficult.

The Adelaide records of the 4 earthquakes were read independently by Fr. Burke-Gaffney, Mr. P. F. Rheinberger and the writer. Taking the observed arrival-times of P_n as zero the arrival-times of onsets agreed on within 2 sec. by all observers are summarized in Table VI.

Table VI.

Arrival-times of prominent phases (after observed P_n).

Earthquake	$\triangle$	Q_1 s.	Q_2 s.	Q_3 s.	Q_4 s.	Q_5 s.
III	8°·88	93	—	119	138	155
IV	9°·48	92	113	117	147	155
VII	8°·76	98	—	116	—	—
VII after-shock	8°·76	94	—	120	—	—

The Table shows that the observed phases fall into 5 groups which are denoted by Q_1, Q_2, Q_3, Q_4 and Q_5.

Travel-times for south-west Australia, obtained from the 1956 atomic explosions at Maralinga, have now been published (Bolt, Doyle and Sutton, 1958). The experiment shows the occurrence of four main phases, called P_n, P_1, S_n, S_1. The surface velocities of P_n and S_n are $8 \cdot 21 \pm 0 \cdot 005$ and $4 \cdot 75 \pm 0 \cdot 01$ km/sec. respectively, both significantly higher than the corresponding velocities from the J.–B. tables, namely $7 \cdot 76 \pm 0 \cdot 03$ and $4 \cdot 36 \pm 0 \cdot 02$ km/sec, respectively. The phase S_1, velocity $3 \cdot 55 \pm 0 \cdot 04$ km/sec, carried energies comparable with S_n and was suggested to be related to *Lg*.

There is evidence from arrival-times of phases from some earthquakes revised above that the Maralinga travel-times apply fairly well in other regions of Australia. For example, the times after P_n of the phases Q_1 and Q_5 from the Finke River shocks agree within the uncertainties with the calculated times for S_n and S_1, tabulated as follows:

Earthquake	$\triangle$	$S_n - P_n$	$S_1 - P_n$
III	8·9	96	152
IV	9·5	102	162
VII	8·8	95	
VII after-shock	8·8	95	

The phases Q_2, Q_3 and Q_4 remain unexplained (Q_3 are about 8 sec. later than the calculated *SS*) but, considering the tectonically complicated region involved, they may be genuine.

Also in agreement is the prominent phase, tentatively called S^* (Bullen and Bolt, *loc. cit.*), which arrived 48 sec. after P_n on the Adelaide record of shock V. The $S_1 - P_n$ interval at $\triangle = 3^\circ \cdot 0$, from the Maralinga times, is 46 sec.

Certain phases recorded at Melbourne, Brisbane and Perth from the 1954 March 1 shock also travel with close to the Maralinga velocities. This is illustrated in the following table:

TABLE VII.

Arrival-time		Observed Travel-time	Calculated Travel-time
Melbourne, $\triangle = 5^\circ \cdot 9$.			
P_n	18 h. 11 m. 20 s.	1 m. 28 s.	1 m. 27 s.
S_n	12 m. 25 s.	2 m. 33 s.	2 m. 32 s.
S_1	12 m. 56 s.	3 m. 4 s.	3 m. 4 s.
Brisbane, $\triangle = 14^\circ \cdot 4$.			
P_n	18 h. 13 m. 16 s.	3 m. 24 s.	3 m. 22 s.
S_n	16 m. 14 s.	6 m. 22 s.	5 m. 51 s.
S_1	17 m. 20 s.	7 m. 28 s.	7 m. 30 s.
Perth, $\triangle = 19^\circ \cdot 3$.			
S_1	18 h. 20 m. 11 s.	10 m. 19 s.	10 m. 6 s.

The anomalous onset at Brisbane tabulated above as S_n also has a large residual (+14 sec.) against the corresponding J.–B. time. Two inferences of practical importance to future studies of local records of Australian earthquakes follow. First, the phase S_1 (or *Lg*) is likely to be prominent; secondly, S_n may be less definitely identifiable than S_1. When S_n and S_1 are satisfactorily identified, the results suggest the use of the Maralinga times to estimate epicentral distance from $S_n - P_n$ and $S_1 - P_n$ intervals.

Acknowledgements.

I am indebted to the Directors of the various Australian stations who kindly supplied records and information; and especially to Fr. T. N. Burke-Gaffney and Mr. P. F. Rheinberger of Riverview Observatory for helpful discussions.

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AN INVESTIGATION OF METAL GLUCONATE COMPLEXES.

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(Communicated by Professor D. P. Mellor)

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Abstract.

The behaviour of metal ions in the presence of gluconic acid or its salts has been studied by various workers (see list of References). In this further study, we have applied the techniques of paper chromatography, electro-chromatography, spectrophotometry and electrometric titrations.

1. Electro-Chromatograms.

Approximately 0·05 ml. of molar and deci-molar metal nitrate solutions were placed in the centre of strips of filter paper previously moistened with a carrier electrolyte. The moist paper was clamped between two glass plates and the two ends of the paper strip were immersed in reservoirs of the carrier electrolyte. A potential of 3 volts/cm. was applied along the length of the papers for one hour and the movement of the metal ions in this field was detected by developing the papers with a suitable colorimetric reagent. The carrier electrolytes used were 0·5 molar solutions of either potassium nitrate, gluconic acid or sodium gluconate containing a little free alkali. In a second series of tests ethanol (1 : 1) was included in the solvent.

The results obtained by using deci-molar spots of metal nitrate solutions are shown diagramatically in Figure 1. The relative movement of the compounds towards the electrodes is indicated by the distance between the leading edge of the symbol (□) and the starting line, while the enclosed area indicates the comparative diffusion of the original spot. Molar " spots " exhibited similar movement with greater diffusion.

The addition of ethanol restricted movement by reducing the solubility of the salts. In another series of tests nitric acid was added to the potassium nitrate electrolyte to give a solution of pH3 and the cations moved as compact zones under these conditions. At a pH of 3 the cations of iron and bismuth migrated a distance similar to other ions in the series yet in the neutral solution (shown in Fig. 1) little movement was observed due to hydrolysis and sorption of the " spotted " salt.

In the presence of potassium nitrate, movement can be attributed to the migration of the hydrated cation. The substitution of a complexing agent as the carrier electrolyte provides an excess of reagent to react with the metal salt and the observed movement may then be due to either simple or complex ions.

The reduced movement of most metal ions in the presence of gluconic acid (*cf.* Fig. 1) can be attributed to the formation of a cationic complex of low charge

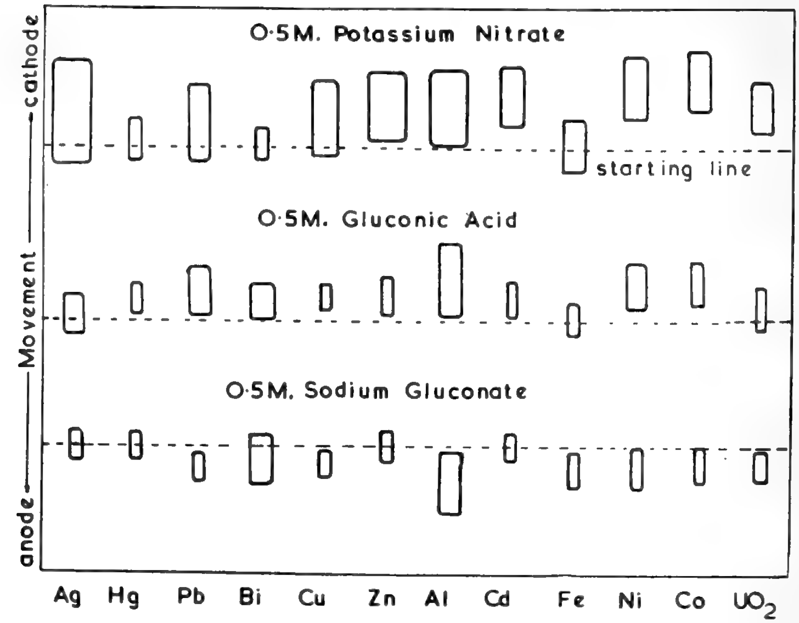
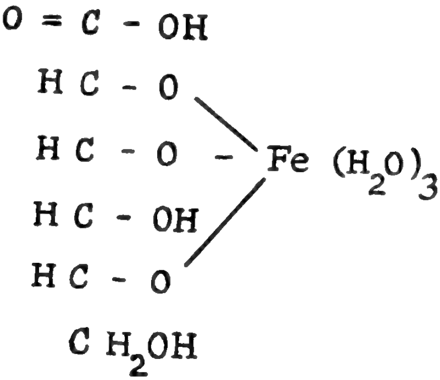


Figure 1.—Paper Electrochromatography. Effect of carrier electrolyte on the movement of 0·1 M. metal salts.

e.g. PbG^{+} (where G represents the gluconate ion). The immobility of ferric ions in the gluconic acid solution of pH 2·5 indicates the presence of an uncharged complex. The existence of such an uncharged molecule, Formula I, has been



(I)

recorded by Pecsok and Sandera (1955). The small movement observed for silver could be due to a tendency to form an uncharged complex or compound. The change of carrier electrolyte had little effect on the movement of mercuric and aluminium ions and hence it could be suggested that these ions have little tendency to form gluconate complexes in acid solutions.

In alkaline sodium gluconate solutions the direction of movement shows that anionic complexes are formed by lead, bismuth, copper, aluminium, iron, nickel, cobalt and uranyl nitrates. No movement was observed with the salts of silver, mercury, cadmium and zinc. This could be due to the formation of an uncharged ion but precipitation of a metal compound is a more probable explanation, since dark precipitates were observed with silver and mercury salts and white precipitates with zinc and cadmium salts were detected in other tests. When lead and bismuth salts were spotted on the paper, a white precipitate was formed, but this disappeared during the application of the applied voltage indicating that the precipitated species was soluble in excess reagent.

II. Paper Chromatograms.

Approximately 0·02 ml. of either molar or deci-molar solutions of twelve metal nitrates were placed near one edge of rectangular strips of Whatman No. 1 Filter Paper. These paper strips were suspended in enclosed glass vessels

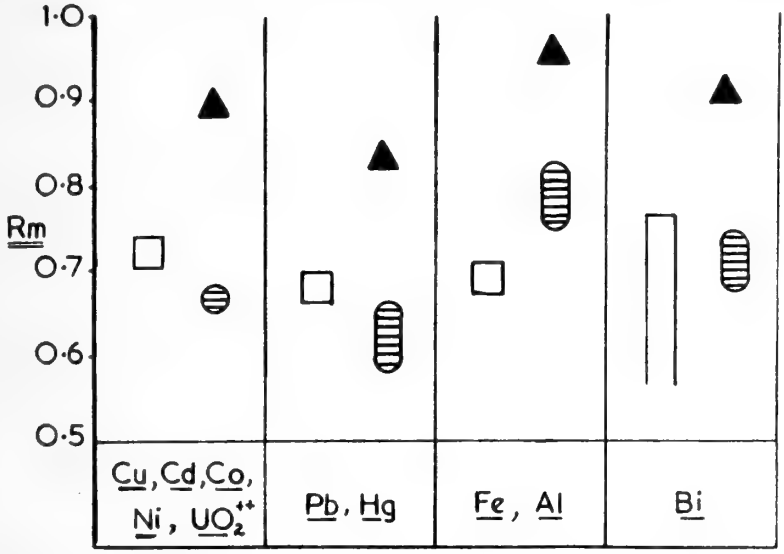


Figure 2.—The relative movement of spots of deci-molar metal nitrate solutions when developed with aqueous acid solvents. Solvents used were 0·1 N. nitric acid (□), 0·1 M. gluconic acid (⊜) and 0·5 M. gluconic acid (▲). Elongated symbols indicate marked tailing of the spots. Each ion in the group acted similarly.

with the " spotted " edge dipping into an aqueous solution. The liquid was allowed to ascend the paper strip to a chosen height and the new location of the metal ions was determined by treating the paper with suitable colorimetric reagents.

The solvents used to develop the chromatograms were 0·1 and 0·5 molar solutions of either gluconic acid or sodium gluconate containing a little free alkali. The observed movements of the cations have been summarised in symbolic form in Figures 2 and 3. The movement of the same cations in acid and alkaline conditions in the absence of the complexing agent has been included for comparison purposes.

It can be seen that the presence of gluconic acid or sodium gluconate produced a marked increase in the movement of the metal ions. This increase in mobility indicates the formation of a new species which has a greater solubility in the moving aqueous phase. For example, alkaline solvents normally precipitate the metal hydroxides near the starting point of a chromatogram, yet in the presence of sodium gluconate the metal ions were detected near the solvent front. Under these latter conditions the metal ions have obviously been converted into a water-soluble complex. The high Rf values suggest that the complexes are only weakly absorbed by the paper.

Earlier studies with solvents containing complexing agents have indicated that an excess of complexing agent in the solvent is desirable if the metal ion is to be transported as a compact spot. With dilute solutions of complexing agent, the solvent front may advance a considerable distance before all the spotted solute is converted to the complex. If the ionic species differ greatly in solubility or absorbability, the resultant spot may tail extensively and the

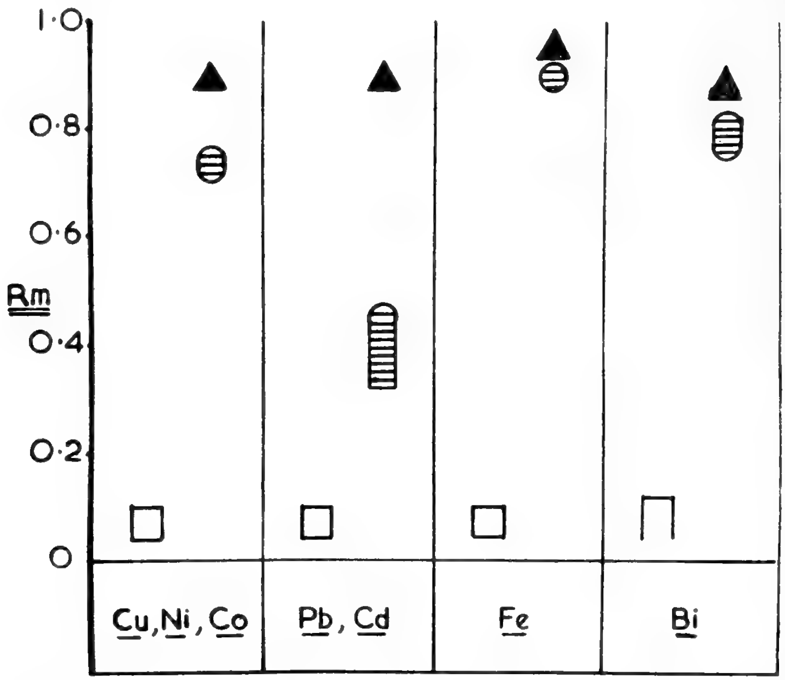


Figure 3.—The relative movement of spots of deci-molar metal nitrate solutions when developed with aqueous alkaline solvents. Solvents used were 0·1 N. sodium hydroxide (□), 0·1 M. sodium gluconate (⊜) and 0·5 M. sodium ion in (▲). Elongated symbols indicate marked tailing of the spots. Each ion in the group acted similarly.

general movement may be greatly affected. The tailing effect is magnified if the complex formed is relatively unstable since the complex will dissociate during the development of the chromatogram as metal ions are adsorbed by the paper (Pickering, 1953, 1956 ; Pickering and Jacobs, 1955).

Reference to Figures 2 and 3 shows that the substitution of 0·1 M. gluconic acid (pH 2·5) for 0·1 N. nitric acid (pH 1) in the solvent caused most of the cations to be transported slightly smaller distances. This could be due to fewer hydrogen ions being available for competitive adsorption on the paper. The increased movement of ferric and aluminium ions and the reduced tailing of the bismuth salt strongly suggest the formation of water-soluble complexes by these ions. The behaviour of lead and mercury could indicate that the complex formed is less soluble than the nitrate or that the complex is relatively unstable. Increasing the concentration of gluconic acid to 0·5 Molar (pH 2) caused all the cations to move as compact spots near the solvent front. This can be interpreted in terms of a displacement of the cations by the higher concentration of acid (*i.e.* assuming that the paper acts as an adsorption column) or it could indicate that the cations tend to form highly soluble complexes in the presence of excess reagent.

In alkaline solution (Figure 3) the increased movement is most logically interpreted in terms of complex formation. The behaviour of lead and cadmium ions indicates the formation of a slightly soluble product which is soluble in excess reagent. The movement of the ions of silver and mercury has not been shown on the diagram since the presence of sodium gluconate appeared to have little effect apart from partially reducing the degree of tailing. These salts formed dark stains on the paper which could indicate alkaline decomposition of the salt. The increased movement of aluminium and uranyl ions has not been tabulated since this movement can also be attributed to reaction with the alkali, *e.g.* the formation of sodium aluminate.

Molar spots of the metal ions behaved similarly to the deci-molar reagents, but the degree of diffusion of the spots during development was much greater.

III. Spectrophotometric Studies.

The spectral transmittance curves of the coloured complexes of iron, copper, nickel, cobalt and uranium were determined in the presence of varying proportions of metal nitrate, gluconic acid and excess of alkali.

The presence of an equivalent amount of gluconic acid in solutions containing copper, nickel, cobalt and uranyl nitrates caused no variation in the spectral transmittance curves of these salts. Increasing the proportion of gluconate ion (*e.g.* by partial or complete neutralisation of the acid) caused intensification of the colour together with changes in the position of regions of maximum and minimum absorbance. The maximum colour intensity was obtained in solutions containing excess gluconate and some free alkali.

Under these conditions the copper salt formed an intense blue solution and cobalt a yellowish brown compound. The colour changes with nickel and uranyl ions were less marked, the peak wave lengths moving approximately 30 mμ towards the red end of the spectrum upon intensification.

The addition of ferric salts to a gluconate solution resulted in a large intensification of the ferric colour, the wave length of maximum absorption varying with the relative concentrations of reactants present. In alkaline solution large excesses of gluconate caused a fading in colour.

The variation in colour of these metal gluconates with changes in conditions suggests that the cations are capable of forming a series of complex salts and indicates that the coloured gluconates could not be readily applied in colorimetric analysis.

The gluconate complexes of copper and iron have been studied in detail by Pecsok and Juvet (1955), and by Pecsok and Sandera (1955), and the spectral transmittance curves of these complexes were shown to vary greatly with changes in the pH of the solution.

IV. Electrometric Titrations.

200 mls. of a solution containing one milli-mole of gluconic acid were titrated with molar solutions of metal nitrate. The conductance of the solutions during titration was determined and the observed changes have been summarised and recorded in Figure 4. For simplicity titrations having similar conductance changes have been grouped together.

A small but distinct break can be observed in these curves at a point corresponding to the addition of an equivalent amount of metal nitrate to the gluconic acid. This indicates that most of the metals examined tend to form 1 : 1 complexes. The changes in conductance obtained when the metal nitrates were added to water only (shown as dotted lines on Figure 4) show that the second portion of the titration curves was due to an excess of the metal salt.

There was no indication of any reaction between gluconic acid and silver, mercury and zinc nitrates but Cannan and Kibrick (1938) report a zinc complex having a log stability constant value of 1·70.

It has been demonstrated (Pecsok and Sandera, 1955) that protons are liberated during the formation of ferric gluconate. In slightly acid conditions this compound is uncharged and hence the first portion of the iron titration

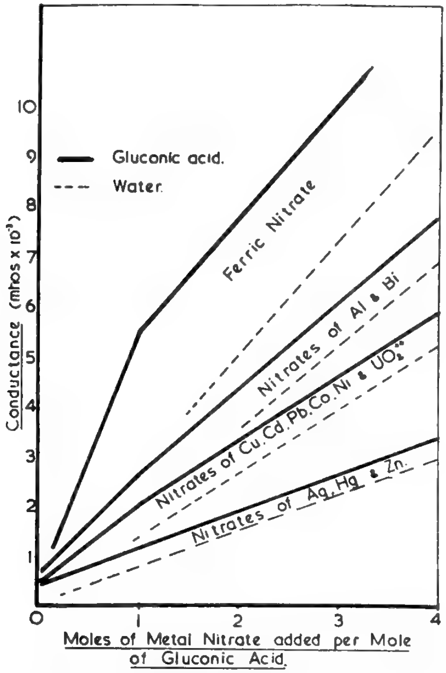


Figure 4.—Conductometric titration of 0·01 M. gluconic acid with metal nitrates.

curve can be attributed to the protons liberated during complex formation. From comparative tests with nitric acid, the increase in conductance was calculated to be equal to that expected from the liberation of two protons per mole of complex formed.

The increase is conductance observed during other titrations, prior to equivalence point, is not sufficiently large to support the theory that a proton is liberated during complex formation. It appears that these metals in acid solution tend to form a compound which does not involve the liberation of a proton from the gluconic acid. The slight increase in conductance could be due to increased ionisation of the acid group resulting from the co-ordination of the metal to the gluconic acid molecule. In acid solution a weak chelate species which does not involve proton liberation has been predicted for copper gluconate (Pecsok and Juvet, 1955). In the pH range of 1 to 6, lead was found to form a 1 : 1 species with a pK value of 2·6 (Pecsok and Juvet, 1956).

In alkaline solutions hydroxyl ions may also enter the complex. This effect was examined by titrating solutions containing one milli-mole of sodium gluconate and a known excess (10 to 15 mls.) of standard 0·1 N. sodium hydroxide with metal nitrate solutions. Titrations of one milli-mole of metal nitrate with alkaline sodium gluconate were also carried out. The pH and conductance of the solutions were determined during the titrations and the results obtained are summarised in Figures 5 and 6. The changes in pH have been plotted against the ratio of the number of milli-moles of excess NaOH in the original solution divided by the number of milli-moles of metal salt added. Each curve is the mean of at least three forward titrations and one reverse titration. Some of the corresponding conductivity curves are shown in Figure 5.

With the exception of titrations involving the nitrates of copper, iron, aluminium and uranium, precipitates were observed during the alkaline titrations. In the titration of nickel and cobalt ions, the solution became turbid after the ratio of metal ion added to gluconate present slightly exceeded unity. In titrations of gluconate with lead nitrate solutions, a precipitate was observed when the pH of the solution lay between 6 and 10. A precipitate was present during all stages of the titrations involving cadmium, zinc and bismuth salts.

The number of hydroxyl ions involved in the formation of the anionic complexes can be predicted from the results shown in Figures 5 and 6. Using the nitrates of cadmium, cobalt, zinc, nickel, lead and copper as the titrant, the equivalence point of the conductometric titrations was found to correspond to the removal of 1·5 hydroxyl ions per mole of metal salt added. Another slight break at 2·0 hydroxyl ions was also observed for copper and lead.

The pH titration curves had sloping rather than vertical sections in the vicinity of equivalence point. From the position of this slope it appears that these metals tend to form complex compounds requiring two hydroxyl ions (the affinity increasing in the order Cd, Zn, Co, Ni, Pb, Cu), but as the concentration of free hydroxyl ions becomes smaller, these complexes revert to the form requiring 1·5 hydroxyl ions per mole of metal salt. Pecsok and Juvet (1955) clearly demonstrated the existence of two such complexes for copper ; Formula II was predicted to exist in solutions of $pH > 9$ and Formula III was predicted for alkaline solutions of $pH < 9$.

Conductimetric titrations with the nitrates of iron, aluminium, bismuth and uranium indicated that initially three hydroxyl ions are taken up in complex formation. Poorly defined breaks were observed at lower values of hydroxyl requirement. The rate of change of pH in these titrations is fairly gradual which could indicate a change of species with pH. Such changes have been demonstrated with ferric gluconates (Pecsok and Sandera, 1955).

The nature of the complexes formed in alkaline solutions is difficult to predict. Structures have been suggested for gluconate compounds with aluminium (Baronnet, 1948), iron (Baronnet, 1948 ; Pecsok and Sandera, 1955), copper (Pecsok and Juvet, 1955), lead (Pecsok and Juvet, 1956) and antimony (Patra and Pani, 1955). The suggested mode of attachment of the metal ion varies in each case and involves the removal of one or more protons from the gluconate ion. The fractional hydroxyl ion requirement found for some copper complexes was explained by the formulation of dimer structures (II, III).

In titrations of alkaline gluconate with cadmium, zinc, nickel and cobalt nitrates, excess hydroxyl ions were removed during the reaction but the final solutions remained slightly alkaline. This could be taken to indicate that the hydroxyl ions are co-ordinated with the metal and are not neutralised by displaced protons. Such hydroxy compounds of metals have previously been suggested as integral parts of the complexes formed in alkaline solutions by hydroxy acids (Hayek *et al.*, 1949) and polyhydric alcohols (Hayek *et al.*, 1949 ; Kuloto, 1940).

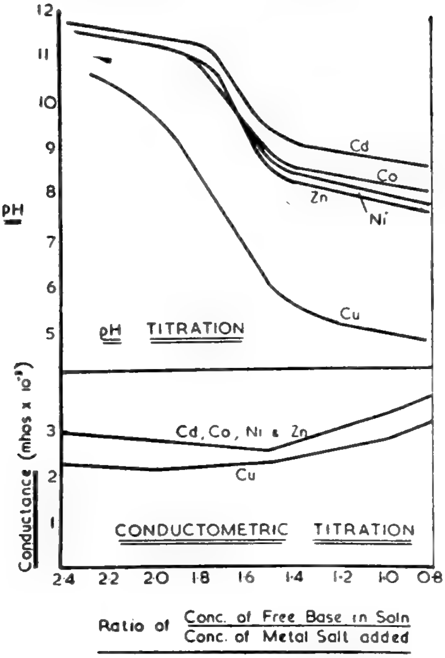


Figure 5.—Titration of alkaline sodium gluconate with metal nitrate solutions.

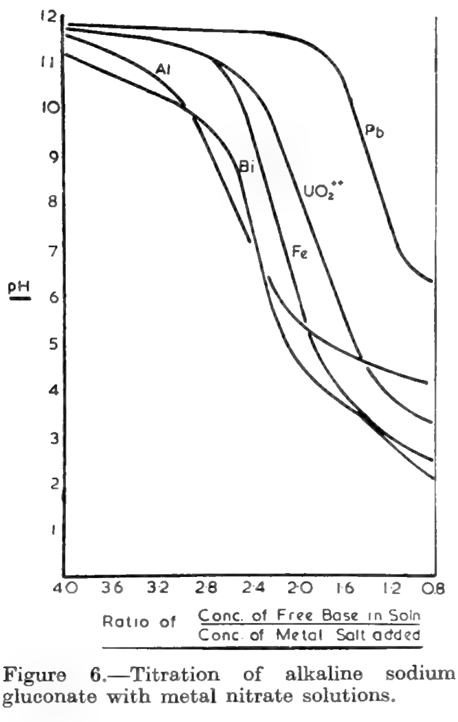
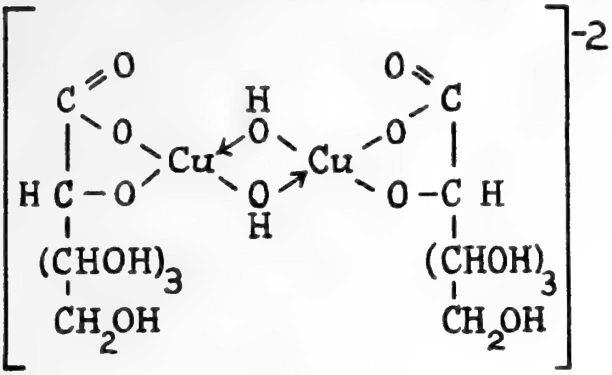
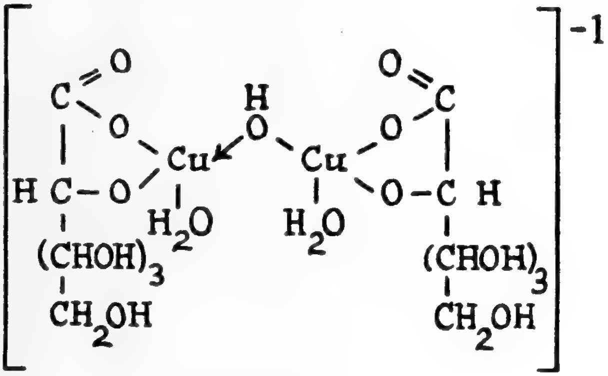


Figure 6.—Titration of alkaline sodium gluconate with metal nitrate solutions.



(II)



(III)

V. Discussion.

This investigation was carried out to obtain comparative information on the behaviour of a number of cations in aqueous solutions of gluconic acid. Some of the techniques used were not those normally used for investigating complexes, yet, where comparable, the results obtained agreed with the conclusions of more detailed studies such as those made by Pecsok.

The electro-chromatograms and spectrophotometric studies illustrated that each cation tends to form more than one species of complex. In alkaline solutions, there was evidence that lead, copper, nickel, cobalt, bismuth, iron, aluminium and uranyl nitrates each formed an anionic species which removed free hydroxyl ions from the solution. It has been suggested that some hydroxyl ions are neutralised by hydrogen ions liberated during complex formation (*e.g.* Cu, Fe) but the pH titration curves indicate that cadmium, zinc, nickel and cobalt form hydroxy compounds without the liberation of protons from the original gluconate ion.

In the published information there is no uniformity in the suggested modes of attaching the metal ion to the gluconate ion and the above study has not elucidated this point.

In acidic solution there was evidence that most of the cations tended to form complexes but the tendency to form complexes was most pronounced with the trivalent metals, Fe, Al and Bi. The paper chromatograms indicated that several elements, *e.g.* Pb, Bi, Cd, and to a certain extent Ni and Co, formed slightly soluble compounds which were soluble in excess reagent. This was confirmed in the titration studies.

The basic theory for the interpretation of the results of paper chromatograms under the conditions described has yet to be fully established, but in this study the conclusions have appeared to be quite valid. Due to the simplicity of the technique, paper chromatograms could prove to be very useful in making preliminary studies of the behaviour of new complexing agents.

The variations observed in the composition and colour of the gluconate complexes under different conditions seem to preclude the development of titrimetric and colorimetric procedures using this reagent.

On the other hand, the ability of sodium gluconate to retain many metal ions in solution in the presence of free sodium hyroxide is of analytical value. One application has been published (Watts and Utley, 1956) and others can be expected in the future.

Summary.

The behaviour of twelve cations in the presence of gluconic acid or alkaline sodium gluconate has been examined by several techniques.

A combination of paper and electro-chromatography is suggested as a suitable technique for rapid general surveys of the tendency of water-soluble reagents to form complexes.

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MACRO- AND MICRO-FLORAS OF NORTH-EASTERN NEW SOUTH WALES

By N. J. DE JERSEY.
(Communicated by C. T. McELROY)

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PART I: FOSSIL PLANTS FROM THE NYMBOIDA COALFIELD.

Introduction

The following is an account of a collection of fossil plants submitted for identification and age determination by Mr. C. T. McElroy, of the Geological Survey of New South Wales. The collection comprises: (1) approximately forty specimens with the plants preserved as carbonised impressions in dark grey shale, from the No. 2 workings, Nymboida colliery; and (2) three specimens preserved as impressions in light grey siltstone, from a locality three miles north of Nymboida. The investigation of these fossils has been greatly facilitated by a recent paper by J. A. Townrow (Townrow, 1957) in which several species previously included in the genus *Thinnfeldia* Ettingshausen have been revised and transferred to Gothan's genus *Dicroidium.* The writer is in agreement with Townrow's conclusions, and accordingly the species recorded here—*D. odontopteroides*, *D. feistmanteli* and *D. narrabeenensis*—have been placed in the latter genus.

Species Present in the Collection

Genus DICROIDIUM Gothan

Townrow (1957, p. 8) summarises the differences between *Dicroidium* and *Thinnfeldia* as follows:

> " (1) *Thinnfeldia* is never forked, *Dicroidium* almost always.
>
> (2) In *Thinnfeldia* the leaf is hypostomatic and the stomata are mostly in interveinal bands. The stomatal pit is rounded and is surrounded by a regular ring of fairly numerous subsidiary cells. The wall between the guard and lateral subsidiary cells is only weakly cutinised. In *Dicroidium* the leaf is amphistomatic, the stomata are scattered, and the subsidiary cells do not form a regular ring and are commonly only four. The common wall of the guard and lateral subsidiary cells is strongly cutinised, at least in those species where the stomatal aperture is sunken.
>
> (3) In *Thinnfeldia* the cell outlines are straight, and the cuticle surface smooth, but in *Dicroidium* the cell outlines are sinuous, or with processes, and there is normally a papilla in each epidermal cell."

With regard to the age of *Dicroidium,* Townrow concludes that it is mainly a Triassic and early Jurassic genus, and states that " On the other hand, the genus *Thinnfeldia,* in a strict sense, is known from rocks of Rhætic and Lower Liassic age (mostly Lower Liassic) in Europe and Greenland . . .; and thus, though it overlaps one end of the time range of *Dicroidium,* it is in the main considerably younger than *Dicroidium* and not contemporary with it as was earlier supposed."

With regard to geographical distribution, Townrow states (1957, p. 13) "*Dicroidium* has only been convincingly recorded from the region of the *Glossopteris* flora" and "On the other hand there are no convincing records of *Thinnfeldia* from rocks in which *Dicroidium* occurs". Thus *Thinnfeldia* is a northern hemisphere genus, while *Dicroidium* is restricted to the Gondwanaland areas, *i.e.* Australia, South Africa, India and South America.

Dicroidium odontopteroides (Morris) Gothan

(for synonymy see Townrow 1957, pp. 13, 14).

Several well preserved specimens of this species are included in the collection from the No. 2 workings, Nymboida Colliery. As they are identical in frond habit and venation with specimens described by Townrow, and earlier workers such as Walkom, Arber, Antevs and Gothan, the diagnosis and description (see Townrow 1957, pp. 14–17) will not be repeated here. Townrow has made out a convincing case for uniting the forms previously recorded as *T. lancifolia* with *D. odontopteroides* as there is a continuous gradation in characters between the two forms. This procedure is also followed here.

Dicroidium feistmanteli (Johnston) Gothan

(for synonymy see Townrow 1957, p. 19)

Under this name are recorded several specimens in the collection from the colliery workings, which are identical in frond habit and venation with the diagnosis given by Townrow (1957, p. 19). Accordingly the description and figures of this common species will not be repeated here.

Dicroidium narrabeenensis (Walkom) Frenguelli

(for further references see Townrow 1957, p. 17).

Two specimens in the collection from the colliery workings can be definitely placed in this species, as they compare closely with specimens figured in Walkom's original account of the species (*e.g.* Walkom 1925, pl. XXVI, fig. 4). According to Townrow (1957, p. 19), while *D. narrabeenensis* has a cuticle like *D. odontopteroides*, it differs from that species in being normally twice as large, and in having long pinnæ with alethopteroid venation. An additional characteristic which is evidently of specific importance is the contraction of the pinnæ at the base; this feature is not shown in any of Townrow's figures of *D. odontopteroides* (1957, Fig. 3).

Dicroidium sp.

Under this heading is recorded an incomplete specimen (labelled NP 33) from the locality 3 miles north of Nymboida. This specimen represents the apical portion of a dichotomous frond, the pinnæ of which have lobed margins and alethopteroid venation. In these features it is similar to those described by Walkom (1921) as *Thinnfeldia talbragarensis*. Presumably, by analogy with the other species, this should also be transferred to *Dicroidium*; however, as the species has not been listed among those revised by Townrow, its specific status is not fully established, and the specimen is simply recorded as *Dicroidium* sp.

Phoenicopsis elongatus (Morris) Seward

(see Jones and de Jersey 1947, p. 62).

This species is characterised by long, narrow linear leaves, up to 15 cm. in length and 1·4 cm. in breadth, which taper gradually from the middle portion both to the base and to the acute apex. It is one of the most abundant species in the collection from the No. 2 workings, Nymboida Colliery.

Tæniopteris carruthersi Tenison-Woods

One specimen from the colliery workings can be definitely placed in this species. It compares so closely with a specimen described and figured by Walkom (1924, p. 85, Text–Fig. 3) from the Esk shales that it is placed without hesitation in Tenison-Woods' species.

Tæniopteris crassinervis ? (Feistmantel) Walkom

Fragments of large fronds from the colliery workings, characterised by coarse venation, may possibly be representatives of this species, but the material is too fragmentary for definite identification.

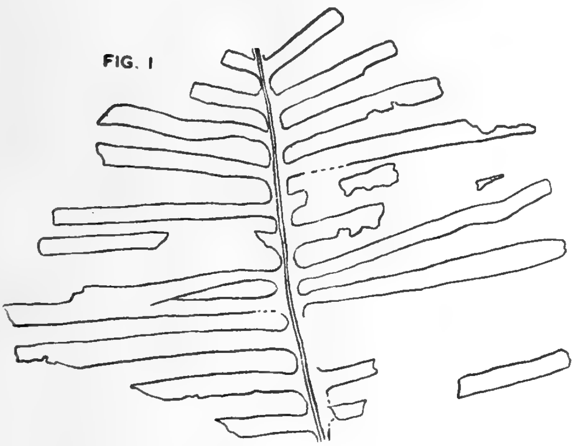
Pterophyllum nathorsti (Seward) Walkom
(see Walkom 1917, p. 18)

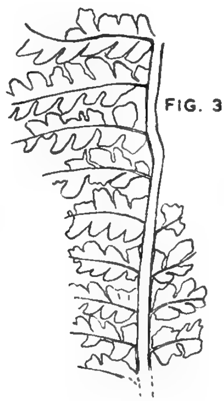
Several leaf fragments on one slab of shale from the colliery workings can be definitely identified with this species on the basis of Walkom's description and figures (1917, p. 18, pl. 5, figs. 4, 5). It is characterised by narrow pinnæ, which are acutely pointed, have a width of 1 to 3 mm. and a length of 2·5 cm. Each pinna is traversed by a small number (3 to 5) of simple, parallel veins.

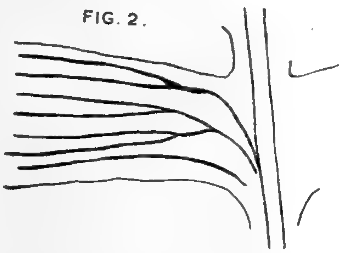
Cladophlebis australis (Morris) Seward

The collection from the No. 2 workings, Nymboida Colliery, includes one specimen of this common Mesozoic species.

Pterophyllum sp. (Figs. 1 and 2).







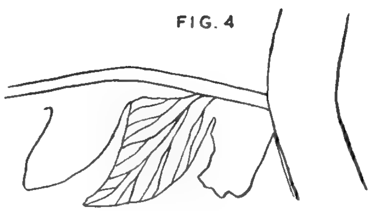


Figure 1. *Pterophyllum* sp. (× ½).
Figure 2. *Pterophyllum* sp, showing venation (× 3).
Figure 3. ? *Hægia* sp. (× ½).
Figure 4. ? *Hægia* sp., showing venation (× 3).

Description.—The frond is relatively large, the specimen, which is far from complete, attaining a length of 14 cm. and a width of 13 cm. The rachis is strong, 3 to 4 cm. in breadth, and the pinnæ are attached laterally. They are at right angles, or almost at right angles (80°–90°) to the rachis, and are well separated, being about 5 mm. apart. The pinnæ are attached by the whole base, adjacent pinnæ being joined by slight expansions, and are approximately parallel sided, narrowing slightly towards the base. The nature of their apices is unknown, no complete pinnæ being present; the largest (incomplete) pinna is more than 7 cm. in length. They average about 5 mm. in width, and are traversed by a small number of parallel veins (average number 6 or 7 at a distance of 3 cm. from the rachis). These veins are produced by dichotomous division of 3 or 4 veins which arise directly from the rachis, the dichotomy taking place near the base of the pinnæ. Branching of the veins further away from the rachis is infrequent.

Remarks.—This species is distinguished by its large size and coarse venation from species of *Pterophyllum* previously recorded from the Mesozoic of eastern Australia. More complete material, with the cuticle well preserved, would be required for comparison with species from other parts of the world or for recognition as a new species. The specimen described and illustrated (Figs. 1 and 2) came from the No. 2 workings, Nymboida Colliery.

Ginkgoites sp.

Under this heading are recorded leaf fragments of Ginkgoalean affinity from the colliery workings. As only the basal portion of the leaf is preserved in each case, no specific identification can be attempted.

Genus HOEGIA Townrow

(see Townrow 1957, pp. 27–31)

? Hoegia sp. (Figs. 3 and 4).

Description.—The frond is bipinnate, with a strong rachis averaging 3 mm. in width in the portion preserved. The rachis appears relatively smooth and unwinged. Pinnæ are opposite to subopposite, rather crowded and with pinnules typically meeting; the pinna rachis is smooth and unwinged. In the portion of the frond preserved the pinnæ diverge at angles close to 90°. Pinnules are borne on the pinnæ only, none being observed on the main rachis between the pinnæ. The pinnules diverge at an average angle of about 45°, the angle becoming slightly greater towards the base of the pinna and slightly less towards its apex. The pinnules are roughly rhomboidal, with bluntly pointed apices, and margins entire or slightly dentate. The lowest pinnule is attached directly to the rachis and is broader than usual.

The veins arise in two or three groups from the pinna rachis, arch strongly at first, and meet the pinnule margin at a wide angle. They branch dichotomously, with the branch veins diverging at an acute angle.

Remarks.—Two specimens from the locality 3 miles north of Nymboida (NP 27 and NP 29) are described here and the larger specimen (NP 27) is figured (Figure 3). They are preserved as impressions in light grey siltstone, and as the cuticle is not available, they are only doubtfully referred to Townrow's genus. The general form of the frond, insertion of the pinnules, and venation, are similar to the characteristics of the genus described by that author, and of the two species distinguished the present material comes closest to *H. antevsiana*. The specimens have been described and figured here in the hope that further collecting may bring to light additional material, preferably with the cuticle preserved, so that the present doubtful identification may be confirmed.

Age and Relationships of the Flora.

Twelve different species have been identified in the collection. They are as follows:

Dicroidium odontopteroides (Morris) Gothan
Dicroidium feistmanteli (Johnston) Gothan
Dicroidium narrabeenensis (Walkom) Frenguelli
Dicroidium sp.
Phoenicopsis elongatus (Morris) Seward
Tæniopteris carruthersi Tenison-Woods
Tæniopteris crassinervis ? (Feistmantel) Walkom
Pterophyllum nathorsti (Seward) Walkom
Cladophlebis australis (Morris) Seward
Pterophyllum sp.
Ginkgoites sp.
? *Hoegia* sp.

These species are of unequal value with regard to age determination and those determined only generically are of little value in this respect. Although Townrow regards *Dicroidium* as mainly a Triassic genus, it has been found in sediments which are definitely of Jurassic age (*e.g.* the Talbragar fish-beds of New South Wales, which, on evidence distinct from the plant fossils, are placed in the Jurassic). However the species *D. narrabeenensis* is only known from Triassic formations (the Narrabeen shales, Esk shales, Ipswich Coal Measures and the Molteno Beds of South Africa). Likewise *Phoenicopsis elongatus* is also restricted to the Triassic, and has been recorded from the Esk shales and Ipswich Coal Measures in Queensland, the Felspathic Sandstone of Tasmania, the Molteno Beds of South Africa and the Triassic of Argentina. *Tæniopteris carruthersi* is another Triassic species, having been recorded from the same formations as listed for *P. elongatus*. It has been shown by Medwell (1954, p. 88) that specimens from the Jurassic of Victoria, previously recorded as *T. carruthersi*, should actually be placed in *Tæniopteris spatulata*. Of the remaining species *Tæniopteris crassinervis* ? is a doubtful record, while *Pterophyllum nathorsti* is, in Australia, only known from the Esk shales, although it has also been recorded from the Jurassic of Scotland. *Cladophlebis australis* ranges through most of the Mesozoic and is of little help in age determination. The record of ? *Hoegia* sp. if confirmed, would suggest a Triassic age, as the genus is so far only known from Triassic formations.

The general character of the flora, and in particular the presence of three species—*Dicroidium narrabeenensis*, *Phoenicopsis elongatus* and *Tæniopteris carruthersi*—which are restricted to the Triassic, thus indicate a Triassic age for the sediments at Nymboida. There is a close similarity to the assemblages in the Esk shales and Ipswich Coal Measures, which are geographically the closest Triassic formations of which the floras are known in detail. Of the two the relationship is perhaps closer to the former, as *Pterophyllum nathorsti*, recorded by Walkom from the Esk district, has not been found in the Ipswich Coal Measures.

Acknowledgements.

The writer wishes to thank Dr. O. A. Jones and Dr. D. Hill, of the Geology Department, University of Queensland, for assistance with the literature, particularly in drawing his attention to Townrow's (1957) paper on *Dicroidium*. The drawings of *Pterophyllum* sp. and ? *Hoegia* sp. (Figs. 1 to 4) are the work of Mr. I. G. Sanker, Assistant Geologist, Geological Survey of Queensland.

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Part II : Report on Spore Distribution in Coals from North-Eastern New South Wales.

Six coal samples from the Mesozoic sediments of north-eastern New South Wales have been submitted by Mr. C. T. McElroy, of the N.S.W. Geological Survey, for examination of their microfossil content. These samples are as follows :

Sample No.	Locality
Co 1	Top Seam, Red Cliff
Co 2	Bottom Seam, Red Cliff
Co 3	4 ft. coal and bands, Red Cliff
Co 4	Bardool No. 2 Adit, near Nymboida
Co 5	Inferior coal from Coaldale
Co 6	Coal from Nymboida Colliery.

Four of these samples (excluding Co3 and Co5) were crushed and macerated by the normal technique adopted for Queensland coals. Of these three (Co1, Co2 and Co4) did not yield any spore or pollen exines, the maceration residue consisting of opaque and semi-opaque highly carbonised material. In the maceration residue from the remaining sample (Co6, from Nymboida) spores and pollens were present, but were so rare and poorly preserved that only a few forms could be identified after prolonged examination. Of the two samples not examined, sample Co3 (4 ft. coal and bands, Red Cliff) was not macerated because two other samples from the same locality gave negative results and sample Co5 (Inferior coal from Coaldale) was not studied because its shale content was too high to permit effective separation of spores by techniques normally applied to coals. The forms identified in the maceration residue from the Nymboida Colliery sample (Co6) were as follows :

Leiotriletes directus Balme and Hennelly
Entylissa sp.
Neoraistrickia sp.

Of these *L. directus* is long-ranged, having been found in both Permian and Jurassic coals, and the other two forms are also of little value in age determination. However, the Triassic age of the sediments at this locality has already been established by investigation of the macro-flora and consequently further attempts to improve the spore yield from this sample have not been made.

The absence, or rarity, of spore material in the samples studied may be due either to lack of spore material in the original plant debris or to alteration of the spore exines by the metamorphism involved in rank advancement. The available evidence supports the latter alternative, as the maceration residues consist largely of opaque and semi-opaque highly carbonised material, and published analyses indicate that the Nymboida coals are of medium-volatile bituminous rank (A.S.T.M. classification), the fixed carbon content (d.m.f. basis) of approximately 72–73 per cent, being appreciably higher than that of Queensland coals from which spores have been effectively separated. In comparison with other New South Wales coals, the Nymboida samples are approximately similar in rank to the South Coast coals, from which Dulhunty (1947, p. 24) experienced difficulty in separating spore material. In this case also the rarity of identifiable spores was attributed to advanced metamorphism rather than to absence of spores in the original coal-forming debris.

The presence of spores in small proportions in the sample from Nymboida colliery, as contrasted with their total absence in the other samples examined, suggests that this seam may be slightly lower in rank than the other samples. If it is a persistent property, this feature may be of use in distinguishing the seam worked at Nymboida from the other seams examined. Apart from this, the general conclusion reached from examination of the micro-fossils from this coalfield is that they are of relatively slight interest, from the stratigraphic aspect, as compared with the macro-floras which are described in Part I of this paper.

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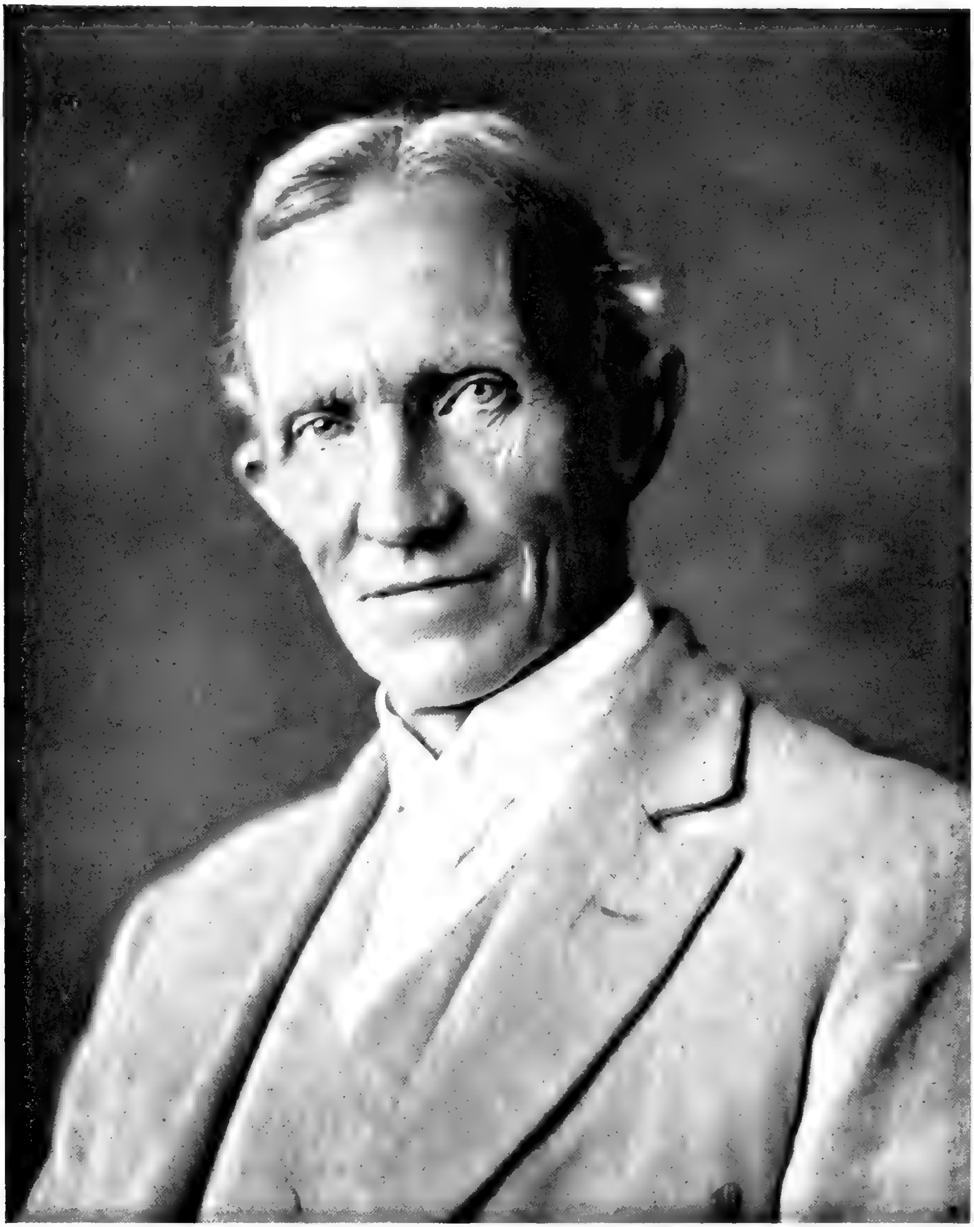

T. W. Edgeworth David

DAVID CENTENARY PART

Contributions to Geology

To Mark the Centenary of the Birth of

PROFESSOR SIR T. W. EDGEWORTH DAVID

By former Colleagues, Friends and Students

CONTENTS

FOREWORD

Sir Tannatt William Edgeworth David was born in 1858, and the Council of the Royal Society of New South Wales resolved to mark the Centenary of his birth by devoting one of its Ordinary Monthly Meetings to addresses on various aspects of his life and work, and by dedicating to his memory Part IV of the Journal and Proceedings for 1958.

He was indeed worthy for whom they should do this, for only rarely is there born into the world a man of such nobility of character and versatility of achievement. In his lifetime he was recognized as a truly great man, and his stature has not diminished with the passage of the years.

Nurtured and educated in the classical and literary tradition, he entered on his life-study of Geology in his later years at the University of Oxford, and there is no doubt that his early training was of immense value to him in later life, enabling him to bring to bear on geological and other problems a broad, philosophic outlook, at the same time reinforcing a natural eloquence and power of vivid imagery in presenting scientific results to colleagues and to laymen.

For long he was the acknowledged leader of scientific effort in Australia, taking a prominent part in the work of scientific societies and associations, and in the organization of international scientific conferences. His own researches were many and varied, and involved not merely much travelling within Australia but also excursions to tropic Funafuti and the icy wastes of the Antarctic.

Great as were his contributions to geological knowledge, however, it is probably no exaggeration to say that his most effective work as a scientist lay in his power of imbuing others with his own enthusiasm. Not the least of his services to geology in Australia was the help and encouragement he willingly bestowed on fellow-workers and the inspiration he imparted to many generations of students. His influence spread far beyond the confines of his own State, and something of the tradition of service he established has been handed on, and appears in a later generation that had no personal knowledge of him. But above all it was the warm humanity of the man, his selflessness, his consideration, kindness and unfailing courtesy, his aloofness from anything mean and petty, that won him a foremost place in the hearts and affections of colleagues, students and others with whom he came in contact. There were few of those that met him that did not yield to the power and the rare charm of his personality.

It is good to know that the Royal Society of New South Wales has perpetuated his name in the Edgeworth David Medal, and that his memory is kept green in Science House, Sydney, by the Norman Carter portrait in the Main Hall and by the Reception Room, recently renamed the Edgeworth David Room.

Of the contributors to this Part some are old students of David's, some are colleagues who knew and admired him, others were students at the University of Sydney during his last years and knew him chiefly by report. But one and all they have welcomed the opportunity to pay homage to the memory of him to whom and to whose work and example they owe so much.

W. R. Browne.

CONTEMPLATIONS ON CERTAIN TYPES OF METAMORPHIC REACTION

By A. R. Alderman, D.Sc., Ph.D.
Professor of Geology and Mineralogy, The University of Adelaide.

Abstract.

The great majority of metamorphic reactions take place in, and are aided by, the presence of water or some other fluid phase. This, however may not always be so, and evidence is assembled to show that under conditions of high-grade metamorphism reactions could take place entirely in the solid state.

Although our knowledge of the conditions of formation of metamorphic rocks is today making great advances, it is still a matter in which there is a great deal of uncertainty. This is particularly striking when we make a comparison with available data on the origin of sediments and igneous rocks.

The actual formation of many sedimentary rocks can be studied by visual observation and the conditions measured with a great deal of accuracy. Where this is impossible, as in the oceanic abysses, methods which are only slightly less direct are available. Similarly the conditions for the solidification of igneous rocks seem to have become reasonably clear to us through the study, first, of simple systems of dry melts, and, more recently, of systems containing volatile components.

Conditions for the formation of metamorphic rocks, however, vary over an extremely wide range. Temperatures vary from as low, possibly, as 100°C. up to 700 or 800°C., pressures up to 15,000 or even 20,000 bars. The effect of directed pressure is controversial, and while the presence of water is known to be of great importance, it may sometimes be absent.

The fundamental feature of metamorphism is that the rocks remain essentially solid. But while this is so the presence of a fluid, which may be in extremely small quantity, is a most important factor. This is supported by theoretical considerations as well as by experimental work. It is obvious that water is much the most important of these fluids.

The great majority of metamorphic rocks provide their own evidence for the presence of potential fluids. The hydroxyl ion can be present in rocks of high metamorphic grade. As an example the (OH) in hornblende is present in amphibolites which persist up into the sillimanite zone of Barrow's classical locality in Scotland. It is only in the rare rocks conforming to the granulite, eclogite and pyroxene-hornfels facies that we have assemblages consisting entirely of anhydrous minerals.

However, we know that an anhydrous assemblage of minerals does not necessarily imply that the system was a dry one when the rock was formed. It does however suggest that we might question the correctness of the assumption that a solvent—generally water—must always be present. Therefore we should consider the possibility of reactions having taken place completely in the solid state.

Reactions in the Solid State.

Our knowledge of the chemistry of solids has recently advanced very rapidly and for this we thank technologists as well as the crystal chemists. Three properties possessed by the solids themselves greatly affect potential reactivity —grain-size, the shape of grains and the crystal structure. As reactions between solids must begin and proceed from points of contact, the effects of grain-size and shape are obvious. Decrease in the grain-size increases the area of possible contact; also a platy mineral will present a greater area per unit volume than will a mineral which consists of spherical grains. A measure of these two factors is combined in one term, *surface area per unit weight*, of which great use is made in industry.

If we wish to bring about a reaction between two solids experimentally we therefore grind them as fine as possible and mix them thoroughly to ensure the maximum number of points of contact between the grains. This would be increased by compressing the mixture. It would then generally be necessary to raise the temperature before reaction proceeded at a significant speed.

The mechanism of reaction in its simplest form between two solids can be pictured firstly as the formation, at the area of contact, of a surface film of the reaction products (Cohn, 1948). This film formed by surface diffusion of the more mobile component would have a thickness of about one molecule and would not be in an orderly arrangement. It would thus not be detectable either by chemical analysis or by X-ray examination. This first interaction which involves only surface particles can take place at comparatively low temperature.

Further reaction depends on the reacting particles possessing enough energy to diffuse through the surface layer of reaction product into the interior of the lattices, and the molecules of the new compound being sufficiently mobile to arrange themselves in the ordered form of the new crystal lattice. Increase in temperature can, of course, supply both these requirements, but the amount of heat necessary may be greatly modified by the nature of the crystal lattice of the reacting substances.

In natural minerals, as well as in prepared solids, the stability of the crystal lattice must be a most important factor, *i.e.* whether the minerals are within their true stability ranges or are metastable under the conditions of metamorphism. As an extreme instance we can think of the instability of tridymite under most conditions of metamorphism. Quartz is the form of silica generally stable under such conditions. The instability of tridymite should make it enter readily into solid reactions. Another point concerns the openness of the crystal structure. Some minerals such as zeolites have an extremely open structure including channels through which ions of quite large dimensions can pass. The base exchange properties of zeolites depend on this and the same may apply to some clay minerals. Ions can thus enter the lattice without having to overcome any high energy barrier and the potential reactivity is increased.

Many of the properties of crystalline solids are greatly influenced by the presence of defects in the crystal lattice. Internal diffusion as well as surface reactivity is among the properties greatly affected in this way. In addition to actual dislocations of the lattice the common defects are due to either the presence of impurities or the misplacing of ions. Disorder of this latter nature can be classified into two types, Frenkel disorder due to the presence of ions in interstices of the lattice, and Schottky disorder characterized by vacant positions in the lattice. Generally the presence of such defects increases the rate of internal diffusion of ions. This is, however, not invariably so and perhaps the most striking examples of the contrary effect occur when the presence of impurities can stabilize an otherwise unstable compound, *e.g.* the prevention of the β to γ inversion in calcium orthosilicate.

The structural instability produced in minerals which are undergoing polymorphic inversion can increase the rate of reaction. Quartz is of course the commonest mineral to undergo such transitions, the $\alpha - \beta$ inversion at 573°C. being well within the range of the temperatures of metamorphism. Hedvall (1938) has shown experimentally that the rate of diffusion of Fe_2O_3

through quartz is notably accelerated at temperatures around 573°C. It is conceivable that under conditions of declining metamorphism the rocks might remain approximately at this temperature for a long time and that the effect might consequently be considerable.

Hedvall has also shown experimentally that newly and rapidly formed crystals, referred to as being in the "nascent" condition, are generally much more reactive than those which have been "aged". Presumably this is largely due to the great number of imperfections "frozen" into the lattice during rapid formation. He has compared two reactions:

$$MgO + FeO.Cr_2O_3 = MgO.Cr_2O_3 + FeO$$
$$MgCO_3 + FeO.Cr_2O_3 = MgO.Cr_2O_3 + FeO + CO_2$$

The second reaction takes place at 100°C. lower than the first and this Hedvall ascribes to the "nascent" state of MgO formed when $MgCO_3$ decomposes to form MgO and CO_2.

That the crystalline state of the reactants is of great importance in controlling the rate of reaction can be illustrated by some syntheses of forsterite which were made from different materials but with other factors kept as uniform as possible.

TABLE I.

Reactants.	Forsterite Yield.
A Clino-enstatite + MgO	60—80%
B "Meta-talc" + MgO	50—70%
C Hydrous silica + MgO	50—70%
D Talc + MgO	30—50%
E Quartz + MgO	*ca.* 10%

All mixtures were heated to 1300°C. for 2 hours. Forsterite estimated from X-ray photographs by Dr. G. F. Walker.

The clino-enstatite used in reaction A had been recently synthesized and would have been in a "nascent" state. Although the temperature 1300°C. is well below the melting point it must be remembered that clino-enstatite melts incongruently to forsterite and a silica-rich liquid and that Mg_2SiO_4 is the primary form of magnesium silicate developed in the solid state.

What is referred to as "meta-talc" is talc which has been dehydrated by heating. It is mainly glass and gives an imperfect clino-enstatite pattern with X-rays. We would expect it to be in highly reactive form.

The hydrous silica and the talc used in reactions C and D would be dehydrated during the heating and again we would expect them to be in a highly reactive state.

The magnesium oxide used in all these reactions was a prepared "reagent" and would be regarded as "aged". When heated with natural quartz the reaction would be expected to be slow. Comparison of the reaction rates of quartz (reaction E) and hydrated silica (reaction C) with magnesia is very striking.

The factors which we have been considering—original disorder in crystals of minerals, the effect of polymorphic transitions or of the nascent condition—may play large or small parts in metamorphic reactions. However, there is no doubt that the influence of temperature is of the greatest importance. A rise in temperature increases the internal vibrational disorder, *i.e.* increases the internal diffusion. When this diffusion proceeds with such energy that it can overcome the energy barrier imposed by the surfaces of crystals the minerals can re-crystallize, and if other compounds of suitable composition are adjacent can react and form new compounds.

Buerger (1948) has described this very clearly. "It is known that the activation energy of grain growth in metals is about twice the activation energy required to make the metal atoms diffuse through their own solid structure. The reason for this evidently is that more bonds must be broken to transport an atom across a crystal boundary than to merely pass it along in the same structure. *There is an important geological significance in this relation for it implies that whenever the temperature is sufficiently high to cause spontaneous growth of the crystals it is already maintaining a very high level of diffusion.* In this condition, the smaller atoms, at least, may be expected to be rather freely migrating through the remainder of the structure of the crystal. Thus whenever the rock is in a condition to recrystallize, it is also something of a blotter for available atoms, thanks to temperature. It is, therefore, evident that wholesale diffusion must play an important role in the transfer of chemical material in metamorphism."

An indication of the temperatures necessary to produce these conditions is given by examining the Tammann temperatures for the common minerals. The Tammann point is the temperature approximately at which there is a rapid increase in the mobility of lattice ions which thus allows reactions between solids to proceed at an appreciable rate (Rees, 1954). Its value is given by 0·5Tm, where Tm is the melting point in degrees absolute.

TABLE II.

	Melting Point °C.	Melting Point °K.	Tammann Point °K.	Tammann Temp. °C.
Quartz	1713	1986	993	720
Anorthite	1550	1823	912	639
Albite	1118	1391	696	423
Orthoclase	1170	1443	722	449
Diopside	1371	1644	822	549
Enstatite	1557	1830	915	642

The minerals and the temperatures quoted in Table II may look somewhat unrealistic but they illustrate the extreme case of the silica minerals, the range of the felspars and give some indication of the thermal properties of pyroxenes. The table is not intended to convey more than that at temperatures between about 400 and 700°C. the lattice ions of many rock-forming minerals will be sufficiently mobile to promote reactions even in the absence of a liquid phase.

It must be remembered that the figures quoted in Table II refer to determinations made at atmospheric pressure. It would be hard to find agreement on the degree to which they would be affected by pressure, both load and stress. Buerger and Washken (1947) have made some exploratory observations on this factor. They have shown that recrystallization of minerals can be caused by plastic deformation but that this only happens if a certain critical temperature is exceeded. This temperature varies with the mineral and the amount of deformation.

We have been considering the possibility of metamorphic reactions taking place in the absence of an aqueous phase. The effects of high pressure and the presence of water are generally to increase the speed of reaction and to lower the minimum temperature required. A striking example of this is shown by E. F. Osborn (1953), who synthesized forsterite from magnesium oxide and quartz in the presence of water vapour at a temperature of 600°C. and a pressure of 1100 pounds per square inch. The reaction was complete in from 2 to 3 hours. This can be compared with the much slower reaction shown by E in Table I under dry conditions at atmospheric pressure and a much higher temperature. The raw materials were of much the same size in both experiments. The effect of stress, or something that could have the same effects as stress, was also investigated by Osborn. In a pressure vessel which gave a steam pressure of 7000 lbs. per sq. in. and at a temperature of 350° sillimanite remained unchanged after 3 weeks. By rotating the pressure vessel, so that it acted as a kind of ball mill, partial alteration to kaolinite occurred in 3 days. The grinding of the sillimanite thus exposing fresh surfaces to alteration and the reduction of grain-size could perhaps have some resemblances to the effects of shearing stress.

Conclusions.

The purpose of this paper has been an attempt to demonstrate that metamorphic reactions can take place in the absence of water at temperatures well within the limits of those generally believed to exist in the higher grades of metamorphism. The factors which have been considered do not conflict in any way with the generally accepted ideas that the presence of water plays an extremely important part in the great majority of metamorphic reactions. Yoder (1955) has recently discussed this subject. It is also hoped that this paper has given an indication that a study of the chemistry of solids as applied to minerals could help in the consideration of geological problems of many kinds.

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SURFACE TEMPERATURES OF AUSTRALIAN SEAS

The Older Records from Fixed Stations

By M. Aurousseau, M.C., B.Sc., F.R.G.S.

The late Sir T. W. Edgeworth David was not only Professor of Geology in the University of Sydney: he was also William Hilton Hovell Lecturer in Physical Geography. He delivered no special course of lectures on physical geography while I was a student, but, throughout the course on geology, he interpreted the past in the light of the present. If we were to understand the conditions of oceanic deposition in the Australian region in Devonian times, we must understand what is going on in the oceans now. He began by explaining the consequences of the difference between the specific heats of land and water, and we soon found that we were not making a narrow study of geology, but were getting a liberal education in a highly philosophical kind of geography.

I have made my contribution to the appreciation of David as a geologist elsewhere; but he was far more than a geologist. His early glaciological studies in Great Britain, his test of the Darwinian hypothesis on coral-reef formation at Funafuti and his first-hand knowledge of Antarctica led him deeply into the study of climate in the geological past. By the time he had finished with us, we had learnt from him something of the fundamental principles of geophysics, oceanography and climatology. It seems, therefore, not inappropriate to offer a paper on the surface-temperatures of Australian seas as a contribution to a part of this journal to be issued in commemoration of the centenary of his birth.

Only slowly are we coming to recognise the importance to Australia of a knowledge of the temperatures of our surrounding seas. Cook's voyages had shown that navigation in high southern latitudes was less impeded by ice in some years than in others, but not until the store-ship *Guardian* struck an iceberg south-eastward from the Cape of Good Hope in 46°–47° S., on 23rd December, 1798, was the practical significance of the observation demonstrated. In the nineteenth century sailing-ships nevertheless continued to push further and further south, until the great-circle track from the Cape of Tasmania came to be regarded as the normal track.

In the early forties of the last century, when Wilkes, Ross and Dumont D'Urville were exploring in Antarctic waters, the high southern latitudes were comparatively free, not only from icebergs, but also from pack-ice. In the early fifties, however, conditions began to change. Towson noted that between 1848 and 1854 there were very few reports of icebergs in the Southern Ocean, but that between November, 1854, and April, 1855, " very alarming accounts were forwarded . . . From the reports of those who have been engaged in the seal trade, we believe that for fifty years previously there had been no season bearing the least comparison with that under consideration ".

This had some interesting consequences. British vessels gave up using the great-circle track in favour of a composite track across the Southern Ocean; and some of the maritime powers, in particular the United Kingdom and the Kingdom of the Netherlands, began the collection of meteorological information from vessels at sea, which has led to the production of the maritime meteorological atlases now in use. It may also have helped to bring into effect the plan for cutting the Suez Canal.

European interest in the Antarctic was thereafter dormant for a long time. The need for systematic investigation of the region, however, had been advocated in Australia by Prof. G. von Neumayer, from the time of his association with the old magnetic and meteorological observatory at Flagstaff Hill, Melbourne, in 1858. Von Neumayer himself made a special study of marine conditions, based upon the logs of vessels. Antarctic exploration was advocated in New Zealand (Purnell, 1878), Tasmania (Sprent, 1886) and Victoria (Royal Society of Victoria and Victorian Branch of the Geographical Society of Australasia, 1886).

The higher latitudes south of Australia were again relatively free from ice in the middle seventies ; but once again conditions began to change. Crutchley, writing in 1891 about the great-circle track between New Zealand and Cape Horn, said " no ice has been seen in the course of the last seven years by observers to the eastward of 117° W. long. . . . for many years past there has been an absence of ice on this route in any such quantities as to seriously impede navigation. Last year was, for instance, much worse as regards icebergs than many which had preceded it ". In October, 1892, bergs drifted north of the Chatham Islands ; and in 1895 Russell wrote that " we have had, within the last . . . eighteen months, an extraordinary accession of icebergs between the Cape of Good Hope and Australia ".

In 1893, after a lapse of at least fifty years, European interest in Antarctic exploration was renewed, and soon thereafter the work of a long series of great expeditions was under way. In 1904 Pettersson announced his hypothesis on the effect of ice-melting on oceanic circulation, which he so developed as to correlate famine in India with climatic conditions in the circum-polar seas. In 1904, too, icebergs again appeared in the Southern Ocean unusually far to the north, and Gregory surmised that " the cold weather of the past few months [in Australia and New Zealand] was probably caused by the proximity of this ice ".

This, I believe, was the first effective statement in a growing belief in Australia and New Zealand that our weather, if not our climate, is so affected by conditions in the Antarctic that we should do our utmost to understand those conditions. For instance, Du Faur, writing in 1907, said : " In those days [the early fifties of last century] the *Marco Polo* and her rivals went into high latitudes seldom I suppose now visited ; and that was a comparatively dry period in southern Australia. Later on, in the later fifties, the obstructive ice was met with in so much lower latitudes that Great Circle sailing was virtually abandoned, on account of the danger ; and 1857 (the *Dunbar* year), and several following years formed a comparatively wet period in these colonies . . . Also in 1888 . . . having noticed that ships passing between the colonies and Cape Horn had reported much ice, unusually far north, I . . . expressed my opinion, based on my earlier observations, ' that we might expect . . . three years of excessive moisture ' . . . The three, even four, following years, as it happened, proved to be almost the wettest we had known ". (This quotation conflicts far less with Crutchley's statement given above, than it seems to). Griffith Taylor correlated the Australian drought of 1914 with the condition of the belt of pack-ice north of Antarctica between the Balleny Islands and Termination Ice Tongue. But the publication of further work by Pettersson soon did as much to restrain as to stimulate speculation concerning climatic cycles in Australia. Taylor was now content to refer to Antarctica as " ' a fluctuating refrigerator ' which must exert an immense effect on the waters surrounding Australia. Unfortunately," he added, " no specific research in this direction has yet been done ".

There is, in fact, evidence in favour of the belief in the 'fluctuating refrigerator '. The British meteorological atlases and charts of the Indian and Southern Oceans cover the period 1855–1917 as far as 30° S., south of which, between 40° and 140° E., and for the Pacific, they cover a period which ended not later than 1884 (probably the period 1855–1878). The geographical value of the oldest charts remains considerable, as they give the range of temperature, as well as the mean, at many positions. Comparing the British atlas of 1904 with the Marine Observer's charts of 1928, and remembering that the relevant observations for the former were made before 1884 (if not actually before 1878) while those for the latter were made before 1895, we notice that the monthly mean temperatures of waters south of Australia and west of 140° E., shown on the former, are slightly higher than those shown on the latter. The two sets of charts are not strictly comparable; but these differences can hardly be imaginary, for it remains that isotherms, or parts of isotherms, were drawn a little further north on the earlier than on the later charts. Now, as a liberation of Antarctic icebergs comparable with that of 1853–1858 also took place in 1892–1895, it is possible that the consequent cooling of the waters of the Southern Ocean was enough to account for the lower monthly mean temperatures over the longer period represented by the charts of 1928.

Fowler's record from Back Beach, Sorrento, Victoria, extends from 1895 to 1899, but the second half of it, unfortunately, was published only in abstract, and my efforts to trace his papers have failed. He was able, nevertheless, to say "the average temperatures and densities of sea water on the southern coasts of Australia have been diminishing of late years, the figures for Bass Strait during the last half of December for three years being as follows: 1897, 66·1 deg., 1·02546; 1898, 64·0 deg., 1·02535; 1899, 63·6 deg., 1·02513". Waters off the southern coast seemed, then, to become perceptibly cooler and fresher after the liberation of Antarctic icebergs which took place in 1892–1895. Three years, however, is a very short run of observations; and we need not only to know the positions to which they apply, but also the rainfall at the times of observation.

An examination of Wilkes's meteorological chart of the Tasman Sea, in the light of what is now known of the region, might be enlightening. His expedition was so large, and its tracks covered so extensive an area, that his chart probably gives a fair picture of conditions in his time. The oceanographical results obtained by the *Uranie* (1819), *La Vénus* (1838) and the *Novara* (1858) are also worth re-examination from the point of view of secular change.

From the marine meteorological atlases the temperature of the surface of the open ocean is readily ascertainable for any month, for the Atlantic, Indian and Southern Oceans, and for any quarter for the Pacific: but hardly for any particular year anywhere. The mass of information so far collected by the maritime nations, and for the most part unpublished except in abstract, is never likely to be re-cast into values suitable for displaying the thermal history of the sea during the historically recent past. I was told, at the Meteorological Office in London, that "To extract the information *you* want from our records would produce such an upheaval in the office as we would tolerate only at the behest of another Sir John Murray". What has been published since the end of the eighteenth century is, with reference to time and area, spasmodic and meagre; enough, perhaps, to tell us something of change in conditions during the last hundred and fifty years, but far short of what we need to know.

The sailing ships are gone, and modern commercial shipping is confined to the regular shipping lanes. Unfrequented tracts of ocean are immensely larger than they were even fifty years ago, and are visited now only by vessels sent out on special commission. And much of the information collected by vessels navigating in the seas around us finds its way, not to Australian authorities, but to the British Meteorological Office, the U.S. Hydrographic Office, or the Scripps Institution of Oceanography (University of California, La Jolla, Cal.).

Unfortunately for Australia, the International Committee on the Oceanography of the Pacific, set up by the Second Pan-Pacific Science Congress

B

TABLE I. EAST.

	1	2	3	4	5	6	7	8	9	10	11	12
S. Lat. E. Long.	9° 55′ 144° 2′	10° 44′ 142° 36′	16° 17′ 149° 59′	16° 23′ 145° 34′	16° 23′ 145° 37′	27° 19′ 153° 14′	33° 50′ 151° 23′	33° 52′ 151° 14′	35° 5′ 150° 47′	42° 53′ 147° 21′	54° 30′ 158° 57′	54° 50′ 158° 52′
Jan.	—	—	82·1	83·53	83·86	76	(70·9)	71·1	—	—	43·4	—
Feb.	—	—	82·0	83·98	85·44	78	71·3	71·6	—	(58·5)	42·0	—
Mar.	—	(82·1)	81·7	82·83	83·21	75	70·4	70·8	—	—	41·1	—
Apr.	—	—	80·4	79·63	79·84	71	68·9	68·5	—	—	40·5	—
May	—	—	—	75·58	75·96	66	(63·1)	64·7	—	—	38·6	—
June	—	—	—	72·19	73·15	62	63·5	60·4	—	—	38·3	—
July	—	—	—	69·96	71·40	62	60·6	57·7	—	—	37·7	—
Aug.	—	—	—	71·04	71·92	63	(59·8)	57·5	—	—	38·2	—
Sept.	—	—	—	75·63	75·79	68	61·2	60·0	—	—	38·6	(40·8)
Oct.	(78·7)	—	—	79·56	78·48	70	63·4	63·3	—	—	39·0	40·4
Nov.	—	—	79·6	81·07	81·03	74	64·7	66·7	(65·1)	(55·7)	41·0	(41·6)
Dec.	—	—	81·5	83·17	83·53	74	68·4	69·3	—	(60·4)	43·0	—
Range	?	?	?	14·02	14·04	16	11·5	14·1	?	?	5·8	?

1. In breakers, S.E. reef, Maër Island (Murray Islands), Gt. Barrier Reef, Queensland. Four observations, 30 Sept.—19 Oct., 1913. Mayer.
2. Off Somerset, Albany Pass, North Queensland. Four noon observations, March, 1867. Rattray.
3. In breakers, edge of reef, Willis Island, Coral Sea. 7·30 a.m., daily (Summers only), 1922—4. Hogan.
4. Luana anchorage, Low Isles, Gt. Barrier Reef lagoon, Queensland. 9 a.m. daily, August, 1928—July, 1929. Moorhouse.
5. 3 miles E. of Low Isles, Gt. Barrier Reef lagoon, Queensland. Forenoon, weekly, July, 1928—July, 1929. Orr.
6. Pile lighthouse, Moreton Bay, Queensland. 9 a.m. daily, June, 1924—May, 1925. Hedley.
7. 3—4 miles E. of entrance to Port Jackson, New South Wales. 3—10 times monthly, 3 March, 1932—4 November, 1933, and 16 September, 1934—12 March, 1935. Dakin and Colefax.
8. Fort Denison, Port Jackson, New South Wales. 9 a.m. daily, April, 1860—June, 1942. Mean, 1860–75. Russell.
9. Jervis Bay, New South Wales. 3 early morning observations, 27–29 November, 1826. *Astrolabe.*
10. Hobart, Tasmania. 5 observations, 5, 16 and 17 February, 1836. *Beagle*; 1–11 November, 1840. Ross; 8 a.m. daily, 20 December, 1827–4 January, 1828. *Astrolabe.*
11. N. end, Macquarie Island, Southern Ocean. 9 a.m. daily, 1912–13, and December, 1914—November, 1915. Ainsworth and Tulloch.
12. Lusitania Bay, Macquarie Island, Southern Ocean. 9 a.m. daily, 8 September—3 November, 1912. Blake and Hamilton.

(Australia, 1923), recommended the plotting of information on charts showing sea-water temperature in each 5° quadrature. Our Federal Government put the recommendation into effect and began to issue such charts in 1925. It has been the international custom to plot this information on a 2° quadrature. The 5° quadrature may be appropriate to the immense size of the Pacific, but for the oceans and seas surrounding Australia its use is a regrettable departure from practice. It will cloak our almost boundless ignorance, rather than display our meagre knowledge.

It seems to me that the only way in which we can obtain information about change in the temperature of the surface of the sea over a long period of years is to take continuous records at suitable coastal and insular stations. It must be pointed out, however, that in-shore records do not necessarily represent the

TABLE II. SOUTH.

	13	14	15	16	17	18
S. Lat.	38° 28′	38° 21′	37° 52′	?	34° 49′	35° 2′
E. Long.	145° 5′	144° 44′	144° 58′	?	138° 27′	117° 54′
Jan.	—	65·8	67·1	—	70·8	—
Feb.	—	66·3	67·6	—	70·9	—
Mar.	—	64·2	66·0	(62·9)	68·2	(66·2)
Apr.	—	(63·0)	59·2	—	64·0	—
May	—	—	55·2	—	59·1	—
June	—	—	51·3	—	54·7	*66·2*
July	—	—	49·4	—	52·2	*64·0*
Aug.	—	—	50·2	—	53·3	*60·8*
Sept.	—	—	52·8	—	56·5	—
Oct.	—	(57·8)	57·4	—	60·7	(58·8)
Nov.	(63·3)	60·9	61·1	—	65·7	—
Dec.	—	64·8	66·0	—	68·6	—
Range	?	?	18·2	?	18·7	?

13. Western Port, Victoria. 8 a.m. daily, 12–18 November, 1826. *Astrolabe.*
14. Back Beach, Sorrento, Victoria. Daily (Summers only), 1895–9. Fowler.
15. St. Kilda Baths, Port Phillip, Victoria. Morning daily, 1935–(in progress). A. M. Laughton, Esq. (Private communication).
16. Hobson's Bay (exact position not stated), Port Phillip, Victoria. 6 a.m. and 2 p.m. daily, 17–31 March, 1874. *Challenger.*
17. Wonga Shoal lighthouse, entrance to Port Adelaide, South Australia. 9 a.m. daily, 1864–1912. Mean for 38 complete years. Communicated by the Divisional Meteorologist, Adelaide.
18. Albany, Western Australia. Three observations, 6–7 March, 1836, *Beagle*; June–August, 1908–12. J. J. East. (Conditions of observation same as for italicised figures in Table III); 8 a.m. daily, 8–24 October, 1826. *Astrolabe*

state of the open sea. Ever since Ross visited Port Jackson in July–August, 1841, we have known that the surface temperature inside the harbour may be perceptibly lower than that of the open sea outside. This is due to the mass of warm water which flows southward along the coast of New South Wales. The *Challenger* found the same thermal relation between the waters of Port Phillip and those of Bass Strait.

What we are seeking is not information about actual temperature, but about secular change in temperature, and this should be shown by long records from coastal and insular stations. My own interest in the subject was aroused some time in 1934, when a colleague on the staff of the Royal Geographical Society (London) asked me if New Zealand was not colder than corresponding parts of

TABLE III. WEST.

	19	20	21	22	23	24	25	26	27	28	29	30	31
S. Lat.	32° 3′	28° 38′	28° 47′	28° 47′	24° 52′	21° 42′	20° 38′	20° 41′	20° 19′	17° 58′	17° 16′	15° 54′	12° 5′
E. Long.	115° 45′	113° 50′	114° 37′	114° 37′	113° 40′	114° 56′	116° 28′	117° 11′	118° 37′	122° 13′	123° 37′	124° 24′	96° 52′
Jan.	*71·9*	—	*72·0*	—	*75·9*	*80·2*	—	*82·9*	*84·9*	*87·2*	—	—	—
Feb.	*72·8*	—	*74·5*	—	*78·1*	*83·1*	—	*85·3*	*86·0*	*86·0*	—	—	—
Mar.	*73·9*	—	*74·7*	—	*78·6*	*82·8*	—	*82·0*	*85·5*	*86·0*	*86·0*	—	—
Apr.	*72·5*	—	*73·9*	—	*77·4*	*83·5*	(76·3)	*84·0*	*82·0*	*85·6*	*84·0*	—	(79·8)
May	*68·5*	—	*71·2*	—	*76·8*	*80·0*	—	*80·9*	*80·0*	*81·8*	*82·0*	(85·1)	—
June	*69·4*	—	*70·5*	—	*72·5*	*72·3*	—	*72·5*	*76·2*	*76·5*	*78·6*	—	—
July	*66·0*	(69–70)	*68·7*	(56–60)	*71·9*	*73·2*	—	*72·9*	*72·5*	*76·6*	*78·0*	—	—
Aug.	*62·8*	—	*67·5*	—	*69·4*	*71·2*	—	*70·5*	*72·9*	*75·9*	*78·6*	—	—
Sept.	*64·0*	—	*67·1*	—	*69·0*	*73·9*	—	*72·9*	*72·9*	*73·9*	*78·0*	—	—
Oct.	*67·1*	(68·4)	*67·1*	—	*71·0*	*75·9*	—	*76·3*	*77·5*	*75·9*	—	—	—
Nov.	*68·0*	(68·5)	*68·7*	(64·4)	*71·0*	*74·8*	—	*78·9*	*80·9*	*82·9*	—	—	—
Dec.	*71·4*	—	*72·8*	—	*73·9*	*82·0*	—	*80·9*	*83·5*	*84·9*	*86·0*	—	—
Range	*11·2*	?	*7·6*	?	*9·6*	*12·3*	?	*14·8*	*14·5*	*13·3*	?	?	?

The figures printed in italics were collected by J. J. East, and are "chiefly based on the engine-room log of *S. S. Paroo*, 1908–12, and various coasting steamers, 1912. The temperatures apply to the sea water as pumped into the condensers. The figures are the mean of the observations taken during the watch (10–40 miles run) after leaving, or when approaching the port named, except in the case of Fremantle, where they were taken 10–30 miles north of the port". (Dakin).

19. Fremantle (offing), W.A.
20. Houtmans Abrolhos Islands, W.A. (Mean position of the group.) Early mornings, July, 1894. Saville-Kent; 22 and 28 October, 1915, and 9, 10, 12, 13 and 15 November, 1913, and 7 November, 1915. Dakin.
21. Geraldton (offing), W.A.
22. Champion Bay, Geraldton, W.A. Early mornings, July, 1894. Saville-Kent; 9, 10, 12, 13 and 15 November, 1913. Dakin.
23. Carnarvon (offing), W.A.
24. Onslow (offing), W.A.
25. Mermaid Strait, Dampier Archipelago, W.A. 6 a.m., 28–30 April, 1875. *Gazelle.*
26. Cossack (offing), W.A.
27. Port Hedland (offing), W.A.
28. Broome (offing), W.A.
29. Derby (King Sound), W.A.
30. Collier Bay and vicinity (mean position), W.A. Three observations, 3 p.m., 14, 15 and 22 May, 1916. Basedow.
31. Port Refuge, South Keeling Island, Indian Ocean. Eight observations, 2, 5 and 6 April, 1836. *Beagle.*

Australia. A search of the more easily available records produced no conclusive answer, but it did show that icebergs have never been known to drift into the Tasman Sea; and it suggested that the Antarctic Convergence, as it was then understood, might act as a climatic boundary between New Zealand and Australia. I therefore set about collecting the observations of sea-surface temperature from fixed stations in Australian seas, and reduced then all to monthly mean values on the Fahrenheit scale. The results are presented in Tables I–III, in which *maxima and minima are underlined, figures from runs of observations too short to represent the mean for the month are in parentheses, and those derived from indirect observation are in italics.* I regarded a ship at anchor as a fixed station; and, like Dakin, I was also obliged to regard a small range of position, occupied at intervals by an observing vessel, as a fixed station. Short, independent

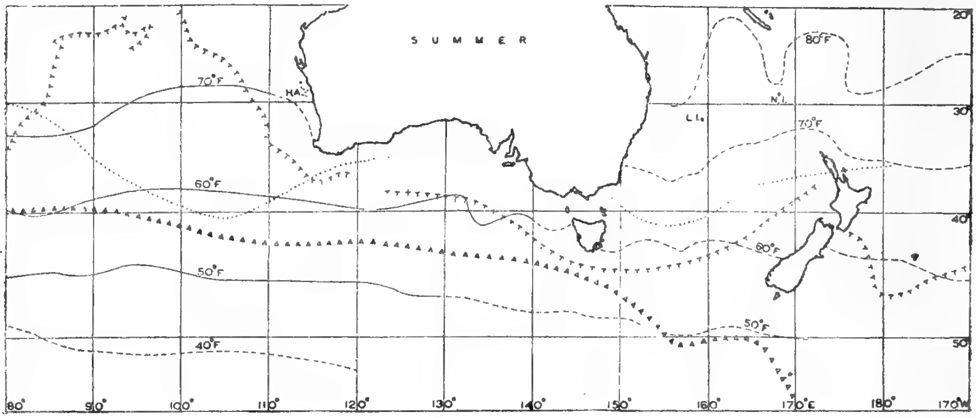

Fig. 1.—SUMMER.

Lines of sub-tropical convergence: T T T T T T
(After Willimzik, Indian Ocean—January;
after Supan-Obst, Southern and Pacific Oceans—Summer.)
Sea-surface isotherms: ——— — — — — } February
Limit of Fog: ························· } February
Limit of Drift Ice, 1772–1933 △ △ △ △ △ } February
L.I.—Lord Howe Island. N.I.—Norfolk Island.
H.A.—Houtmans Abrolhos.

records, which merely confirm other records from the same place, I have disregarded; for instance, the *Gazelle* recorded a mean temperature of 69·8° F. for the surface-waters of Moreton Bay from 29th September to 20th October, 1875. This, though of importance in the calculation of mean temperature over a long period, merely confirms Hedley's 70° F. for Moreton Bay in October.

So far as I can discover, we have only two long records in Australia, that kept at Fort Denison in Port Jackson from 1860 to June, 1942, and that kept at the Wonga Shoals lighthouse in the entrance to Port Adelaide from 1864 to 1912. The results of their harmonic analysis would be of decided interest. The Macquarie Island station, established by Mawson in 1911, passed under the control of the Navy Department in September, 1915, when it went out of use. It was re-established in 1948, and is still in operation.

I have compared East's figures for Western Australian waters with those which might be expected according to the meteorological atlases, and found that the former were an average of 1·7° F. higher than the latter. The calculations were made about 1936, and my notes do not show whether I used the official

British or the official Dutch atlases, or the Marine Observer's charts. The differences were not regular, but were greater in the tropical than in the temperate waters. Conversely, the October temperature recorded at Maër Island (northern extremity of the Great Barrier Reefs) is lower than would be expected from Halligan's charts, but is confirmed by the *Challenger* results. I also plotted the temperature curves for the stations represented in Tables I–III. Those for Port Jackson and Port Adelaide approximate to simple sine curves, but those for Moreton Bay and the Low Isles show a slackening in the rate of increase in November, and those for the Western Australian stations show subsidiary peaks in June–July and October–November. Schott was unaware of these Western Australian results when he considered the question of upwelling water, and Dakin seems to have accepted the figures without analysing them.

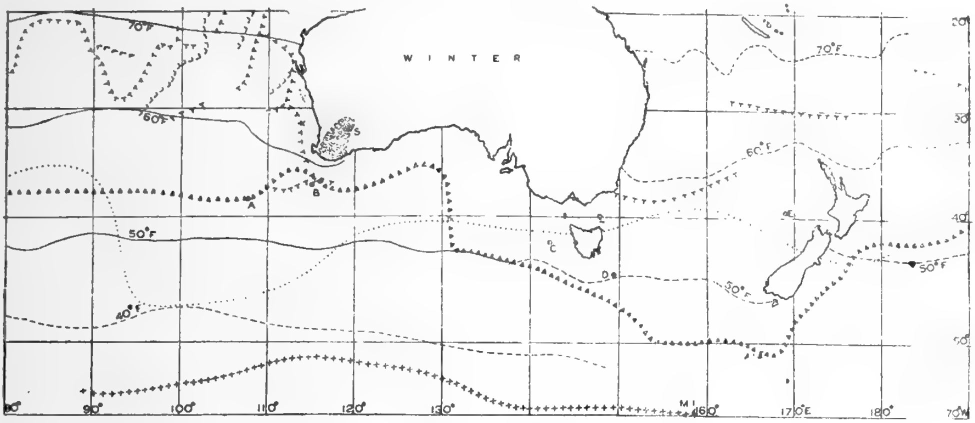

Fig. 2.—Winter.

Lines of sub-tropical convergence T T T and divergence ┌ ┌ ┌
(After Willimzik, Indian Ocean—July;
after Merz, Pacific Ocean—Winter.)
Positions of sub-tropical convergence detected by R.R.S. *Discovery II*, May–July, 1932: A, B, etc.
The Antarctic Convergence as located by R.R.S. *Discovery II*, May–June, 1932: + + + + +
Sea-surface isotherms: ———— — — — — } August
Limit of Fog: ························ } August
Limit of all ice, all months, 1772–1933: △ △ △ △
Area in which snow has fallen in West Australia: S
M.I.—Macquarie Island. A.I.—Auckland Island.

My work was done in England, and had to be laid aside on account of the war. It is possible that the conception of "water masses" has rendered the old faith in surface isotherms less important than it was, but the value of long records from fixed stations is, for many purposes, unquestionable. Text-figures 1 and 2 are compilations on which I have tried to show the extent of our knowledge of some of the geographical limits which have to be considered in the interpretation of our maritime meteorological data. They make it clear that authorities were not agreed (in 1935) on the subject of convergences; and my tables for temperature show that the 70° F isotherm should appear across the South Australian gulfs on charts for Summer.

Not until my recent return to Australia did I become properly aware of the activity of C.S.I.R.O. in recording sea-temperatures; of that of the Antarctic Division of the Department of External Affairs; of that of certain stations in northern Barrier Reef waters, which are said to report to the Crohamhurst

Observatory (Beerwah, Queensland); or of that of some of our surf clubs. I hope that I shall be allowed to study the results of their work, though most of it is official and much of it unpublished.

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STRATIGRAPHY AND STRUCTURE OF THE DEVONIAN ROCKS OF THE TAEMAS AND CAVAN AREAS, MURRUMBIDGEE RIVER, SOUTH OF YASS, N.S.W.

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(Plates IV–VII.)

Abstract.

A geological sketch-map and sections of the Taemas–Cavan Area, on the Murrumbidgee River, south of Yass, N.S.W., accompanies the description of the stratigraphy and geological structure of the Middle Devonian fossiliferous limestones and associated rocks. These are well-bedded deposits, not reefs, formed in portion of the Tasman geosyncline, and they show good evidence of turbidity currents and other shallow-water phenomena.

Introduction and Acknowledgements.

The first published work of T. W. Edgeworth David after his arrival in this country in 1882 was a " Report on the Fossiliferous Beds, Yass ", and this marked the beginning of his life-long interest in the geology and palæontology of the Yass district. It therefore seems fitting that a paper on the subject should be included in a publication to mark the centenary of his birth.

The Taemas–Cavan area, about 16 miles south of Yass, on the banks of the Murrumbidgee River, which there forms the upper part of the Burrinjuck Reservoir, is geologically famous for its Middle Devonian fossils and for its strikingly folded limestone formations.

The field-work for the present study was commenced many years ago, but was confined to short periods during University vacations. The complexity of the geological structures and the lack of suitable base-maps handicapped progress ; also it was found that much more detailed work than can be shown on the accompanying map (Plate VI) was necessary to establish the stratigraphical succession and to permit the interpretation of the geological structures.

During the early part of the investigation, I was accompanied in the field by students and others, particularly Miss D. Crosby, B.A. (Mrs. C. J. Smith), and Mrs. K. M. Sherrard, M.Sc., whose help I gratefully acknowledge. The travelling expenses of these trips were partly covered by grants from the Commonwealth Research Fund administered through the University of Sydney.

More recently I have been accompanied in the field by my husband, Dr. W. R. Browne, without whose help and encouragement this work would not have been completed. We are both deeply indebted to residents of Cavan district for kindness and hospitality, particularly to Mrs. Grace and the late Mr. B. Grace of " Little Plain ", Mr. and Mrs. E. W. Longley and family of " Mountain Creek " and Mr. and Mrs. W. Roche of " Cavan ".

The accompanying map is based on old Shire and Parish Maps issued by the Department of Lands, N.S.W., which, however, were found not to be sufficiently accurate in detail for geological purposes. Consequently air-photographs taken by the R.A.A.F. in December, 1944, were also used, and I am grateful to the authorities at Victoria Barracks, Sydney, for the loan of these photographs, and to their issuing officer, Sergeant R. Stafford, for his courtesy on all occasions.

The cost of the blocks for the geological map and sections (Plates VI and VII) has been defrayed by an anonymous donor.

I wish also to thank Professor L. A. Cotton and Professor C. E. Marshall of the Department of Geology, The University of Sydney, for their kindness in arranging research facilities in the field and the laboratory.

Thanks are also due to Mr. A. J. Shearsby for permission to use his photograph of the anticline illustrated on Plate IV, figure 1.

Previous Investigations

The earliest reference to the geology of the area appears to be that of T. L. Mitchell (1838), who in 1836 recognized Devonian limestones in the Goodradigbee and Murrumbidgee valleys. From 1848 onwards Rev. W. B. Clarke made extensive collections of fossils from " the black limestones of the Murrumbidgee " at Yarradong (=Cavan) (Clarke, 1878, p. 18). These were sent to Europe and were later described by de Koninck (1877, 1898), who recognized their Middle Devonian age.

More recently many fossils have been described from the region, reference to which is made below, but no detailed stratigraphical work has been done, and it has not been possible to refer the collected material to definite stratigraphical horizons. In 1905 Mr. A. J. Shearsby, who is still in Yass and interested in its geology, having been inspired by a visit in 1902 of Professor David and Mr. Robert Etheridge to " Euralie ", near Yass, published a paper on the unconformity between Silurian and Devonian rocks near Cavan and suggested the correlation of the Taemas lavas with the Snowy River Porphyries of Victoria described by Howitt (1876).

A few years later L. F. Harper (1909) mapped the Silurian rocks of Boambolo and some of the Devonian beds in the vicinity of Cavan.

Generalized accounts of the geology of the Yass–Canberra area have been given by L. A. Cotton (1923), T. W. E. David (1950), I. A. Brown (1941) and others.

Stratigraphical Succession

In 1954 I described briefly the Devonian succession, but much more detailed mapping and palæontology of the Devonian formations have been done since then and the present interpretation of the stratigraphy and structure supersedes that given in the previous paper.

Reference to the map and sections (Plates VI and VII) will show that the limestones and interbedded sediments overlie a sequence of lavas and tuffs and occur in a structure called here the Taemas synclinorium, which is some 10 miles long and up to 5 miles wide and which is divided into two basins by the Shearsby Fold, described in more detail in a later section.

The sequence of Devonian formations is shown in Table A. The basal formations constituting the **BLACK RANGE SERIES** (Brown, 1941) consist of the Narrangullen Rhyolites and the Mountain Creek Tuffs.

The **Narrangullen Rhyolites** are best exposed at Narrangullen Mountain to the south-south-west of the Taemas synclinorium, but may be traced continuously to the south and east, across the Uriarra road and thence north along the range of hills leading to Clear Hill, Cavan. The outcrop continues north to the Devil's Pass on the Yass River, along the Black Range to Illalong Railway Station and thence south towards Burrinjuck Dam. Along its south-eastern, eastern, northern and western borders it rests unconformably on Silurian crystal tuffs.

The overlying **Mountain Creek Tuffs** include basal black shales overlain by coarse and fine bedded tuffs, greywackes and red shales. They have already been described briefly (Browne, 1954) but are worthy of more detailed petrological study. The tuffs are possibly of the order of 700 feet thick in the south, but thin out to the north-east, and their outcrops are further reduced by faulting near the mouth of Warroo Creek.

The geological age of the Black Range Series lies between that of the " Upper Trilobite Bed " of Bowning (Upper Silurian or Lower Devonian) and the lower Middle Devonian of the Cavan Limestone, and is therefore probably Lower Devonian (Brown, 1949).

The succeeding **MURRUMBIDGEE SERIES** (David, 1932) may be divided into three stages, here called the **Cavan, Majurgong and Taemas Stages,** represented by two series of limestones separated by fine-grained siliceous sediments including conspicuous red beds, which crop out in the Taemas synclinorium. This subdivision is different from that of Harper (1909), who mapped and described a relatively small part of the structural basin in the Parish of Cavan, south of

TABLE A

	Thickness in Feet
Murrumbidgee Series :	
Taemas Stage :	
Fine tuffs and shales	100
Crinoidal Limestone, with current bedding	500
Warroo Limestone : thin-bedded, very fossiliferous ; zone of *Metriophyllum*	370
Receptaculites Limestone : very fossiliferous, with zone of *R. australis* above a basal zone of *Xystriphyllum mitchelli*	590
Bloomfield Limestone : shaly, bedded	400
Currajong Limestone : massive, bedded, with zone of *Breviphyllum* (*Campophyllum*) *recessum* above zone of *Syringopora speleana* ..	400
Spirifer yassensis Limestone : richly fossiliferous, with brachiopods, tabulate corals, cephalopods, arthrodires, etc.	400
Majurgong Stage :	
Red shales, sandstones and quartzites. Zones showing current-bedding, ripple-mark, etc., and thin bands containing gastropods and *Lingula*	400
Cavan Stage :	
Thin-bedded Limestone (100′),	
Bluff Limestone : with *Disphyllum gemmiforme*, *Tipheophyllum bartrumi*, etc. (150′),	
Flaggy limestones, shales and quartzite (150′)..	400
Black Range Series	
Mountain Creek Tuffs :	
Coarse tuffs ; fine red tuffs and basal black shales	700+
Narrangullen Rhyolites	1800 ?

the present Taemas Bridge. Unfortunately the area he examined was too small for him to recognize therein : (a) both regional and close local folding in the limestones, producing repetition of the outcrop of strata along his East-West section line (Harper, 1909, Map II, Section A–B–C), and (b) the significance of the interbedded " siliceous shales " in his Yellow Limestone. Thus he was misled in his interpretation of the geological structure and consequently of the sequence, thickness and fossil content of the various formations. In particular no species is ubiquitous in the Cavan and Taemas limestones, as he supposed. Forms like *Receptaculites australis, Xystriphyllum mitchelli* and *Disphyllum gemmiforme* are in fact restricted to separate narrow zones and never occur together. Harper's faunal lists are therefore quite inaccurate and misleading, and should be disregarded. Moreover, his " Second Limestone Series ", placed by him stratigraphically above those he mapped as " Basal Limestone Series " (Map II), is actually equivalent to the lower part of the basal limestone.

A striking feature of the Series is the constant character of the lithology, thickness and fossil content of each of its main subdivisions.

This paper is concerned chiefly with indicating the order of succession of the fossil zones, and only the characteristic or abundant species will be mentioned. Later it is hoped to publish descriptions of the faunas of the successive limestones, based on the study of collections made during the present survey.

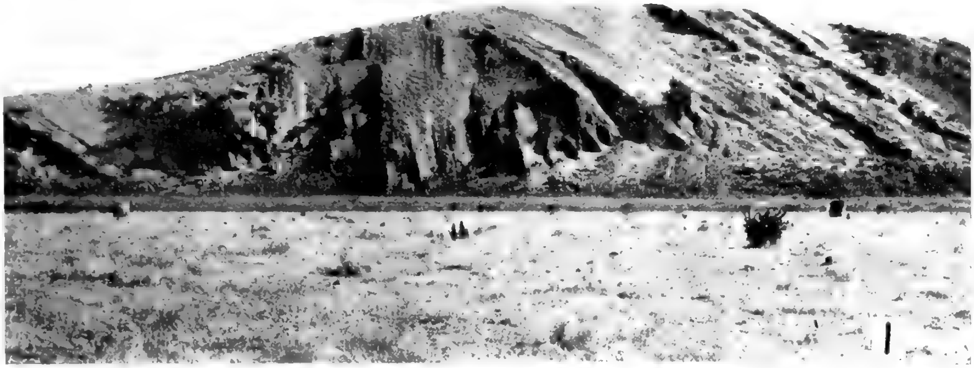
The **Cavan Stage** is represented by the limestones lying directly and conformably over the Mountain Creek Tuffs, the " Bluff Limestone ", and the part of the " Yellow Limestone " below the Majurgong Stage (=" siliceous shales " of Harper). It is proposed to restrict the name " Cavan " to this lower limestone group, which occurs typically at Clear Hill, Pors. 5, 136, Parish of Cavan, the type-locality for many described fossil corals.

The Cavan limestones outcrop almost continuously around the Taemas synclinorium as well as along the crest of the median anticline. Between Warroo house and Good Hope the outcrop is cut off by the Warroo Fault, which throws successively higher formations against the underlying rhyolite of the Black Range Series.

Excellent exposures of the Cavan limestones occur in many places, as in the valleys of the eastern tributaries of Mountain Creek near the Uriarra road, in the valleys of Spring, Salt Box and Bushranger's Creeks, at Narrangullen Cave and along the road-cuttings west of the bridge over Mountain Creek, as well as in the vicinity of Good Hope and Alum Creek.

The lowest beds consist of impure, flaggy limestones interbedded with shales and quartzites, about 150 feet in thickness, and usually not very fossiliferous; they frequently show ripple-mark and mud-cracks (Plate V, fig. 6). The limestones are black when freshly broken but weather yellow. These are followed by a bed of more massive limestone, some 20 feet thick, which makes prominent outcrops and shows fine, almost varve-like, lamination. Next in succession is the Bluff limestone, approximately 150 feet thick, which forms the top of the Bluff at Clear Hill, Cavan, south of Styles' house. Certain thin bands in this limestone are richly fossiliferous, and it is in these that the more interesting rugose corals are found. *Disphyllum gemmiforme* is probably the most abundant and widespread, *Tipheophyllum* (*Eridophyllum*) *bartrumi* is not uncommon, but most of the other rugose corals, like *Acanthophyllum aequiseptatum* Hill, *Thamnophyllum abrogatum* Hill, *T. curtum* Hill and *Mictophyllum trochoides* Hill are restricted to a couple of thin beds. A zone of *Cystiphyllum* aff. *australe* Eth. *fils* with occasional specimens of *Acanthophyllum* sp. and spiriferids occurs low in the sequence, and a zone of *Hypothyridina* cf. *cuboides* has been recognized at a number of localities, stratigraphically below the main *Disphyllum* zone. This occurrence supports the contention of Cooper *et al.* (1942) that *Hypothyridina* is not confined to early Upper Devonian, as believed by many stratigraphers, but may range from high in the Lower Devonian to the middle of the Upper Devonian. Tabulate corals are very abundant; the type specimen of *Favosites murrumbidgeensis* Jones comes from Clear Hill, and other fossils include stromatoporoids, bryozoans, brachiopods, pelecypods, gastropods and straight cephalopods, *Hyolithes*, *Tentaculites*, crinoid remains and fragments of trilobites. A few fish plates have also been found. Some of these fossils were identified by de Koninck in W. B. Clarke's collections but not all have been named.

The Bluff Limestone is overlain by flaggy, thin-bedded limestone, which weathers to a yellow colour—the lower part of Harper's " Yellow Limestone ". Along the whole of its outcrop it is richly fossiliferous, containing many small brachiopods, bryozoans, small solitary and tabulate corals, crinoid stems and molluscs. Current-ripples, oscillation-ripples, mud-cracks and other evidences of shallow-water deposition may be seen in the sections along the road-cuttings west of the bridge over Mountain Creek on the Yass–Wee Jasper–Tumut road.



1

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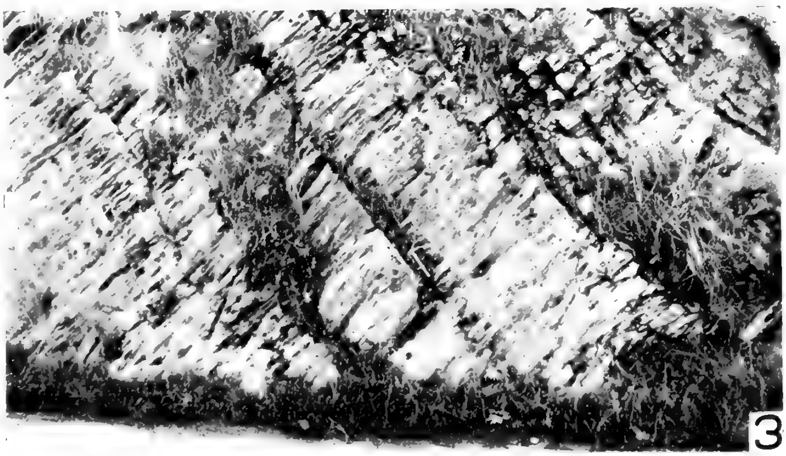
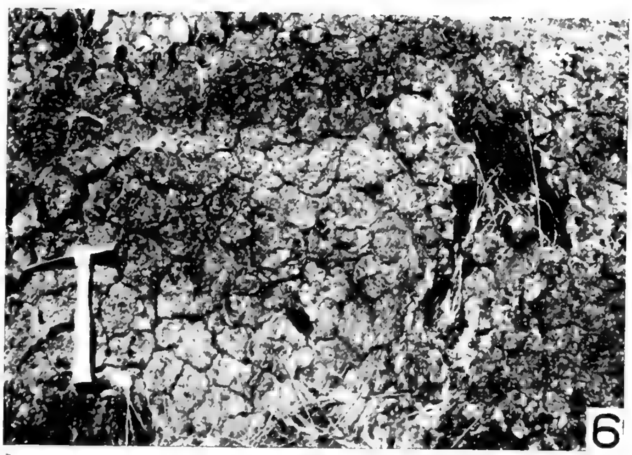


3

Journal Royal Society of N.S.W., Vol. XCII, 1958, Plate V



The **Majurgong Stage** comprises the sediments conformably overlying the Cavan limestones, which make prominent outcrops along the crest of the ridge on the western (left) bank of the Murrumbidgee River, running in a N.N.W. direction from the mouth of Mountain Creek. It is named for Majurgong Trigonometrical Station (1780′), the highest point on the ridge, although this is actually situated on a small inlier of Cavan limestone.

The outcrop of the Majurgong beds completely surrounds that of the overlying limestones, except where it is cut off by the Warroo Fault. Along the Majurgong ridge the beds dip at high angles, being in places nearly vertical, and differential weathering has produced conspicuous rocky ribs of quartzite along the upper slopes of the river valley. Along the eastern side of the synclinorium the outcrops are in many places quite inconspicuous, but they are to be seen on a sharp turn in the road near the northern approach to Taemas Bridge and again about a mile south of the Bridge, where they dip at an angle of nearly 80 degrees W.S.W.

The Majurgong beds consist of fine-grained sandstones and grey and red shales, with a few beds—up to 6 feet thick—of more massive quartzite. The lithology may be studied in outcrops east of the Uriarra road and south of the Tumut road, where gently folded beds plunge to the north. The cutting on the Tumut road west of the Mountain Creek bridge exposes beds whose dip is 65 degrees and more towards the east, with marked cleavage dipping towards the west-south-west. (Plate IV, fig. 3).

The red shales are not usually very fossiliferous ; a few calcareous bands contain small gastropods, as in Pors. 232–111, Parish of Taemas, (north of the junction of Salt Box and Chimney Creeks), and *Lingula* sp. is not uncommon at many localities. An impression of a fish-plate was found in red shales in Por. 105, Parish of Warroo, near " Fifeshire " property. Towards the top of the sequence small spirifers of the gens *S. yassensis* de Kon. become increasingly abundant in thin bands alternating with unfossiliferous beds a couple of inches in thickness, and these merge into the overlying limestones.

The associated red, white and grey sandstones and quartzites are usually fine-grained and frequently show well-marked fine current-bedding, ripple-mark, mud cracks and other structures indicative of shallow-water deposition under the influence of turbidity currents.

The overlying limestones of the **Taemas Stage** outcrop along both banks of the Murrumbidgee River below Taemas Bridge for more than ten miles. They consist of alternating series of thin-bedded or flaggy, impure limestones and more massive limestones. In newly-exposed cuttings the limestones appear to be massive, but lithological differences are greatly accentuated by weathering (Plate IV, fig. 2). The faunal assemblages in these rocks are distinctive and the restriction of certain species to particular beds has made possible the mapping of the palæontological zones that exhibit the geological structure of the formation.

At the base of the Taemas sequence is the **Spirifer yassensis Limestone.** It consists of numerous thin bands of pure limestone interbedded with more shaly limestone, and the lower portion is always packed with *S. yassensis*. Outliers of the main outcrop, which occurs along the banks of the Murrumbidgee, are to be found in the axes of small synclines or narrow basins in the vicinity of " Middle Station " and in the valley of Oakey Creek. Along the eastern flank of the Shearsby Fold the *yassensis* beds dip easterly at a high angle, and in Por. 65, Par. Taemas, the cutting of the old road north of the mouth of Oakey Creek exposes bedding planes of the top beds of the Majurgong shales and the lowest beds of the overlying limestones, which are crowded with remains of *Spirifer yassensis* de Kon. and *Chonetes culleni* Dun, and which generations of University students have called " Shearsby's Wallpaper ".

The *yassensis* limestone also occurs in the core of the " Taemas anticline " figured by Harper (1909, Pl. V), Süssmilch (1914) and David (1950), which is at the place marked " Horseshoe " on the map (Plate VI). This place is also locally known as " the Shark's Mouth " and " the Devil's Elbow ", names which appear on old museum-labels of specimens from this locality.

Besides *S. yassensis* and *Chonetes* spp. rhynchonellids and smooth spiriferids are also present; stromatoporoids are important and there are solitary cystiphyllids and other small undescribed rugose corals. Tabulate corals are very common; this is probably the type horizon for *Gephuropora duni* Eth. *fils*, and there are species of *Favosites*, *Coenites*, *Syringopora* and *Aulopora*. Small Scaphopoda, *Hyolithes* or *Coleolus*, are common, also many gastropods and pelecypods: cephalopods are abundant in some beds and are represented by species of *Pectinoceras*, *Buchanoceras*, *Macrodomoceras* and (?) *Polyelasmoceras* similar to, if not identical with, those described by Teichert and Glenister (1952) from Buchan in Victoria.

Among the most important fossils are the remains of the armour-plated fishes. Isolated plates are not uncommon, and it was from this formation, at a place less than half-a-mile north of the present " Taemas " house, that the almost complete head-shield of the dipnoan *Dipnorhynchus süssmilchi* (Eth. *fils*) was found by C. A. Süssmilch. This specimen was studied and redescribed by E. S. Hills (1933, 1941, 1943). From the same locality arthrodires have been described by E. White (1952) and named by him *Buchanosteus murrumbidgeensis* and *Taemasosteus novaustrocambricus*. From probably equivalent beds in the Goodradigbee valley he also described *Williamsaspis bedfordi* and *Notopetalichthys hillsi* A. S. Woodward. Dr. White is now studying extensive collections of fish remains made by Mr. H. A. Toombs in 1954.

The **Currajong Limestone** is a more massive, well-bedded limestone, which often weathers to a rocky outcrop, a favourable environment for the growth of the Currajong tree, *Brachychiton populneus*, for which Harper (1909) named the limestone (Plate IV, fig. 2).

Some beds of the Currajong Limestone are very fossiliferous and there is a certain amount of surface silicification of the included fossils. This limestone was useful as an index formation in the unravelling of the geological structure of the eastern part of the synclinorium. At the southern end of the structure its outcrop is very complex, a number of small corrugations having been superimposed on a few larger folds, which plunge to the north. Throughout the main structure to the north it has been crumpled into several long, close folds, some of which are very asymmetrical, one limb of the fold being nearly vertical and the other nearly horizontal, the associated beds being folded in sympathy with it.

An abundance of a small-celled *Syringopora* is characteristic of its lowest bed; about 50 feet stratigraphically above this is a zone containing some *Breviphyllum* ('*Campophyllum*') *recessum* (Hill) and (?) *Roemeria* sp. and about 80 feet above this again is a two-foot zone packed with *Breviphyllum recessum*; this zone may be identified along much of the outcrop of the Currajong Limestone, and it was from it that the holotype of this coral was obtained from near the Devil's Elbow.

Syringopora speleana and *Roemeria* occur in a zone a few feet below the *Breviphyllum* zone. Stromatoporoids are again abundant in this limestone, and other fossils include coarse, massive *Favosites* spp., (?) *Gephuropora* sp., *Thamnopora* spp., *Syringopora* spp. *Spirifer* spp. and other brachiopods, also numerous gastropods, including *Michellia striatula* de Koninck.

The **Bloomfield Limestone**, between the Currajong and the Receptaculites Limestones, outcrops over much of " Bloomfield " property, on Duffy's Point north of Majurgong Trig. Station and on " Cavan " hill, south of Taemas Bridge. North of the Bloomfield road to old Taemas Bridge it is gently folded in conformity with the overlying Receptaculites Limestone, and its lithology is somewhat similar to that of the *yassensis* Limestone, thin-bedded limestones and shaly limestones which weather down to yellowish soil and limestone pebbles. The fauna consists chiefly of brachiopods (spirifers and rhynchonellids) and small colonies of tabulate corals.

The base of the **Receptaculites (or Sponge) Limestone** is marked by a zone of *Xystriphyllum mitchelli* (Eth. *fils*), in places associated with a small species of *Hexagonaria* (=*Cyathophyllum dunstani* auctt.). The largest colonies of *X. mitchelli* that have been observed, several feet in diameter, occur at the northern end of Duffy's Point across the Murrumbidgee from Good Hope.

The Receptaculites Limestone is a massive, bedded limestone, lithologically similar to the Currajong Limestone but with a greater amount of silicification and a much more varied fauna. Being higher in the sequence within the synclinorium its outcrop occurs within that of the Currajong Limestone. South of the Murrumbidgee River it is confined to two small synclines; the eastern one is an elongated basin sharply pinched within the Bloomfield beds, and appears in section across the Tumut road near " Cavan " gate with almost vertical dip. The more westerly syncline, with the base of another on its north-easterly margin, is more open and its northerly continuation across the River is well-exposed in the southern part of " Bloomfield " property.

On the hill about half-a-mile north of the Bloomfield road, Por. 208, Par. Warroo, the basal beds of the Receptaculites Limestone occur in three synclines, the small easterly one being isolated while the others carry on northwards towards the mouth of Warroo Creek. The more easterly of these becomes closely pinched and is finally cut off by the Warroo Fault, while the other crosses Warroo Creek and the Murrumbidgee River to Por. 206 and adjacent portions, Par. Warroo, and again across the River to Duffy's Point in the Parish of Taemas, opening out to form the striking basin in which the overlying beds occur.

A single zone of *Receptaculites australis* Salter occurs within about twenty feet of the base of this limestone, and specimens have been found at this horizon in all outcrops shown on the accompanying map, and not elsewhere. In addition to the fossils already mentioned the fauna includes *Devonospongia* ('*Archaeocyathus* ?') *clarkei* (de Kon. 1877), (?) *Disphyllum* sp. (not *gemmiforme*), *Favosites* spp., *Thamnopora* spp. *Syringopora* spp., *Roemeria* cf. *ocellata* Hill *Lioclema* cf. *reeftonensis* Allan, and a fenestrate bryozoan; *Amphipora* sp.: species of *Spirifer*, *Chonetes*, *Camarotoechia* and other small brachiopods; *Loxonema* spp. and other gastropods and pelecypoda.

The **Warroo Limestone** overlies the Receptaculites Limestone at the mouth of Warroo Creek and to the north-west of it. The lower part consists of thin-bedded limestone and shaly limestone, richly fossiliferous in small forms and showing differential surface silicification of the included fossils. About 40 to 50 feet above the base there is an abundance of a small zaphrentid coral, *Metriophyllum* sp. (*cf. M. erisma* Hill in the Buchan beds in Victoria). In its upper part the Warroo limestone is more massive.

The **Crinoidal Limestone** occurs in the centre of the syncline exposed along the crest of the ridge in Pors. 206, 126 and 127, Parish of Warroo, and across the Murrumbidgee River in Por. 133, Parish of Taemas. It is a massive well-bedded limestone, composed of coarsely crystalline pink and white calcite, and consisting almost entirely of the ossicles of crinoids. It is unlike any other limestone I have seen in Australia. Some bands of fine tuff are interbedded with the limestone, which is overlain by about 100 feet of fine tuff towards the southern end of its outcrop. No complete crinoid specimens have been identified; the disintegrated remains have been water-sorted and the rock shows an extraordinary abundance of current-bedding. The lower beds contain an appreciable amount of iron hydroxide, chiefly along the planes of true and false bedding, which stand out in relief on weathering (Plate V, fig. 5). The difference in body-colour due to the content of iron hydroxide in the lower and upper parts of the Crinoidal Limestone is sufficiently marked to be distinguishable in air-photographs of the area.

A fairly large cave in the Crinoidal Limestone occurs in Por. 126, Par. Warroo, and there are several large sink-holes in this limestone to the north. Other such caverns occur in the Currajong Limestone and seem to be related to widely-spaced bedding and joint planes in the more massive limestones. Similar caves are known in the Goodradigbee limestones, but little exploration has been done in those of the Taemas area, so that their full extent is not known.

Igneous Intrusions

In the valley of Majurgong Creek and along the road to Good Hope north of Hume Park there is an outcrop of granite—shown on the map as the Hume Park Granite. It is a biotite-granite, coarse to medium grained, with petrological and structural characters similar to those of post-Middle Devonian granites of this region of New South Wales. Its full extent is not known, but it is intrusive into Silurian tuffs and Yass sandstones, and on its western margin is faulted against Devonian rhyolites between Hume Park and Good Hope. No evidence of its intrusion into the rhyolites is known. Possibly co-magmatic with this granite is the quartz-mica-felspar-porphyry intrusive into Silurian tuffs on the hillslopes west of Warroo Trig. Station, near the Yass road.

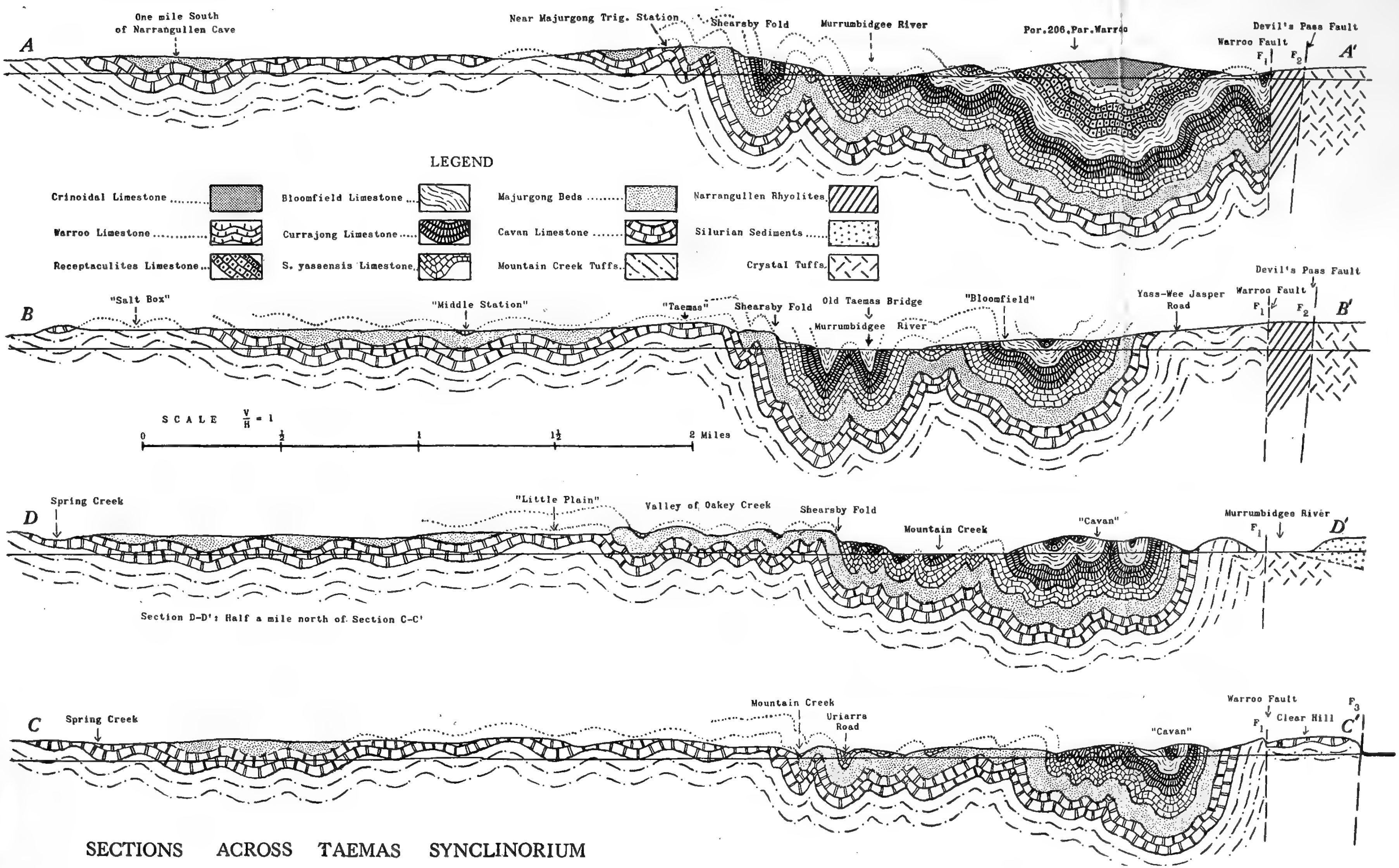
At present the age of this granite is not known; it post-dates the Silurian sediments and is older than the faulting that has dislocated the Middle Devonian limestones. Provisionally it may be regarded as late Middle Devonian.

Geological Structure

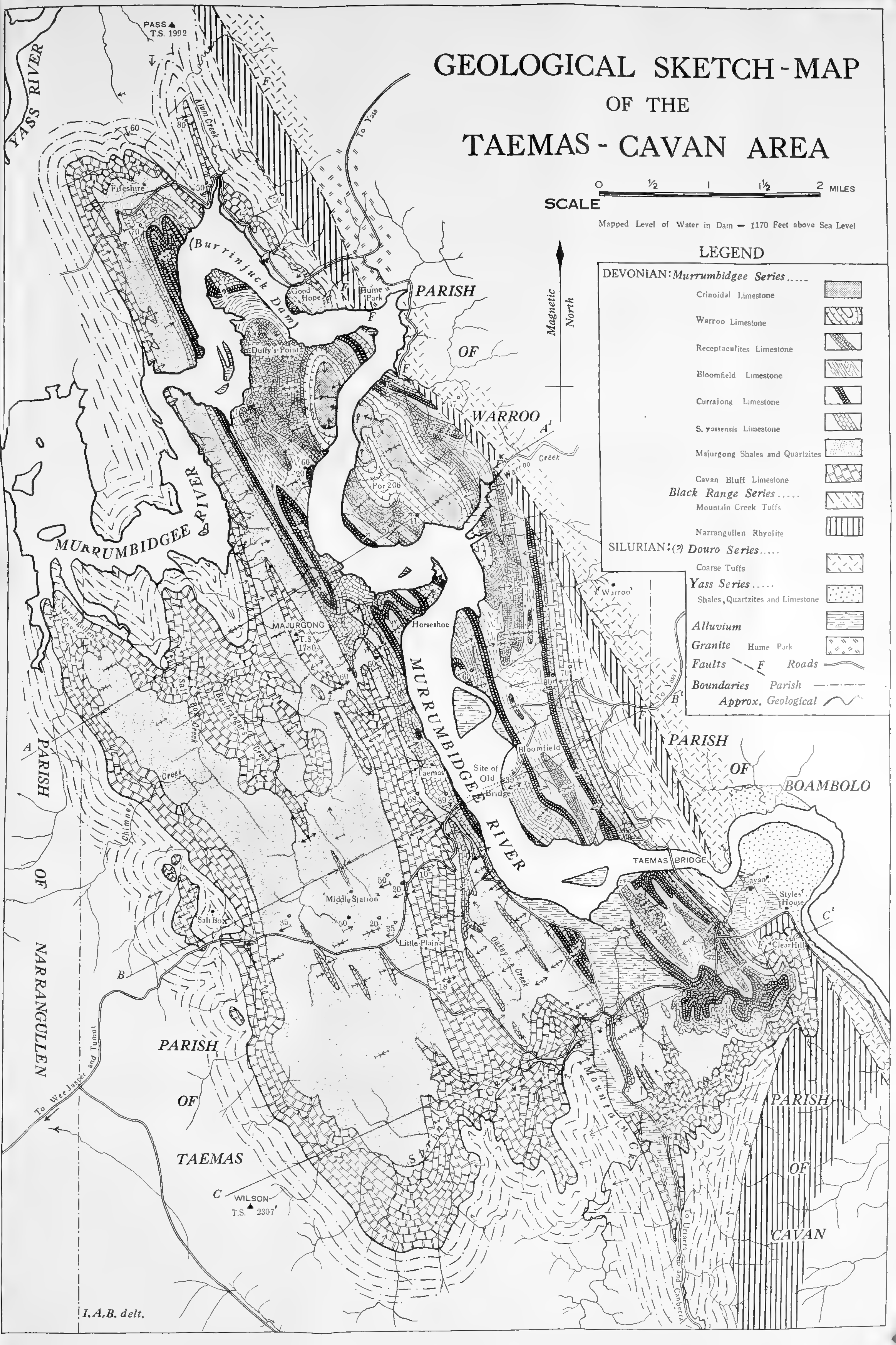
Folding. The general geological setting of the Taemas synclinorium has already been described (Browne, 1954). Briefly, rhyolites of Narrangullen Mountain form the core of an anticline plunging gently to the north. These are overlain by the Mountain Creek tuffs, black shales and greywackes, which are succeeded by extensive marine beds, chiefly limestone. Folding has produced synclinal structures on either side of the Narrangullen anticline, and subsequent erosion has separated the outcrops of the limestones. The western basin, situated in the lower part of the Goodradigbee valley, appears to be a relatively simple structure, but the eastern one, which has been called the Taemas synclinorium, is much more complex.

Reference to the accompanying map and sections shows that the Taemas synclinorium may be regarded as a double basin on which corrugations and minor folds are superimposed. The axes of folding run approximately N.N.W. and S.S.E. The western basin, centred about "Middle Station", is very shallow; on its eastern boundary is an anticline whose steeply dipping eastern limb forms the western side of the eastern basin. This structure is named the Shearsby Fold; it runs through the locality of "Shearsby's Wallpaper", near the mouth of Oakey Creek. The eastern basin lies between the Shearsby Fold and the Warroo Fault, and is a downfolded area about 10 miles long and two miles wide. The sections given on Plate VII along the lines indicated in the map (Pl. VI) are drawn to natural scale to illustrate my interpretation of the structure and are based on all the field-evidence available to me.

The relative depths of the two main basins are clearly seen; the eastern basin at its greatest depth below the Crinoidal Limestone hill contains limestone



SECTIONS ACROSS TAEMAS SYNCLINORIUM


GEOLOGICAL SKETCH-MAP
OF THE
TAEMAS - CAVAN AREA
SCALE
0 ½ 1 1½ 2 MILES
Mapped Level of Water in Dam — 1170 Feet above Sea Level
Magnetic North
LEGEND
DEVONIAN: Murrumbidgee Series.....
Crinoidal Limestone
Warroo Limestone
Receptaculites Limestone
Bloomfield Limestone
Currajong Limestone
S. yassensis Limestone
Majurgong Shales and Quartzites
Cavan Bluff Limestone
Black Range Series.....
Mountain Creek Tuffs
Narrangullen Rhyolite
SILURIAN: (?) Douro Series.....
Coarse Tuffs
Yass Series.....
Shales, Quartzites and Limestone
Alluvium
Granite Hume Park
Faults F
Roads
Boundaries Parish
Approx. Geological
YASS RIVER
PASS T.S. 1992
Alum Creek
To Yass
Fifeshire
(Burrinjuck Dam)
Good Hope
Hume Park
PARISH OF WARROO
Duffy's Point
Por 206
Warroo Creek
Warroo
MURRUMBIDGEE RIVER
Narrangullen Caves
MAJURGONG T.S. 1780
Horseshoe
Salt Box Creek
Bushrangers Creek
Chimney Creek
Taemas
Site of Old Bridge
Bloomfield
To Yass
PARISH OF BOAMBOLO
TAEMAS BRIDGE
Cavan
Styles' House
Clear Hill
Middle Station
Salt Box
Little Plain
Oakey Creek
PARISH OF NARRANGULLEN
To Wee Jasper and Tumut
PARISH OF TAEMAS
Spring Cr.
Mountain Cr.
WILSON T.S. 2307'
PARISH OF CAVAN
To Uriarra and Canberra
I.A.B. delt.

to a total thickness of about 3,500 feet. The eastern basin itself is a double one, being divided by an anticlinal structure which takes a somewhat sinuous course from the south-eastern boundary of the Cavan Limestone through the mouth of Mountain Creek, along the eastern bank of the Murrumbidgee River on " Bloomfield ", across the Horseshoe (Taemas) peninsula, through Duffy's Point and northwards across the River again to the west of Alum Creek. The more easterly syncline is the deeper, but that immediately east of the Shearsby Fold shows the greater degree of crumpling.

The major folds are all composite, having minor folds superimposed on them; some of these are symmetrical, like the much-photographed Taemas anticline, others are asymmetrical, as illustrated in Plate IV, fig. 1. The axes of the more regular, symmetrical folds are approximately parallel to the Shearsby Fold, and their crests are about 400 yards apart (Plate V, fig. 4).

A small composite basin has been formed in the valley of Oakey Creek by the bifurcation of the Shearsby Fold near the western approach to old Taemas Bridge. The cross-warping developed here has produced several small domes and basins, seen in section along D–D′, a line about half-a-mile north of the line C–C′ marked on the Map.

Axes of both major and minor folds rise and fall appreciably, producing minor elongated domes and basins, as for instance in the vicinity of " Middle Station ".

The **Shearsby Fold** may be regarded as a large asymmetrical fold caused by the abrupt downwarping of the eastern half of the Taemas synclinorium. The fold affects a zone nearly half-a-mile wide through the Mountain Creek Tuffs, the Cavan Limestone, the Majurgong beds and the lower part of the Taemas beds. It runs in a direction approximately N. 30° W. from the Uriarra road on the south, through the Tumut road-cutting west of Mountain Creek bridge, along the ridge east of Majurgong Trig. Station, across the Murrumbidgee River and on towards the Yass River. On its western flank is a long narrow syncline, which has produced a complicated pattern of outcrops of the Majurgong beds in contact with the underlying and overlying limestones. On the eastern limb of the fold the beds dip at angles of from 65 to almost 90 degrees. No real overfolding has been observed in the district.

The Shearsby Fold has had a spectacular effect on the outcrops of the limestones; the Cavan Limestone on the Tumut road west of Mountain Creek bridge appears to have been displaced horizontally as if by faulting to a position about a mile to the south-south-east. Careful investigation shows that no significant dislocation has occurred; the rocks have behaved as if plastic and the strain of folding has been taken up by slickensiding along closely-spaced bedding-planes in the limestones and associated shales.

The outcrop of the steeply dipping limestone swings sharply to the south on the bank of Mountain Creek south of the Tumut road and is covered by alluvium in the bed of Mountain Creek for about three-quarters of a mile to the south, but reappears on the same line of strike on the left bank of Mountain Creek before turning east to form part of the eastern Taemas basin. The overlying Majurgong beds and Taemas limestones show sympathetic folding.

Along the northern extension of the Shearsby Fold a similar effect has been produced on the outcrops of the basal limestones and the overlying sediments, which are carried around to the north of " Fifeshire " property.

Faulting. In the earlier paper (Browne, 1954) it was considered that four or more major faults occurred in the Taemas synclinorium, but re-examination of the outcrops under more favourable conditions has shown that there are only two major faults and that the other supposed dislocations are the effects of folding.

The two important faults may be termed the **Devil's Pass Fault** and the **Warroo Fault.**

The former, which crosses the Yass River at the Devil's Pass, throws basal Devonian rhyolites against coarse crystal tuffs of the Yass Silurian sequence; north of Good Hope road these are probably the Laidlaw Tuffs and south of Majurgong Creek they are possibly the Douro Tuffs (Brown, 1941). In the valley of Majurgong Creek and at Hume Park, south of Good Hope, the rhyolite is faulted against the Hume Park granite.

The Devil's Pass Fault crosses Warroo Creek and continues south to the Yass–Wee Jasper–Tumut road near the boundary of the parishes of Boambolo and Warroo; between this point and the Murrumbidgee River half-a-mile above Taemas Bridge it is difficult to tell whether the Silurian–Devonian boundary is a fault or an unconformity. The Devil's Pass fault may cut through Silurian tuffs and be difficult to distinguish, otherwise it dies out on its old line of strike and re-appears *en échelon* to the east; this fault again throws rhyolites against Silurian crystal tuffs and fossiliferous Yass sediments, and has been traced from Styles' house, near Clear Hill, for several miles to the south-east.

The Devil's Pass Fault dips at a high angle towards the south-west and appears to be a normal fault with a throw of considerable but indeterminate magnitude.

The Warroo Fault, observed chiefly in the Parish of Warroo, runs approximately parallel to the Devil's Pass fault and about a quarter of a mile to the west of it. A considerable amount of silicification is associated with it. It also appears to be a normal fault, with a high dip to the south-west, and in the vicinity of Warroo Creek it has brought rhyolite against stratigraphically higher tuffs, limestones and shales. South-east of Taemas Bridge, at the western end of Clear Hill, it causes dislocation of the strata, but south-east of this it dies out as a flexure.

The occurrence of these two major faults is responsible for the relatively insignificant outcrops of the Narrangullen rhyolite and Mountain Creek tuffs along the eastern side of the Taemas synclinorium.

Cleavage, etc. The rather intense folding of the Taemas and Cavan sediments has set up strains that have been relieved by cleavages in the limestones, shales and quartzites which are frequently more obvious than the true bedding-planes.

Good exposures showing the relation of cleavage to bedding defined by fossil-shells occur in the road cuttings on the Tumut road both east and west of Mountain Creek and in the valleys of the creeks tributary to the Murrumbidgee River to the north. Cleavage and possibly also tension-jointing are very prominent in the steeply dipping quartzite bands in the Majurgong beds along the eastern slopes of the Majurgong ridge.

In general the cleavage planes run in the direction of the fold-axes and cut the bedding planes at high angles; some of these may be regional, others appear to be approximately radiating from the axes of curvature of the folds. General observations only have been made so far, but there are good exposures for a detailed study of the structures within the sediments of this region. (See Plate IV, fig. 3).

Structural Relations with the Silurian

It has already been stated (Brown, 1941; Browne, 1954) that the Devonian formations of the region overlie the Silurian with a marked unconformity, and more recent observations at special points around the main Devonian structure between Bowning and Burrinjuck have confirmed this conclusion.

In the area under consideration the boundary of the Silurian and Devonian is in the main a faulted one along the Devil's Pass fault. However, the fact that various formations low in the Silurian sequence dip in directions widely different from those in the Devonian with which they are in contact, suggests that even prior to faulting unconformable relations existed between them. It is possible that movement took place along an old unconformity.

In the small area between " Cavan " house and Clear Hill, between the two meridional faults, the structure is obscure on account of poor outcrops. The Cavan limestones at the Bluff, Clear Hill, overlie a thin bed of Devonian lavas and tuffs, and are separated from sandstone, probably belonging to the Yass stage of the Silurian, by the alluvium of an old ox-bow lake of the Murrumbidgee River. As there seems to be no evidence of cross-faulting in the adjacent rocks it is possible that an unconformity is present here.

There is certainly an important faunal break between the fossiliferous shale of the "Upper Trilobite Bed" of Bowning and the next known fossiliferous formation, the Couvinian Cavan Limestone of Clear Hill.

Geological Age and Correlations

De Koninck (1877) described from the Cavan area a sponge, " ?*Archaeocyathus clarkei* " [which Howell (1957) has made the type of a new genus *Devonospongia*], several corals, about twelve species of brachiopods, and about twenty species of pelecypods and gastropods. Many of these he recognized and named as new species, but some he referred to European species occurring at Torquay, Plymouth, the Eifel and elsewhere in Europe and North America. He was therefore convinced of the Middle Devonian age of the Cavan fauna.

This verdict has been accepted by all later palaeontologists who have published descriptions of fossils from the Taemas and Cavan limestones, including Dun (1897, 1904), Etheridge (1906, 1920), Hills (1933, 1941, 1943), Allan (1935), Hill (1941), Bassler (1944), White (1952), Howell (1957) and others, reference to whom is made by Benson (1922).

A more precise age for the Bluff limestone was suggested by Dr. D. Hill (1941). Her study of the rugose corals and their comparison with extra-Australian forms led her to believe that the coral fauna " of the lowest (Bluff) limestone indicates either the beds transitional from the Coblenzian or the very base of the Couvinian ; the rather higher Sponge [=Receptaculites–I.A.B.] limestone may represent part of the Upper Couvinian ".

The discovery of fossiliferous limestones younger than the *Receptaculites* bed during the course of the present investigations, and the study of additional material collected, should lead to a clearer picture of the general composition, geological range and order of succession of the faunas than has been presented hitherto. At present only brief reference will be made to occurrences of similar age.

It is natural that the closest correlation is to be made with the limestones along the Goodradigbee River, some of which were mapped by Harper (1909, Map I). The lithology and fauna of the most easterly belt of limestone, on the right bank of the Goodradigbee valley, are exactly similar to those of the Cavan limestone, and the overlying red beds are to be correlated with the Majurgong beds. The upper limestones are much more massive than their equivalents at Taemas and Cavan, and are not so fossiliferous, although there are a number of species in common.

Thus there seem to be both lithological and palaeontological facies distinctions between the Taemas and Goodradigbee occurrences, although they belong to the same sedimentary basin, as believed by Benson (1922).

The Middle Devonian limestones of Lobb's Hole or Ravine on the Yarrangobilly River, originally described by Andrews (1901) and since examined by other members of the Geological Survey of New South Wales, are both lithologically and palaeontologically similar to at least part of the Taemas succession.

Receptaculites australis has been found in Middle Devonian rocks at Tarago, in the Garra beds near Molong (Joplin and Culey, 1938), and in the Sulcor limestone north of Tamworth (Brown, 1942), as well as in the Buchan and Bindi beds in Victoria.

Correlations based on the occurrence of rugose and tabulate corals may also be made with other limestones of New South Wales and Reefton, New Zealand (Allan, 1935 ; Hill, 1956).

The faunas of the Middle Devonian limestones of Buchan, in Victoria, described by Hill (1950), Teichert and Glenister (1952) and Talent (1956) indicate that this area also was part of the same faunal province in south-eastern Australia in Middle Devonian time.

Geological History

A general account of the suggested geological history of the region has already been given (Browne, 1954).

The conditions of sedimentation of the limestones and associated beds is of special interest. The lithological and palaeontological uniformity of individual beds suggests that similar conditions of sedimentation and biological environment existed over a wide area.

Such conditions obtain in some of the large coral atolls of the present time, as for example, the Bikini Atoll (Ladd, 1950 ; Emery, 1948), where the reef-building organisms are chiefly corals, forams and algae. However, there seem to be important differences from the Devonian limestones. The Taemas sediments form only portion of a much more widely spread occurrence, which probably occupied much of the Tasman geosyncline during Middle Devonian time. In the Taemas area corals played only a minor role ; small, solitary and tabulate corals are widely distributed, but with minor exceptions like *X. mitchelli*, there are no " coral reefs ", the corals occurring in biostromes, not bioherms. Brachiopods are the most abundant fossils, occurring in widely distributed shell-beds or coquinas, which must have been formed under shallow-water conditions. This inference is confirmed by the presence of ripple-mark (both oscillation and current ripples), current-bedding (notably in the Majurgong beds and in the Crinoidal Limestone—Plate V, fig. 5), and other evidences of wave and current action.

A considerable thickness of true sedimentary limestone, some of it with varve-like lamination, is found throughout the sequence. The amount of dolomitization of the limestones has not yet been determined, and further study is to be made of the cause—possibly biological—of the differential, partial silicification of some of the limestones. A study of the sedimentation of this area is being made by Dr. Gordon Packham.

On the available evidence it would seem that the Taemas and possibly the Goodradigbee and Lobb's Hole limestones are to be compared with the edge of the " basin " deposits—in contrast with those of the " shelf " or the " reef " (marginal) deposits—of the Delaware Basin of Permian age, described by Newell *et al.* (1953). All of the characters of the Taemas limestones and associated red-beds may be matched with those of parts of the Guadalupian deposits of the Delaware Basin.

The tectonic history has not been fully investigated in relation to the surrounding region and there is no direct evidence within the Taemas synclinorium of the precise age of the folding and faulting.

The remarkable folding of the beds of limestone and shale without significant accompanying fracture suggests that it occurred before complete lithification of the strata, probably at the close of Middle Devonian time (Tabberabberan epoch).

The Warroo and Devil's Pass faults post-date the folding of the strata, but their parallelism with the Shearsby Fold on the other side of the eastern basin suggests that the faulting belonged to the same epoch of orogeny.

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Explanation of Plates.

Plate IV.

Fig. 1.—Asymmetrical Fold in S. yassensis Limestone on the north side of the peninsula, Murrumbidgee River, Por. 11, Parish of Taemas, viewed obliquely from the north-east. Photo. by A. J. Shearsby.

Fig. 2.—Typical appearance of the outcrop of the Currajong Limestone, Por. 85, Parish of Cavan. View one mile south-east of Taemas Bridge along the strike of the beds, which dip to the west (right) at about 80 degrees.

Fig. 3.—Red shales and quartzites of Majurgong Stage, showing beds dipping to the east (direction of hammer handle), with conspicuous cleavage dipping to the west. Cutting on the Yass–Wee Jasper Road 100 yards west of the Bridge over Mountain Creek, Por. 6, Parish of Taemas.

Plate V.

Fig. 4.—Gentle folds in Cavan Limestone showing radiating cleavage. Pors. 119–113, Parish of Cavan. East of Uriarra Road one mile south of Yass-Wee Jasper Road.

Fig. 5.—Current-bedding in Crinoidal Limestone. Exposure in north-western part of Por. 206, Parish of Warroo, overlooking the Murrumbidgee River, about a mile south of Hume Park, near Good Hope.

Fig. 6.—Surface of mud-cracks in calcareous shales of Cavan Limestone. The cracks extend down for more than six inches, producing columnar structure in the rock. Por. 14, Par. Cavan, east of Uriarra road one mile S.E. of Mountain Creek bridge.

Plate VI.

Geological Sketch-Map of the Taemas–Cavan Area.

Plate VII.

Sections across the Taemas Synclinorium along the lines A–A′, B–B′, C–C′ and D–D′, (the last being half a mile north of C–C′), as shown on the Map—Plate VI.

NOTES ON THE EARLY TERTIARY BASALTS OF SOUTH-EASTERN QUEENSLAND.

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Abstract.

A re-arrangement is made of Richards' subdivisions of the Tertiary volcanic rocks of South-eastern Queensland involving the transfer of the Bundamba basalt (part of the Booval Group) from his upper to his lower division, where its chemical and petrological affinities lie. This basalt is demonstrably Palæogene. In a tabular statement the author's view that the Upper Basalts and the Rhyolites, etc. are Oligocene and the Lower Basalts Eocene is compared with the interpretations of other workers.

General.

Richards (1916) divided the " Volcanic Rocks of South-eastern Queensland " into an upper division of basaltic rocks of " ? Upper Cainozoic " age, a Middle Division of acid and sub-acid rocks of " ? Middle Cainozoic " age and a Lower Division of basaltic rocks of " ? Lower Cainozoic " age.

To his Lower Basalts Richards admitted only those which the local evidence showed were beneath the Middle Rhyolites in an almost literal sense.

On the other hand his Upper Basalts included, apparently for geomorphological reasons, not only those which were securely placed above the Rhyolites, but a third suite of basalts in the neighbourhood of Brisbane and Ipswich, which form part of the stratigraphical succession that is now known as the Booval Group (Staines, 1959). It is the purpose of this paper to emphasize :

1. That the basalts of the Booval Group are of Lower Cainozoic age.
2. That they are closely comparable in chemical, mineralogical and textural characters with Richards' Lower Basalts *sensu stricto*.
3. That, ironically, the transfer of the basalts of the Booval Group from Richards' Upper to his Lower Basalts establishes securely the Lower Cainozoic age that he had tentatively suggested for the Lower Division.
4. That the Lower Basalts as redefined, instead of being indistinguishable from those of the Upper Division as Richards declared, form a natural group with clearly marked characteristics.

The Age of the Basalts of the Booval Group.

Richards (p. 123) stated that " The basalts of Coopers Plains and the trachytic material at Redbank Plains both overlie the Oxley beds as shown by Marks and Cameron. The Oxley beds which contain remains of dicotyledonous plants, fish and reptiles are most probably Tertiary, though they may be Cretaceous. In any case these occurrences of volcanic rocks are certainly post-Trias-Jura and most likely Cainozoic in age ".

In an earlier paragraph (p. 106) Richards had expressed the opinion that " Owing to the absence of any important development of fossiliferous rocks since late Mesozoic times, physiographical considerations must be availed of in elucidating the Cainozoic history of this area ".

It was thus probably as a result of geomorphological evidence, although this is not specifically stated, that Richards' said of the Bundamba basalt (p. 175) " This represents one of the most recent flows in the whole of the area ".

But this basalt, together with that of Coopers Plains and others in the district, is now regarded as contemporaneous with fossiliferous freshwater sediments that on the evidence of the fish fossils was assigned by Hills (1934) to the Oligocene and later by other authors including David (1950, Table XXVI) to the Eocene. There is at least general agreement that these basalts are Palæogene and they are now included in the Booval Group which embraces the Redbank Plains Formation followed conformably by the Silkstone Formation.

Comparison of Basalts of Booval Group with Lower Basalts.

Although some variety exists within each of the groups to be compared, attention is directed to one rock type from each, for which Richards provided a full microscopical description, a microphotograph and a chemical analysis. These very similar rocks came from Bundamba and Chinghee Creek respectively.

Of specimen 237 from the Quarries, Bundamba, Richards wrote (p. 175):

" It is a compact non-porphyritic basalt, and under the microscope it is seen to be holocrystalline. The brown glass which is studded with rod-shaped crystals of iron-ore is not very abundant. (See Plate XIV, fig. 4). The rock is rather coarse in texture, the plagioclase laths averaging 0·6 mm. in length, and the augite which occurs in ophitic patches well developed may extend to 1·5 mm. in length.

Olivine is abundant, and occurs in rounded crystals up to 1 mm. in diameter. The plagioclase is an acid labradorite.

This rock is certainly a flow, and it shows ophitic structure better developed than in any other rock examined. Specific gravity 2·92. Name: Basalt."

The above description (which is also applicable word for word to the neighbouring basalt from Coopers Plains) should be closely compared with that of Richards' typical Lower Basalt, namely Specimen 94 from Chinghee Creek, portion 69, Parish of Telemon, which is as follows: " This is one of the flows from the first eruption, and it is found below the rhyolite agglomerate. In the hand-specimen it is a compact rock, which shows occasional plagioclase phenocrysts. When examined microscopically it is seen to be holocrystalline with very occasional plagioclase phenocrysts set in a groundmass with plagioclase averaging ·5 mm. in length, and showing a rough fluxion structure. The plagioclase is both medium and basic andesine, but the latter is the more abundant. (See Plate XIV, fig. 3). Ophitic structure is very well developed, and the enclosing augite by its violet colour is apparently the titaniferous variety.

Olivine granules which are altering into serpentine are abundant, and they have an average size of 0·25 mm. in diameter. Allotriomorphic grains and rods of iron-ore are plentiful. The specific gravity of this rock is 2·76 and an analysis is given. Name: Basalt." (See p. 169.)

Each of the above descriptions was accompanied by a microphotograph and fortunately for our purpose, they are shown in juxtaposition. (See Plate XIV, figs. 3 and 4). As these are so very similar and are both so unlike any of the other seven basaltic rocks illustrated, one wonders whether they were deliberately set side by side, to emphasize their similarities in spite of their having been assigned to two different groups separated by a considerable time interval.

Turning now to the chemical evidence (Table VII) it is interesting to compare the analyses of the two rocks, the descriptions of which have just been quoted.

Although the chemical composition of the Bundamba basalt is clearly similar to that of Chinghee Creek, the composition of the Cooper's Plains basalt is even more closely comparable (see Richards' Table VII, No. 29).

It is even more significant that, in the series of Brögger diagrams which have been assembled by Richards on Plate V (based on purely chemical similarities and regardless of whether the basaltic rocks were from the upper or lower division), the only diagram representing his Lower Basalts, namely No. 30 from Chinghee Creek, is placed by him adjacent to No. 29 from Cooper's Plains, which in turn lies next to No. 26 from Bundamba whereas, on the other hand, there is not one closely comparable diagram among those of the Upper Basalts proper.

The Place of the Booval Group in Richards' Scheme.

The evidence that has been presented—stratigraphical, chemical, mineralogical and textural—all points to the necessity for removing the basalts of the Booval Group from Richards' Upper Division and inserting them into

	No. 26 Quarries, Bundamba	No. 30 Chinghee Creek
SiO_2	51·69	49·90
Al_2O_3	13·16	15·79
Fe_2O_3	3·99	4·52
FeO	8·65	6·25
MgO	6·84	5·77
CaO	8·41	9·12
Na_2O	2·76	3·24
K_2O	0·45	0·89
H_2O+	1·00	1·36
H_2O-	0·55	1·28
CO_2	—	—
TiO_2	1·70	1·98
P_2O_5	0·28	0·43
MnO	0·14	0·12
&c	—	—
Total	99·62	100·65
Sp. Grav.	2·92	2·76

his Lower Division where they can be securely correlated with the typical basalt of that Division as defined by Richards himself. Such a transfer would strengthen very considerably, indeed would establish, Richards' own tentative suggestion that his Lower Basalts were of Lower Cainozoic age.

The Lower Basalts as a Natural Group.

Richards (p. 165) came, reluctantly one thinks, to the conclusion that: "It is impossible to distinguish between the basalts of the lower and upper divisions, as they do not differ chemically, macroscopically or microscopically to a sufficient extent to enable one to do so".

The chief reason for this inability was almost certainly the admission to the upper division of rocks which at the same time resembled closely those of the lower division and differed very considerably from those of the upper division proper.

When the lower basalts are re-defined to include those of the Booval Group they form a suite with quite well-defined characteristics, for they are typified by coarsely crystalline olivine basalts with certain notable features, such as pronounced ophitic texture, usually found in dolerites.

Following the extraction of the basalts of the Booval Group from the Upper basalts of Richards, these become a somewhat less heterogeneous assemblage.

Volcanic Rocks of South-eastern Queensland.

<table>
<tr><th>Age</th><th>Richards 1918</th><th>Bryan & Jones 1946</th><th>David (Browne) 1950</th><th>Bryan (herein)</th><th>Richards' views reinterpreted</th></tr>
<tr><td>Pliocene</td><td>Upper Basalts including Basalts of the Booval Group</td><td>Upper Basalts Rhyolites Lower Basalts</td><td></td><td></td><td>Upper Basalts excluding Basalts of the Booval Group</td></tr>
<tr><td>Miocene</td><td>Rhyolites, etc.</td><td></td><td></td><td></td><td>Rhyolites, etc.</td></tr>
<tr><td>Oligocene</td><td rowspan="2">Lower–
–Basalts</td><td>Basalts of the Booval Group</td><td>Upper Basalts Rhyolites, etc. Lower Basalts</td><td>Upper Basalts Rhyolites, etc.</td><td rowspan="2">Lower Basalts including Basalts of the Booval Group</td></tr>
<tr><td>Eocene</td><td></td><td>Basalts of the Booval Group</td><td>Lower Basalts including Basalts of the Booval Group</td></tr>
</table>

Conclusion.

The accompanying table has been drawn up to show as simply as possible the changing views that have been advanced with regard to the place of the Lower Basalts.

I have also indicated, incidentally, my personal view as to the upper limit of Richards' three-fold development in which I find myself in full agreement with David (1950, p. 572) and for the reasons given by that author.

I have, too, after considerable hesitation and with some diffidence, added as a final column a re-interpretation of Richards' succession, of which I think he would have approved and which I think may appeal to many geologists, but to which I personally am now unable to subscribe.

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MICROFOSSILS IN AUSTRALIAN AND NEW GUINEA STRATIGRAPHY.

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Introduction.

It seems appropriate that a review of the progress of Micropalaeontology in Australia and New Guinea should be contributed to the David Centenary Volume, because, as far back as 1896, Professor David was associated with scientific publications on the presence of one of the groups of microfossils, the Radiolaria, in the Palaeozoic rocks of New South Wales (David, 1896 ; David and Pittman, 1899). He also made valuable contributions to the study of diatomite deposits in that State (David, 1896).

Micropalaeontology has since assumed considerable importance in stratigraphical work throughout the world, and this contribution presents, for the first time, a comprehensive historical review of progress made in Australia and New Guinea. Each group of microfossils is dealt with individually and a comprehensive but not exhaustive bibliography relating to each group is given.

Uses of Micropalaeontology.

Advances in the study and use of micropalaeontology in Australia over the last decade have been tremendous, primarily because of the increased activity in the search for oil. It has also played a part in coal research and subsurface water investigations. Microfossils have been studied in great detail both from surface outcrop and subsurface sections, and recent investigations have shown them to be abundant in rocks as old as the Lower Ordovician.

Glaessner (1945) discusses at some length the problems of micropalaeontological correlation of sedimentary rocks and the use of micropalaeontology in petroleum exploration.

Microfossils in Australian and New Guinea Sediments.

The groups of microfossils so far recognised in Australian and New Guinea sediments are :

- Foraminifera
- Radiolaria
- Calpionellidae
- Holothurian sclerites
- Alcyonarian sclerites
- Sponge spicules
- Conchostraca
- Ostracoda
- Microplankton
- Conodonts
- Spores and Pollens
- Microscopic algæ including Diatoms

* Submitted for publication with permission of the Director of the Bureau of Mineral Resources, Geology and Geophysics, Canberra.

Included under microfossils are the microscopic parts of skeletons of larger animals such as sponges, and spores and pollens of plants. Minute fragments of bryozoa are sometimes included under microfossils, but this group is not discussed in this contribution.

Early micropalaeontological investigations in Australia and New Guinea, especially in connexion with oil-field exploration, were practically restricted to the foraminifera, but new fields of research have been opened up recently with the study of microplankton and spores and pollens.

Although palaeontologists, notably Professor Walter Howchin, had published papers on the foraminifera in the latter part of the nineteenth century, the use of micropalaeontology greatly increased when Frederick Chapman arrived in Australia in 1902 as Palaeontologist to the National Museum, Melbourne.

Shortly after the Commonwealth Government became interested in the search for oil in Papua (Wade, 1914) Chapman (1918) recognised the importance of the foraminifera in sediments of that region. After the Geological Section of the Department of Home Affairs was created in 1927, with Dr. W. G. Woolnough as the first Commonwealth Geological Adviser and Chapman as Commonwealth Palaeontologist, foraminifera were extensively used in age determination of rocks throughout the Commonwealth; they now play an exceedingly important part in major stratigraphical correlations. In 1940 Woolnough arranged that the Water Conservation and Irrigation Commission of New South Wales should submit samples from bores for micropalaeontological examination. Foraminifera have also been extensively used in connexion with boring for coal in New South Wales. In 1944 Beasley suggested that ostracoda might be useful in correlation in the Triassic coals of Queensland.

Although the foraminifera still maintain their importance in geological work, probably the most striking advances in micropalaeontology in Australia in the last few years have been in the application of the study of spores and pollens to age determination of non-marine sediments and the discovery of microplankton in marine Palaeozoic rocks. In 1945 Dulhunty made the first detailed study of microspores in the Permian Coals of New South Wales. More recently Dr. I. C. Cookson and B. E. Balme have made comprehensive studies of spores and pollens and have shown their usefulness in stratigraphy. Cookson (1953) also pioneered the study of microplankton in Australia when she found them in rocks of Mesozoic and Tertiary ages. The advances in the study of these microfossils will be discussed later.

Foraminifera.

An exhaustive list of references to foraminifera in Australia is given by Crespin (1955) and the publications listed later in this review include only references used in this section, together with publications since 1954. The bibliography contains names of many well-known micropalaeontologists who have contributed to the knowledge of Australian and New Guinea foraminifera: such names as Chapman, Earland, Glaessner, Heron-Allen, Howchin, T. R. Jones, W. K. Parker, Parr and Schlumberger.

Some correlations of Tertiary deposits have been based on the presence of larger foraminifera (Crespin, 1948, 1950); but the smaller forms, especially the planktonic genera, are now most widely used in stratigraphic work (Glaessner, 1943; Crespin, 1956, 1956a; Belford, 1959). The apparent absence of fusulines in Australian Permian deposits (Crespin, 1958) has delayed the correlation of these beds with Permian sequences outside Australia.

Two references to foraminifera in the Australian region were given by early micropalaeontologists. In 1826 d'Orbigny described the well-known warm-water form *Alveolina quoyi* from the "L'Ile de Rawack, Nouvelle-

Holland ", and in 1843 Ehrenberg listed three species from Australian waters. The first published record of fossil foraminifera was in 1860 in a note by Parker and Jones on the foraminifera from the Tertiary limestone of Mt. Gambier, South Australia.

Apart from a few doubtful references to earlier material (Chapman, 1914, 1918, 1923) the oldest beds containing authentic foraminifera are in the Devonian of Western Australia, where numerous well-preserved arenaceous genera have recently been discovered in the Upper Devonian Virgin Hills Formation of the Fitzroy Basin (Glenister and Crespin, 1959).

Many of the foraminifera-bearing rocks previously referred to the Carboniferous are now included in the Permian (Howchin, 1894, 1895) but P. J. Jones of the Bureau of Mineral Resources has discovered an assemblage of foraminifera containing endothyrid genera in the Carboniferous of the Bonaparte Gulf Basin, Northern Australia.

The first record of Permian foraminifera in Australia is given by Jones (1882) who listed forms from the Piper River area, Tasmania, later described by Howchin (1894). One species, now referred to *Calcitornella stephensi*, is an important zonal species in the lower part of the Lower Permian in Australia. Howchin (1895) described new species from the Permian of the Irwin River district, Western Australia, and foraminifera are now known to be widely distributed in Permian sediments of that State (Crespin, 1958). Chapman and Howchin (1905) described several species from the " Permo-Carboniferous " of New South Wales, and Etheridge (1907) recorded forms from Northern Territory. Crespin (1945) found species in Queensland, and Ludbrook (1957) recorded them from a bore in South Australia. The only record of Permian foraminifera in New Guinea is by Glaessner (Glaessner, Llewellyn and Stanley, 1950).

The reference by Chapman (1909) to foraminifera in the Triassic Wianamatta beds of New South Wales is not now regarded as authentic (Lovering, 1953) and up to the present no Triassic foraminifera have been found in Australia.

Chapman (1904) described the first Australian Jurassic foraminifera from Geraldton, Western Australia ; but although rich assemblages are known from this area no further systematic work has been undertaken.

Lower and Upper Cretaceous foraminifera are known from both Australia and New Guinea. The first record of Lower Cretaceous forms was made by Moore (1870) from Wallumbilla, Queensland. The writer has studied surface and subsurface assemblages throughout the Great Artesian Basin (Crespin, 1953, 1956e) and many of the species have been recognised in sediments in Queensland, Northern Territory and Western Australia.

Chapman's publication (1917) on the Upper Cretaceous foraminifera of the Gin Gin Chalk, Western Australia, was the only systematic contribution on species of this age for many years. He listed many species from the Upper Cretaceous of the Carnarvon Basin (in Raggatt, 1936). More recently Edgell (1954, 1957) published two systematic papers on Upper Cretaceous genera in the Carnarvon Basin. D. J. Belford of the Bureau of Mineral Resources recently (1958) described a new genus from the same region and has made a contribution to Upper Cretaceous stratigraphy of Western Australia based on the foraminifera (1959).

Tertiary foraminifera of Australia have been studied since 1860, when Parker and Jones listed species from a limestone at Mt. Gambier. Howchin described foraminifera, including large forms, from the Miocene of Muddy Creek, Hamilton, Victoria (1889) and from subsurface Eocene beds of South Australia (1891). Schlumberger (1893) described the form *Trillina howchini*, now *Austrotrillina howchini*, from the Miocene beds at Hamilton. These beds were considered to be of Eocene age, because of a wrong generic determination by

Howchin of the larger foraminifera. *A. howchini* is now regarded as of zonal importance in Lower Miocene sediments throughout the Indo-Pacific region.

Two outstanding contributions have been made in recent years to the lower Tertiary stratigraphy of Australia. The first is the discovery by Parr (1947) of the Eocene pelagic genus *Hanktenina* in the Brown's Creek beds, Otway Coast, Victoria. The second one is the discovery of an assemblage of smaller foraminifera of Paleocene age in the Giralia area, Carnarvon Basin (Edgell, in Condon *et al.*, 1956). *Hantkenina* is of world-wide distribution in Middle to Upper Eocene sediments; it is associated in Victoria with an assemblage of small species described by Parr (1938) from the Eocene of the King's Park Bore, Perth. Crespin (1958) recently found the genus in a bore core from the Carnarvon Basin. The Giralia assemblage contains species which are world-wide in their distribution, and is closely comparable with the Paleocene faunas of Sweden and of the Midway Formation of Texas.

Considerable stress has been placed in recent years on the distribution of the smaller foraminifera, especially the pelagic forms of the family Globigerinidæ. Carter (1958) has discussed this problem in his study of the pelagic genera in the Tertiary of Victoria. Morphological studies of individual genera are also being made (Wade, 1955, 1957; Wade and Carter, 1957).

As regards the larger foraminifera, which are especially valuable in long distance correlation in the Indo-Pacific region, some interesting discoveries have been recorded. Large tests of *Nummulites* and *Discocyclina* have been found in the Eocene of the Carnarvon Basin (Chapman and Crespin, 1935; Edgell, in Condon *et al*, 1956) making correlations possible with Eocene localities in the Indo-Pacific region. The discovery of very large tests of *Lepidocyclina* (*Eulepidina*) and other larger foraminifera in the Lower Miocene sequence of the Cape Range area, Carnarvon Basin, (Crespin, 1952) has been significant in correlation with Indo-Pacific localities. This large species, *L.* (*E.*) *badjirraensis*, has since been found in Cebu, Philippines (Crespin, 1956c) and in Saipan (Cole, 1957) and is known to occur in the Fiji Islands.

Little systematic work has been undertaken on the Tertiary foraminifera of New Guinea. Chapman (1914), Chapman and Crespin (1932), and Crespin (1938) described some larger foraminifera, but nothing has been published on the smaller forms. Crespin (1938) described the Eocene genera *Biplanispira* and *Lacazina* from the Central Highlands. These forms had been previously found only in islands off the west coast of Dutch New Guinea. Glaessner (1952) recorded *Lacazina* from the Port Moresby area, and Rickwood (1955) listed further occurrences of the genus in the Central Highlands.

Although no systematic contributions are available on the smaller foraminifera of Papua and New Guinea, the species are listed, together with larger forms, in several papers (Chapman, 1918, 1930; Crespin, 1942; Glaessner, 1943, 1952; Paterson and Kicinski, 1956). Rich assemblages of smaller species are present in the widespread Mio-Pliocene siltstone of the area and in beds of similar lithology and age throughout the Indo-Pacific region.

As regards Recent foraminifera, Collins published a comprehensive paper on the Foraminifera of the Great Barrier Reef (1958).

RADIOLARIA.

Radiolaria are pelagic marine protozoa with siliceous skeletons. They occur abundantly in the seas at the present time and are found in rocks of all ages, especially in the Ordovician, Devonian, and Mesozoic. Because Recent radiolaria are deposited at depths between 1,800 and 2,250 fathoms, it has been generally supposed that fossil radiolaria have been deposited at similar depths. Accumulations of radiolaria are known, however, to have been deposited at much shallower depths, and the evidence for deep-sea origin of fossil deposits is rare (Campbell, 1952).

Radiolaria are found in Australia from the Cambrian upwards, being especially abundant in the Devonian and Lower Cretaceous and comparatively rare in the Tertiary. In New Guinea they are present in the Upper Jurassic and abundantly in the Eocene. Radiolaria are found in cherts, jaspers and siltstones; they are so abundant in certain Lower Cretaceous localities in Australia and in the Eocene of New Guinea that the rock is termed "radiolarite".

Until recently radiolaria were not regarded as of any value in Australian stratigraphy, but more recent investigations have shown that they can be used in zonal correlation, especially in the Lower Cretaceous of Western Australia and perhaps in the Eocene of New Guinea. It seems certain that with detailed studies of this group their importance as zonal microfossils will increase.

No descriptive work has appeared on the radiolaria since Hinde published his papers in 1893 and 1899. However, W. Riedel, formerly of Adelaide, is studying Australian fossil radiolaria at Scripps Institution of Oceanography, California. David and Howchin (1896), David (1896), Dun, Rands and David (1901), and Bryan and Jones (1955) figured specimens but gave no description. Literature contains many references to radiolaria and specific papers have been published on their restricted occurrence in southern Queensland.

According to Daily (1958) the forms that David and Howchin (1896) suggested were casts of radiolaria from the ? Pre-Cambrian rocks of South Australia are no longer regarded as " identifiable organic remains ". Glaessner (1959) in his study of the oldest fossils of South Australia states that " The result of this review is that the occurrence of Radiolaria and possibly other " Protista " in the Torrensian and Sturtian Series of the Adelaide System remains a possibility but there is at present no new or more precise evidence than that presented by David and Howchin sixty years ago ".

Thomas and Singleton (1958) record the occurrence of radiolaria in the Heathcote Greenstones (Lower—? Middle Cambrian) of Central Victoria. Tests are so abundant in some of the Middle Ordovician sediments (Pittman Formation) of the Canberra area, that the rocks are radiolarites (Öpik, 1954). Radiolaria are widely distributed in the jasperoid rocks of Ordovician to Silurian age in southern Queensland (Richards and Bryan, 1923, 1924, 1925; Denmead, 1928; Bryan and Jones, 1946, 1952, 1954, 1955). Abundant beautifully preserved tests are present in the Devonian of New South Wales and Western Australia (Hinde, 1899; David, 1896; David and Pittman, 1899; Glenister and Crespin, 1959); they also occur in subsurface Permian sediments in Queensland (Crespin, 1945).

They have not been recorded from the Triassic and Jurassic of Australia, but the writer discovered them in Upper Jurassic and Lower Cretaceous sediments of the Waghi Valley, New Guinea (Edwards and Glaessner, 1953; Rickwood, 1955).

Radiolaria occur abundantly in surface and subsurface rocks of Lower Cretaceous age in the Carnarvon Basin (McWhae *et al.*, 1958) and are widely distributed in Northern Territory and Queensland, where they occur in rock cappings on mesa-like structures (Crespin, in Sullivan and Öpik, 1951; Noakes, 1949; Noakes, Öpik and Crespin, 1952). Hinde (1893) described Lower Cretaceous radiolaria from Fanny Bay, Darwin, and these forms are characteristic of all Cretaceous assemblages. The presence of abundant radiolaria in a siltstone from the Carnarvon Basin (" Windalia Radiolarite ", Condon *et al.*, 1956), was recognised by Chapman (in Raggatt, 1936) and later by Crespin (1946).

No radiolaria are described from the Tertiary rocks of Australia and New Guinea, but rich radiolarian Eocene cherts occur in the Port Moresby area (Chapman, 1930; Glaessner, 1952; Edwards and Glaessner, 1953).

Calpionellidae

The Calpionellidæ belong to the loricate Infusoria of the Order Oligotricha (Colom, 1955). The earliest known representatives of this group are of Tithonian age and they are important zonal microfossils in the Upper Jurassic, especially in the Mediterranean area.

The only genus recognised in Australia and New Guinea is *Calpionella.* Brunnschweiler (1951) found it in the Upper Jurassic of Dampier Peninsula, Western Australia, and Rickwood (1955) recorded it from the Upper Jurassic of the Waghi area, New Guinea.

Holothurian Sclerites.

Reference to the skeletal parts of holothurians are rare in Australian literature ; the only published record available is by Hall (1902) who described a holothurian sclerites wheel as *Chirodota* sp. from the Miocene deposits at Spring Creek, Torquay, Victoria. P. J. Jones of the Bureau of Mineral Resources has discovered many remains of this group in the Carboniferous rocks of the Bonaparte Gulf Area.

Alcyonarian Sclerites.

The study of alcyonarian sclerites was neglected until recently, when the French micropalaeontologist Deflandre-Rigaud (1955, 1957) described many species primarily on specimens from the Miocene rocks of Balcomb Bay near Mornington, Victoria. She states that " It was their very abundance in the material from the Balcombian (Middle Miocene) of Australia that started me on my research ". It is understood that the material was made available by Dr. Cookson.

Spongida.

Individual spicules of calcareous and siliceous sponges are very common in some Australian and New Guinea sediments. They are mostly needle-shaped or stellate and are a few millimetres long (Glaessner, 1945). Records of the occurrence of spicules, chiefly siliceous ones, are numerous in Australian stratigraphy and a complete list cannot be given in this review. Spicules of the siliceous *Protospongia* vary considerably in size ; they are included here as microfossils.

The genus *Protospongia* has been recorded several times from the Cambrian of Australia. Chapman (1917) and Thomas and Singleton (1958) refer to it from the Middle Cambrian of the Heathcote area, Victoria, and Thomas (1935) from the Howqua district. Öpik has identified *Protospongia* from the Upper Cambrian of Tasmania (Banks, in Öpik *et al.*, 1958). Hall (1889) described two species of the genus from the Lower Ordovician of Central Victoria. Sponge spicules occur in the Middle Ordovician of the Canberra area (Öpik, 1954).

Hinde (1900) figured many excellent individual spicules from calcisponges from the Tertiary of Victoria and later (1910) described siliceous spicules from the Eocene of Norseman, Western Australia. Chapman (1908) figured the varied forms of spicules from the siliceous sponge *Ecionema newberyi* McCoy from the Tertiary of Victoria.

Siliceous spicules are very abundant in Eocene cherts at Port Moresby ; the rocks have become spongolites (Glaessner, 1952).

Conchostraca.

Certain microscopic non-marine bivalve remains are referred to the group Conchostraca. Authorities on this group have now created many new genera, whereas formerly most of the forms were placed in the genus *Estheria.* It is generally considered that undoubted conchostraca did not appear until the Devonian. However, some doubtful forms described from the Cambrian of Australia and elsewhere are included in this group by certain authors (Ulrich and Bassler, 1931; Kobayashi, 1954). In Australia they occur in considerable abundance in the Triassic of Western Australia (Brunnschweiler, 1954) and of New South Wales (David, 1887).

The bivalve remains described as ostracoda by Chapman (1918) from the Cambrian of South Australia have been referred to conchostraca by Daily (1958), who also gives references to other occurrences in the Cambrian of that State. Dr. Öpik (personal communication) considers that the Cambrian forms belong to the Archæostraca, all genera occurring in marine sediments.

The earliest record in Australia of the occurrence of "*Estheria*" is by Cox (1881), who recognised them in a bore at Moore Park, Sydney, between the depths of 1,543 feet and 1,826 feet. These specimens were later described by Etheridge (1888). Etheridge described a species from the Triassic Ipswich Coals of Queensland (1882) and species from Port Keats Bore, Bonaparte Gulf, Northern Territory (1907). He regarded the age of the latter as post-Permian; Brunnschweiler (1954) supported this idea.

The most important publications on Australian conchostraca are by Mitchell (1925, 1927). He described many forms from the Permian Newcastle Coal Measures and from the Triassic Wianamatta Beds of New South Wales. Mitchell's work has been widely discussed by overseas authorities on the group (Kobayashi, 1954; Raymond, 1946; Tasch, 1956).

More recent investigations have revealed the presence of conchostraca in many Western Australian deposits. Brunnschweiler (1954) records abundant tests of *Isaura* (formerly *Estheria*) from the Triassic Blina Shale of the Fitzroy Basin, and Öpik reports conchostraca from the Upper Carboniferous (Anderson Formation) of the same basin (McWhae *et al.*, 1958).

Ostracoda.

Ostracoda occur in both marine and non-marine sediments of Ordovician and younger age. They are valuable as index fossils, especially in local correlation, and their importance is increasing in regional stratigraphy. Overseas investigations have brought about drastic changes in ostracod nomenclature, but only Krommelbein (1954) on the Devonian ostracoda from Buchan, Victoria, and Kellett and Gill (1956), reviewing the forms described by Chapman (1904) from Geraldton, Western Australia, have attempted to revise the nomenclature used in Australia.

Although known occurrences of ostracoda in Australian rocks are numerous, systematic investigations are comparatively few. The first record of fossil ostracoda in Australia is by Morris (in Strzlecki, 1845) in limestone of Carboniferous age from New South Wales. McCoy (1851) listed species from rocks of the same age. In 1876 de Koninck described a species from the Permian of New South Wales and referred to a form from the Silurian of Yarralumla (from what is now the Canberra area).

The reference to ostracoda in the Cambrian by Chapman (1918) is discussed under the heading Conchostraca. The only published record of their occurrence in the Ordovician is from Price's Creek area, Fitzroy Basin, Western Australia (Guppy and Öpik, 1950). Chapman described forms from the Silurian and Devonian of Victoria and New South Wales (1903, 1904, 1912, 1913, 1920) and Öpik (1953) from the Lower Silurian of Heathcote of Victoria. Rich Carboniferous assemblages from Western Australia are being investigated by P. J. Jones and these forms will be of considerable importance in local correlation. Ostracoda are numerous in the Permian of both Eastern and Western Australia, especially in subsurface sediments. Crespin (1945) described several species from eastern Australia.

No systematic work has been undertaken on Mesozoic ostracoda since Chapman (1904) described Western Australian Jurassic species from Geraldton and (1917) Upper Cretaceous species from Gin Gin. The Jurassic assemblage was reviewed by Kellett and Gill (1956). In places the only fossil present in sediments from the Lower Cretaceous of the Great Artesian Basin are fragments of a form referred to the well-known species "*Cytheropteron*" *concentricum* (Reuss).

Ostracoda occur abundantly in Tertiary deposits but have received little attention. Tate (1877) described a few species and Chapman made several contributions (1910, 1914, 1926, 1928). Crespin (1943) listed many species from the Tertiary deposits of East Gippsland.

Ostracoda from non-marine Tertiary to sub-Recent sediments were first recognised by Johnston (1885) from travertine in Tasmania. Chapman described several Sub-Recent species (1914, 1919, 1936). Beasley (1944, 1944a) used ostracoda in local correlation of oil-shale deposits in Queensland.

Early workers on post-Tertiary marine ostracoda were King (1885), Etheridge (1876) and Brady (1886). Chapman made a small contribution in 1915.

Conodonts.

These tooth-like microfossils of uncertain affinities are being found in great numbers in the Palæozoic rocks of Australia. Müller (1956) considers conodonts to be disjunct parts of a still unknown animal, and discusses the advantages and limitations of conodonts in stratigraphy. Brian and Anne Glenister are making detailed investigations of assemblages of conodonts in Western Australia.

The writer (Crespin,1943) first discovered conodonts in Australian sediments in Lower Ordovician (Larapintine) beds of Waterhouse Range, Central Australia. No further systematic work has appeared, although Müller (1956) figured specimens from the Devonian of the Fitzroy Basin, and Glenister and Glenister (1957, 1958) have written short notes on the discovery of conodonts in Ordovician and Silurian sediments of Western Australia.

Although conodonts are known from the Cambrian, their earliest record in Australia is from the Lower Ordovician. Many references appear in McWhae *et al.* (1948). Guppy and Öpik (1950) record them from the Lower Ordovician Emmanuel Limestone of Price's Creek area, Western Australia, and Öpik found them in the Pander Greensand of the Bonaparte Gulf Basin (Traves, 1955). He also records abundant conodonts in rocks of this age in the Canberra area (1954). Conodonts occur in great abundance in the Upper Devonian of the Fitzroy Basin (Glenister and Crespin, 1959) and Glenister and Glenister are studying this fauna, which contains at least 9,000 specimens. Many genera and species are referable to forms from America and Europe.

Microplankton.

The study of microplankton is very specialised and is in comparative infancy in Australia. However, a small group of workers is producing evidence of its importance in Australian stratigraphy. Dr. I. Cookson pioneered the study in this country when in 1946 she found microplankton in Tertiary sediments. Since then her investigations have included Mesozoic rocks in Australia and New Guinea (Cookson, 1956; Cookson and Eisenack, 1958; Deflandre and Cookson, 1954, 1955).

More recently Dr. P. R. Evans of the Bureau of Mineral Resources has been engaged almost entirely on the investigation of microplankton in the

Palaeozoic rocks of Australia, chiefly in subsurface material. This work has met with considerable success, rich faunas being found in the Ordovician, Carboniferous and Permian rocks, where their position in the sequence has been established by the presence of larger fossils.

Spores and Pollens.

The study of plant spores and pollens in sedimentary rocks is increasing in importance. Definite remains have been found in sediments as old as the Devonian. These microfossils are extremely valuable in Australian stratigraphy, in rocks which at first sight seem to be unfossiliferous; they have special application in subsurface investigations.

J. A. Dulhunty (1945) made use of microspores when he published the results of his investigations on the group in the Permian coals of New South Wales. This work was followed in 1946 by investigations by N. J. de Jersey of the spore content of Triassic coals of Queensland. Dr. Cookson and her fellow workers have contributed greatly to our knowledge of spores and pollens in both surface and subsurface sediments. B. E. Balme of the University of Western Australia and J. P. F. Hennelly of the C.S.I.R.O. Coal Research section have carried out excellent work on the Permian and Mesozoic spores and pollens (1955, 1956, 1956a, 1957). Balme has been especially engaged on determinations of subsurface samples, which are proving of great value in the microfaunal study of deep bores, especially in Western Australia.

Diatoms.

Fossil diatoms and microscopic algæ with siliceous skeletons are the basic components of diatomite, which may be of freshwater or marine origin. Deposits of diatomite are extensive in the Tertiary of eastern Australia and in Recent lakes and swamps in Western Australia. All are of freshwater origin (Crespin, 1947). Reference can be made to Crespin (1947) for publications on diatomite in Australia prior to that year.

The earliest reference to fossil diatoms in Australia is given by Coates (1861) who listed many genera and species from a sub-Recent deposit at South Yarra, Melbourne. Tindale (1953) re-examined material from this locality.

Substantial deposits of diatomite exist in New South Wales and Victoria, and lesser ones in Queensland. David (1896) discussed some of the New South Wales deposits and since then many geologists have published reports on individual deposits in all three States. However, none was microscopically examined in any detail until 1946, when the writer reviewed the contents of all known deposits in Australia. Later all available material was studied in more detail and typical individual diatoms and diatom assemblages were figured (Crespin, 1947). A revision of this work is about to go to press.

Queensland and New South Wales diatomites are dominated by the cylindrical genus *Melosira*, but the diatoms in the Victorian deposits show a great variety of beautiful forms. Excellently preserved species are present in Recent deposits in Western Australia.

Other Microscopic Algæ.

Microscopic algæ of the genera *Globochaeta* and *Eothrix* were discovered by the writer (in Lovering, 1953) in the Triassic Minchinbury Sandstone of the Wianamatta Group of New South Wales. In parts of Europe and in the Western Mediterranean area, these microfossils are characteristic of Upper Jurassic—Lower Cretaceous (Tithonian) (Colom, 1955) and the occurrence in the Triassic of New South Wales is probably the first record of that age.

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AN HYPOTHESIS FOR THE FUNDAMENTAL MECHANISM OF INSTANTANEOUS OUTBURSTS OF GAS AND COAL DURING THE MINING OF CERTAIN COAL SEAMS.

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Introduction.

The fundamental mechanism of instantaneous outbursts of gas and coal during the mining of certain coal seams has not been conclusively established. However, investigations carried out at the University of Sydney have provided results upon which may be based a tentative hypothesis explaining some features of the phenomenon. The hypothesis and the results upon which it is based are presented in this paper.

Instantaneous outbursts of gas and coal differ from the well-known rock-bursts due to concentration of mechanical stresses in the vicinity of working faces during mining operations. Instantaneous outbursts involve spontaneous and sudden evolution of large quantities of gas, usually carbon dioxide or methane, which flows with dislodged coal into the mine workings. The gas displaces mine air in the vicinity of the outburst, and may asphyxiate mine workers in the section of the mine concerned.

For a detailed review of instantaneous outbursts in Australian coalfields, outburst problems in coal mining, and literature on the subject, reference should be made to Hargraves (1958).

Characteristic Features of Instantaneous Outbursts, and the Coal Seams in Which They Occur.

1. Instantaneous outbursts normally occur in recently worked coal faces. They may take place at any stage of the mining operation, but usually during, or shortly after, coal cutting or blasting which tends to move coal immediately in front of the face.

2. Coal is dislodged from part or whole of the face simultaneously with the evolution of gas. The outburst takes place suddenly, but it does not appear to occur with the explosive violence of normal blasting. Miners working within a few feet of an outburst have been asphyxiated by gas without suffering bodily injury, and heavy mining equipment has been pushed away from an outbursting face without damage.

3. Coal dislodged from the face by an outburst is reduced to a fine condition. As much as 80% may be of a size less than 0·25 inches, 60% less than 0·1 inches, and 20% less than 0·01 inches.

4. Instantaneous outbursts always occur during the mining of seams in the vicinity of faults, crush zones, rolls, or otherwise disturbed areas when the coal has suffered shearing, slickensiding or crushing.

5. Coal seams subject to instantaneous outbursts are always of high rank, with moisture contents of 1 to 2% (A.F.). It is at this rank stage that most coals attain maxima in coking properties, friability and dust hazards, and minima in moisture content and radii of sub-microscopic inter-micelle spaces.

6. Instantaneous outbursts occur mainly in deep seams with more than about 600 feet of cover.

7. Coal seams subject to instantaneous outbursts always contain gas under pressure. Boreholes drilled into the seams from working faces reveal gas pressure gradients rising from atmospheric pressure at the face to pressures which may exceed 100 lbs. per sq. in. at depths of 10 feet or more ahead of the face.

8. The amount of gas which escapes at working faces, and from boreholes in the seams, is small in view of the high gas pressures and large volumes of gas known to exist in the seams.

9. In some seams instantaneous outbursts have occurred very infrequently at widely separated points throughout the mine workings, whilst in other seams successive outbursts have occurred at very close intervals during the advance of certain headings.

Mode of Occurrence of Gas in Coal Seams Subject to Instantaneous Outbursts.

The existence of steep gas pressure gradients from working faces into the solid coal, and the relatively small escape of gas at the faces and from boreholes, indicate low gas permeability of seams prone to gas outbursts. This, and the occurrence in some seams of successive outbursts at close intervals, strongly suggest that the gas evolved during an outburst is mainly that which was stored in the seam in the immediate vicinity of the outburst, or even in the coal dislodged by the outburst.

The volume of gas contained in the macroscopic and microscopic openings of the seam, under the existing gas pressures, represents only a small fraction of the total volume of gas evolved during an outburst. From this it would appear that large amounts of gas occur within the sub-microscopic or ultra-fine structure of the coal itself, in addition to relatively small amounts existing in macroscopic and microscopic openings.

Chemical tests on coal from an outbursting area of the Bulli Seam at Helensburgh in New South Wales show very little carbon dioxide chemisorbed or in solid solution in the coal. When the coal is removed from the elevated gas pressure in the seam, and is maintained in carbon dioxide at atmospheric pressure, it loses only portion of its gas content. However, on exposure to air at atmospheric pressure, the coal loses practically all its carbon dioxide by diffusion, which proceeds rapidly at first and then slowly in the later stages. When crushed in a gas-tight rod-mill, carbon dioxide is evolved as new external surface area increases. From the foregoing it would appear that most of the carbon dioxide in outbursting seams occurs sorbed on the snb-microscopic internal surface of intermicelle spaces within the coal.

It is well known that the amount of carbon dioxide sorbed on the internal surface of coal varies with the gas pressure on the coal. This would certainly apply to coal in a seam, and at any given pressure of seam gas a state of equilibrium appears to exist between sorbed and gaseous carbon dioxide. At equilibrium the quantity of sorbed carbon dioxide in the coal, although occupying a much smaller volume, far exceeds that in the gaseous state.

Hypothesis for the Mechanism of the Instantaneous Outburst.

As a coal face advances with mining operations, the gas pressure gradient behind the face recedes into the seam. The steepness of the pressure gradient will depend on rate of advance of the face and permeability of the seam. If the gradient is very steep, reduction in pressure of gaseous carbon dioxide behind the face may exceed desorption of carbon dioxide from the internal surface of the coal. When this happens, coal behind the face may contain more sorbed carbon dioxide than the equilibrium quantity for the reduced pressure of gaseous carbon dioxide. Unstable conditions may then exist in relation to sorbed gas, and conditions favourable for an instantaneous outburst of gas could prevail. Under such circumstances, it is suggested that movement in the seam behind the face, due to mining operations, may cause breaking of the coal and creation of new external surface area. This could initiate desorption which, under the unstable conditions, would result in rapid evolution of gas and sudden increase in gas pressure. The increased gas pressure might cause further movement and breaking of the coal and creation of new external surface area. This in turn would accelerate desorption already initiated, and cause further increase in gas pressure, and consequently further movement and breaking. The process may then continue, developing into spontaneous desorption of practically all the sorbed gas, sudden generation of high gas pressures, and reduction of the coal to small size. The expanding gas would carry the fine coal out into the mine workings, constituting an instantaneous outburst of gas and coal.

It follows that movement in the coal behind a working face, such as may promote an outburst, could be caused by coal-cutting or blasting operations, and that it would be most likely to occur in the vicinity of faults, crush zones, or disturbed areas where the seam is weakened by shearing, crushing and slickensiding.

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In conclusion, it is wished to acknowledge the practical co-operation and financial support given by Metropolitan Coal Co. of New South Wales in research on instantaneous outbursts of gas and coal, contributions to laboratory work by Dr. A. Draycott in the early stages of the work, and the advantage of working with Mr. A. J. Hargraves, Department of Mining Engineering, University of Sydney, throughout the investigation.

Reference.

Hargraves, A. J., 1958. *Proc. Aust. Inst. Min. Met. No.* 186, p. 21.

DISTRIBUTION AND SEQUENCE OF SILURIAN CORAL FAUNAS.

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Abstract.

After a review of the Silurian coral faunas of the different continents, in which intra- and intercontinental correlations are made (with reference to the graptolite zonal sequence where possible), it is concluded that Silurian coral faunas were in general cosmopolitan as to genera; weak evidence of zoogeographical (generic) provinces is seen only in Asio-Australian and in North American seas. The fauna had its origins in the uppermost Ordovician, gradually increased in number of genera during the Lower Llandovery, then so rapidly increased as to give an evolutionary 'burst' during the Upper Llandovery and at the beginning of the Wenlock; thereafter this evolutionary vigour rapidly decreased into the basal Devonian, with gradual extinction of the characteristically Silurian families and genera. The development of rich coral-stromatoporoid-algal reefs in northern latitudes between 50° and 70° N. suggests to the author that at least the northern Silurian oceans were warmer than those of today. The rarity or absence of Silurian corals in S.W. Europe, S. America, Africa, Antarctica and New Zealand is remarked.

I. Introduction.

The beginning of the Silurian is taken in this review at that point in time represented by the base of the *Glyptograptus persculptus* zone of the Valentian graptolite sequence, and the base of the brachiopod zone with *Sowerbyella præcursor*, *S. gracilis*, *S. tricostata* and *Whitfieldella angustifrons*, which presumably lies at the base of the Lower Llandovery sediments of Wales (Evans and Stubblefield, 1929). The best known sequence where corals are developed across the Ordovician–Silurian boundary is in Estonia, and here the Porkuni horizon (F_2=Borkholm Beds) is now correlated (Jaanusson, 1956; Martna, 1957) with the *Dalmanitina* beds of Sweden (and with 5b of Norway), the *Dalmanitina* beds (Jones, 1949) apparently being correlatable with Welsh Upper Ordovician beds (see also Magnusson, 1958). The view that 5b and its Scandinavian correlatives were to be equated with the basal Llandovery was however held by many, and I subscribed to it in my 1951 essay on the Ordovician coral faunas; the Porkuni horizon of Estonia (Borkholm Beds=F_2 and the nearly equivalent 5b) is indeed still regarded in Russia and in Estonia as basal Silurian, though here now considered Upper Ordovician. Its fauna, now being described (Kaljo, 1956, 1957, 1958; Sokolov, 1951, 1955), is predominantly Ordovician in type. The Rugosa are still dominated by non-dissepimented streptelasmids, *Brachyelasma*, *Streptelasma*, "*Lindstroemia*", "*Sclerophyllum*", "*Kodonophyllum*" *rhizobolon* (Dybowski); but rare solitary tryplasmids (*Neotryplasma* Kaljo, 1957) continue from the Lyckholm beds and are joined by the first fasciculate species of *Tryplasma*, *T. tubulus* (Dybowski). The first dissepiments known in the Columnariina are seen in the earliest *Strombodes* species (*middendorfi* Dybowski), and these are the large, lonsdaleoid type characteristic of the suborder. The earliest 'normal' type dissepiments, characteristic of the Streptelasmatina, small and formed in the loculi between major and minor septa only, are seen in the probably streptelasmid species "*Pilophyllum*" *porosum* Kaljo (1958), but only sporadically. The aberrant *Calostylis* (with retiform septa), fairly common in and characteristic of the Silurian, enters herein. In 5b of Norway (Scheffen, 1933) the columellate, non-dissepimented streptelasmatinid *Dalmanophyllum* ("*Lindstroemia*" and "*Tyria*") appears, with the insufficiently figured "*Stegophyllum*".

Of the Tabulata several characteristically Ordovician genera occur in, but not above, the Porkuni horizon. These include *Sarcinula* (the last of the syringophyllids), *Rhabdotetradium* Sokolov (1955), the last of the tetradiids, and *Proheliolites*, while *Palæoporites* is known within it only. *Propora* and *Stelliporella* continue through it. *Paleofavosites* is joined by *Mesofavosites* Sokolov with pores appearing mid-wall as well as at angles, and by the first *Multisolenia*; this represents the beginning of the great favositid development that becomes so characteristic of the Silurian. In Norway *Calapoecia* is found in 5b, but does not continue above it.

The Porkuni horizon thus contains a fauna that is in many respects a transition fauna between Ordovician and Silurian; many "Silurian" characteristics have already appeared in it, albeit rarely, while many Ordovician genera become extinct within it.

The end of the Silurian is taken herein as at the top of the Upper Ludlow and the base of the Ludlow Bone Bed in Britain, and at the base of the Gedinnian of N.W. Europe, though suggestions have been made (Schouppé, 1954a, 1954c) that the Gedinnian is but a facies of the uppermost Ludlow.

The Ordovician coral faunas (Hill, 1951) from which the Silurian fauna must have evolved, were characterised by non-dissepimented Rugosa, though all three suborders of Rugosa were present—Streptelasmatina, Columnariina and Cystiphyllina, and by the presence of all six superfamilies of Tabulata, the Syringophyllidæ, Tetradiinæ and Palæoporitinæ not continuing beyond the Ordovician.

Compared with the Ordovician corals, the Silurian corals are striking because of the overwhelming development of dissepimented genera in all three suborders of the Rugosa and in the appearance of important subfamilies of Favositidæ like the Alveolitinæ, the Thamnoporinæ, and the Theciinæ.

Four general works are indispensable in the study of Palæozoic corals—Lang, Smith and Thomas (1940), Bassler (1950), Sokolov (1955) and Hill, and Hill and Stumm in Moore (1956). The systematic classification used herein is that of the last mentioned work, amended to profit by Russian and other work not available when it was being written.

The attempt will be made throughout this review to indicate the equivalence in time of the coral faunas with the successive graptolite zones.

Knowledge of corals is insufficient as yet to enable species to be used in palæogeographic discussion or inter-continental correlation, and this review therefore concerns itself with genera or subgenera only.

II. Coral Faunal Sequences in the Continents.

Europe

The Silurian here is now commonly divided into the stages Llandoverian (=Valentian), Wenlockian and Ludlovian, the first seemingly occupying a much longer period of time than the others.

Lower (and Middle) Llandoverian strata contain the successive graptolite zones of *Cephalograptus acuminatus*, *Orthograptus vesiculosus*, *Monograptus cyphus*, *M. fimbriatus*, *M. triangulatus*, *M. argenteus* and *M. convolutus*. Graptolites of the lowest Valentian zone, *Glyptograptus persculptus*, appear not to have been recognised in early Llandovery strata in Wales.

In Great Britain the early Silurian was poorly coralliferous. The Mulloch Hill beds of Girvan, Scotland, which are possibly of the zone of *Cephalograptus acuminatus*, contain only small solitary non-dissepimented Rugosa, *Streptelasma* and the columellate *Dalmanophyllum subduplicatum* (McCoy), with the tabulatans *Paleofavosites*, *Pinacopora* (=? *Propora*) and *Heliolites*. At Llandovery in Wales *Calostylis* occurs also. No corals as old as these are known in Gotland, and in

Norway 7_α and 7_β are very poor in corals. In Estonia the Juuru horizon (=G_I=Jorden) is probably Lower Llandovery, and contains (Kaljo, 1956, 1958, Orvik, 1958 and Dybowski, 1873–4) *Palæohalysites* and the small solitary non-dissepimented Rugosa *Brachyelasma*, ? *Pycnactis*, ? *Rhegmaphyllum* and "*Sclerophyllum*", with the dissepimented *Paliphyllum soshkinæ*. This last genus, with a wide normal dissepimentarium, includes the species *Cyathophyllum kjerulfi* Kiaer (1932) from the Kalstad limestone of Norway, which is probably not younger than Middle Ordovician, and which has the oldest known dissepiments. *Paliphyllum* is common in the Upper Ordovician Upper Stolbo group of the Stony Tunguska in Siberia. The systematic position of the species at present included in the genus is doubtful.

The UPPER LLANDOVERIAN includes the graptolite zones *Monograptus sedgwicki*, *M. turriculatus*, *M. crispus*, *M. griestonensis* and *M. crenulatus*.

In Great Britain Upper Llandovery corals are found in the *Pentamerus* beds and Purple shales of Shropshire (Smith, 1930) and are possibly of the *M. turriculatus* zone. They include the small, solitary non-dissepimented *Rhegmaphyllum whittardi* (Smith) and *Streptelasma aranea*, and the non-dissepimented lykophyllinids *Pycnactis crassiseptata* (Smith) and *Pycnactis* (*Onychophyllum*), dissepimented and large *Phaulactis*, the phaceloid *Petrozium*, the cystiphyllinids *Palæocyclus*, *Rhabdocyclus*, *Cantrillia* and *Cystiphyllum* and the aberrant *Calostylis*, with the tabulatans *Paleofavosites*, *Favosites*, *Heliolites* and *Halysites*. Probably none of the Gotland corals is as old as this, but the Estonian G_{II} Tamsal horizon (=*Pentamerus borealis* or *oblongus* beds), which contains bioherms, may be equivalent or even a little older. It contains *Brachyelasma*, *Rhegmaphyllum whittardi*, "*Sclerophyllum*", the lykophyllinids *Pycnactis crassiseptata* and *Phaulactis* (*Cyathactis*), with *Petrozium*, *Paliphyllum* and a species like *Paliphyllum* but which Kaljo (1956, 1958) refers to *Pilophyllum* Wedekind, and *Schlotheimophyllum*, with the columnariine *Cyathophylloides*. Tabulata (Sokolov, 1955 and Orvik, 1958) include *Protaraea*, *Propora*, *Paleofavosites*, *Mesofavosites* and *Halysites* and doubtless others described in Sokolov (1951) which I have not seen. The G_{III} (Zone 5) Raïkull horizon of Estonia has a similar but less rich rugosan fauna, with "*Sclerophyllum*", *Paliphyllum*, *Petrozium* (ex. *Donacophyllum*), *Strombodes* and *Cyathophylloides*, with *Favosites* amongst others. It also has bioherms and would seem to be early Upper Llandovery.

The most striking feature of these early Upper Llandovery faunas is the richness in lykophyllinids, a feature that is continued in all later Silurian faunas.

In the later Upper Llandovery fauna we have a widely occurring rich and distinctive unit, whose upper and lower limits are still not precisely defined in relation to graptolite zones. This is the fauna of *Arachnophyllum*, *Palæocyclus*, *Dinophyllum*, *Dalmanophyllum* and *Schlotheimophyllum*.

The H (Zone 6) or *Pentamerus estonicus* Adavere horizon of Estonia contains *Arachnophyllum*, *Calostylis* and *Favosites*; it has been correlated by some with *Pentamerua oblongus* or 7β beds of Norway. It may correlate with the Red or *Arachnophyllum* layer of Gotland that occurs below low water mark along the N.W. shoreline, and that has yielded according to Lindström the colonial rugosan *Arachnophyllum*, the solitary *Dinophyllum* with the vortical axial structure, and the prismatic *Goniophyllum pyramidale*, *Favosites* and a great richness in heliolitids of the genera *Heliolites*, *Stelliporella*, *Cosmiolithus*, *Plasmopora* and *Propora*. The lower Visby marls (*Stricklandia* marls=Horizon I of Hedström and b of Lindström) above the Red layer contain an even richer fauna, with in addition to the above genera *Palæocyclus*,* the small button-shaped coral that seems particularly useful as an index fossil for the Upper Llandovery, *Rhabdo-*

* The generic name *Palæocyclus* was saved from synonymy with *Porpite* by Wells (1936) though this was overlooked by Lang, Smith and Thomas (1940) and by Hill (1956).

cyclus, and numerous small solitary *Tryplasma*, *Cystiphyllum* and the endemic and prismatic *Aræopoma*, numerous lykophyllinids and an early *Kyphophyllum*, *Calostylis*, and the additional tabulatans *Paleofavosites*, *Alveolites*, *Syringolites*, *Halysites* and the endemic heliolitid *Pycnolithus*. In the Upper Visby marls (about 20 metres thick) the Upper Llandovery graptolite *M. spiralis* occurs (Hede, 1942), indicating a horizon somewhere over the range *M. crispus* zone to *M. crenulatus* zone, possibly as late as the *crenulatus* zone (Waern, 1948); the fauna is very similar to that of the Lower Visby marl, but *Palæocyclus* disappears and *Schlotheimophyllum patellatum*, *Polyorophe*, *Holophragma calceoloides*, " *Zaphrentis* " *vortex*, omphymoids (doubtfully *Spongophylloides*), and *Hedströmophyllum* are new rugosan entries that seem to indicate a late subfauna within this late Upper Llandovery fauna. New tabulatan entries are the branching favositids *Striatopora* and *Pachypora*, and the massive favositid *Angopora* with *Planalveolites*. Some small reefs occur in the Upper Visby marls.

Thus in Gotland this Upper Llandovery fauna appears on present evidence to be divisible into three: the oldest with *Arachnophyllum*, *Goniophyllum* and *Dinophyllum*; the second with these, and *Palæocyclus* and *Aræopoma*; the third with all these except *Palæocyclus*, and with in addition *Schlotheimophyllum*, *Polyorophe* and *Holophragma*.

We are unfortunately without any modern monographic treatment of the Gotland corals; interpretations of the stratigraphy have varied much in the past, and in the above lists I have taken all figured Gotland corals and tried to place them correctly in the stratigraphic sequence worked out by Hede (1942).

If the Upper Llandovery–Wenlock boundary lies between the Upper Visby marls and the Hogklint group, the early Wenlockian can be said to be distinguished by the entry of *Acervularia* and the (local) absence of *Aræopoma*, *Goniophyllum*, *Schlotheimophyllum*, *Holophragma* and *Dinophyllum*.

In Great Britain the " Coralliferous Series " of Wooltack Park and Marloes Bay in Pembrokeshire contains a rich fauna (Hill MS.) that seems to correlate perfectly with the Lower Visby marls, containing as it does the brachiopod *Stricklandia lirata* and the corals *Palæocyclus*, *Dinophyllum*, *Dalmanophyllum*, *Rhegmaphyllum*, ? *Brachyelasma*, *Calostylis*, the lykophyllinids *Pycnactis* and *Phaulactis*, the cystiphyllines *Rhabdocyclus*, *Tryplasma*, *Cystiphyllum* and the tabulatans *Favosites*, *Alveolites*, *Multisolenia*, *Heliolites*, *Propora* and *Halysites*. It also is therefore probably within the range *M. crispus* zone to *M. crenulatus* zone.

This Pembrokeshire fauna may thus be very slightly older than the Herefordshire fauna of the *Petalocrinus* Band and the 80 feet of beds overlying it in the Herefordshire area, which correlates well with the third Gotland subfauna, that of the Upper Visby marks. This Herefordshire fauna (Hill MS.) consists of *Goniophyllum pyramidale*, *Dalmanophyllum*, *Schlotheimophyllum patellatum*, *Pycnactis*, *Phaulactis*, *Streptelasma* (? *Rhegmaphyllum*) *roemeri*, *Rhabdocyclus*, *Tryplasma*, *Cystiphyllum*, ? *Polyorophe*, *Calostylis*, *Syringaxon* and the tabulatans *Favosites*, *Paleofavosites*, *Alveolites*, *Angopora*, *Thecia*, *Heliolites*, *Propora*, ? *Pœckelmannopora* and *Halysites*. If we accept the evidence of *M. spiralis* in the Upper Visby marls and the above correlation, these beds in Herefordshire should still be Upper Llandovery. Whether the Woolhope limestone is distinguishable by its coral fauna from these 80 feet of strata remains to be shown. It is traditionally regarded as basal Wenlockian and is now commonly correlated with the Hogklint group.

The full sequence of WENLOCKIAN graptolite zones in Wales is *Cyrtograptus murchisoni*, *Monograptus riccartonensis*, *M. symmetricus*, *M. linnarssoni*, *C. rigidus* and *C. lundgreni*, but some of these are missing in Shropshire (Whittard, 1952).

In Gotland the Hogklint reefal group may be basal Wenlockian; *Dalmanophyllum* and *Polyorophe* are prominent early, *Hedströmophyllum* becomes important and *Zelophyllum* is restricted to it. *Acervularia* appears nearly everywhere, and early solitary *Kodonophyllum* and *Pseudomphyma* enter. Notable absences, so far as illustrations in the literature show, are *Aræopoma*, *Goniophyllum* and *Schlotheimophyllum*, and probably also *Holophragma* and *Dinophyllum*, but lykophyllinids continue as does *Kyphophyllum*. '*Zaphrentis*' *vortex* is replaced by *Rhegmaphyllum conulus* (Lm). Changes in the tabulatan fauna are the entry of *Nodulipora*, *Thecia* and *Diploepora*. *Xiphelasma*, the dissepimented and cerioid tryplasmid, must have been collected from one of the three Upper Llandovery formations or the Hogklint reefal group, since it is recorded as from Visby, and Ma (1956) records *Pseudolindstroemia* and *Stortophyllum* from Visby.

The Slite group of marls and limestones is certainly Wenlockian, older than the zone of *Cyrtograptus lundgreni* on the graptolite evidence (Hede, 1942). It contains the same Rugose genera listed below for the British Wenlock shale, with additional records of *Pseudomphyma*, *Hedströmophyllum*, lykophyllinids, *Rhegmaphyllum*, *Helminthidium*, *Circophyllum*, *Stauria* and the endemic *Rhytidiophyllum*. Amongst the Tabulata *Thecia* and *Diploepora* are notable.

A Lower Wenlockian coral fauna in Great Britain is, if traditional correlations are correct, that of the Woolhope limestone of Herefordshire; but this requires restudy, to separate its species from those of the *Petalocrinus* bed and the succeeding 80 feet of strata, as mentioned above. The Wenlock Shale coral fauna so far known from Great Britain is mainly that of the uppermost parts of the Shale, the Tickwood Beds of Shropshire and the beds immediately below the Wenlock Limestone in the Midlands. Perhaps the most important feature is the appearance of the phaceloid *Entelophyllum*, but *Acervularia*, *Spongophylloides*, '*Omphyma*', *Pycnactis*, *Phaulactis* and *Plasmophyllum*, *Syringaxon*, *Strombodes*, *Calostylis*, *Tryplasma*, *Rhabdocyclus*, *Cystiphyllum* and many Tabulata occur.

The Lower Oesel (J) beds of Estonia, traditionally regarded as a Wenlock equivalent, contain no graptolites and their Rugosa have not been revised since their original descriptions by Dybowski (1873–1874), whose figures permit doubtful identifications of *Rhabdocyclus*, *Schlotheimophyllum*, *Cystiphyllum*, lykophyllinids and *Pseudomphyma* (or *Mucophyllum*). Twenhofel (1916) listed *Palæocyclus*, and if this is correct this fauna could well be Upper Llandovery rather than Wenlock. The beds are now divided into the Jaani horizon (J_1) with the tabulatans (Sokolov, 1952 and 1955) *Paleofavosites*, *Subalveolites*, *Syringolites*, *Mastopora*, *Palæohalysites*, *Thecia*, *Heliolites* and *Propora* and the J_2 Jaagarachu horizon with *Favosites* and *Jaaremolites*.

The Upper Wenlockian Wenlock Limestone of Shropshire and the Midlands is of the zone of *Cyrtograptus lundgreni*. It is reefal in Britain, and contains a rich fauna that requires modern monographic treatment. Genera I have studied from it are *Entelophyllum*, *Acervularia*, *Arachnophyllum*, *Kodonophyllum*, *Pycnactis*, *Phaulactis*, *Plasmophyllum*, *Strombodes* (rare), *Spongophylloides*, *Syringaxon*, '*Omphyma*', *Calostylis*, *Helminthidium*, *Rhabdocyclus*, *Tryplasma*, *Cystiphyllum* and *Goniophyllum fletcheri* with *Streptelasma pseudoceratites*. Tabulata are very rich, and include *Paleofavosites*, *Favosites*, *Alveolites*, *Coenites*, *Angopora*, *Nodulipora*, *Thecia*, *Heliolites* (a dominant reef builder, Colter, 1957), *Stelliporella*, *Plasmopora*, *Propora*, *Diploepora*, *Striatopora*, ? *Pachypora*, ? *Cladopora*, *Halysites* and *Syringopora* being very common. This is the fauna usually called 'Wenlock fauna'.

In Gotland the Mulde Marls may correlate with the Wenlock limestone. Of the fauna listed for the Slite group, *Pseudomphyma*, *Hedströmophyllum*, *Rhegmaphyllum*, *Circophyllum* and *Stauria* are apparently not recorded in the Mulde Marls, but *Acervularia*, *Arachnophyllum*, *Entelophyllum* and *Thecia* are common.

In Estland some part of the Oesel group may be equivalent to the Wenlock limestone, but present lists suggest that the Wenlock limestone fauna is not represented there.

In the Urals small Wenlock faunas occur (Soshkina, 1937 ; Sytova, 1952 ; Yanet, 1955) with ? *Dinophyllum* (" *Stereophyllum* " *spirale* Soshkina), ? *Favistella* (" *Dokophyllum* " *sociale*), " *Tenuiphyllum* ", omphymoids, tryplasmids, *Entelophyllum* and *Micula* (with which some of the British and Gotland *Entelophyllum* species may be congeneric) and the tabulatan *Thaumatolites* Yanet.

In Bohemia corals are common in reefal masses in eα_2 and eα_2/eβ_1 at horizons possibly near the Wenlock–Ludlow boundary ; *Tryplasma*, *Cystiphyllum*, *Microplasma*, *Acervularia*, *Arachnophyllum*, *Entelophyllum*, *Spongophylloides*, *Phaulactis*, *Favosites*, *Paleofavosites*, *Alveolites*, *Coenites*, *Heliolites*, *Propora*, *Halysites* and *Aulopora* from the America Quarry (Prantl, 1939) certainly suggest a Wenlock Limestone horizon. The classical Tachlowitz fauna is now regarded as a little younger than the America and possibly Ludlow.

In England in the Lower Ludlow shales, corals are not uncommon, but are mostly undescribed. No new genera are known ; *Syringaxon*, *Entelophyllum*, *Favosites*, *Heliolites* and *Halysites* are amongst the few recorded. The graptolite zones of the Lower Ludlow are *M. nilssoni* and *M. scanicus*. The Aymestry Limestone (zones of *M. tumescens* and *M. leintwardinensis*) contains *Phaulactis*, *Spongophylloides*, *Rhabdocyclus*, *Tryplasma*, and *Hedströmophyllum* with *Favosites*, *Heliolites* etc. Upper Ludlow corals are practically unknown ; *Syringaxon* occurs in Westmoreland.

In Gotland Ludlow coral faunas are much richer. That of the Klinteberg reefal group is possibly basal Ludlow. It is not well figured, but *Pilophyllum* enters and is important and *Gyalophyllum* is endemic, making but a brief appearance. *Spongophylloides*, *Helminthidium*, *Kodonophyllum*, *Acervularia* and *Entelophyllum* are recorded.

The Hemse marls (Petesvik, Hablingbo etc.) are to be correlated by their graptolites (Hede, 1942) with the *M. nilssoni* zone of the Lower Ludlow. They have the phaulactid *Plasmophyllum* (as *Lamprophyllum*), phaceloid *Tryplasma*, *Rhizophyllum gotlandicum*, *Arachnophyllum*, *Acervularia*, omphymoids and some phaulactids, *Weissermelia lindstromi*, " *Fascicularia* " *dragmoides* (these last two could possibly be the same species), *Strombodes munthei* (Wdkd.) and *Prisciturben*. The Tabulata are significantly different from the Wenlockian generic assemblage only in the absence of *Diploepora* and *Syringolites*.

The Eke marls at Lau Backar, overlying the Hemse marls, may be Lower or Middle Ludlow and have the endemic *Stortophyllum* and *Holmophyllum holmi*, *Entelophyllum*, *Rhizophyllum* (forming a *Rhizophyllum* limestone), *Kodonophyllum* and *Spongophylloides*, while the overlying Burgsvik sandstone and oolite has *Favosites clausus*, *F. hisingeri*, *Spongophylloides* and cf. *Striatopora calyculata* Lm. figured from it. The Hoburg reef at the top of the Gotlandian has *Favosites gotlandica* and *F. hisingeri*, cf. *Striatopora calyculata*, *Heliolites*, *Plasmopora* and *Propora*, but the full fauna remains to be described. Spjeldnaes (1950) has suggested that the Hoburg reef is possibly basal Devonian (Downtonian).

These Ludlow faunas are thus seen to be almost entirely of genera relict from the Wenlock.

In Estonia the upper Oesel (K) Beds (Zone 8) are usually regarded as Ludlow. Here again the Rugosa have not been revised since Dybowski (1873, 1874) originally described them ; his figures may be interpreted doubtfully as of *Tryplasma*, *Cystiphyllum*, *Entelophyllum*, *Phaulactis*, *Micula*, *Stauria* and

Strombodes. Twenhofel's list (1916) also includes *Acervularia* and *Omphyma*. This list could equally well imply a Wenlock age. Sokolov (1955) figures *Thecia, Romingerella, Laceripora* and *Syringopora* from the K_2 Paadla horizon, *Multisolenia* and *Favosites* from the K_3 Kaugatoma horizon with *Lissatrypa* (? *Atrypella*), and *Favosites* from K_4.

In Bohemia the classical Tachlowitz ($e\alpha_2$ according to Prantl and Pribyl 1944 quoted by Flügel, 1956a) and Kozel ($e\beta$, according to Zelizko 1904 quoted by Flügel, 1956a) are both a little younger than the America fauna regarded as probably Upper Wenlock above ; they are possibly Lower Ludlow, and contain the genera listed above for the America Quarry, plus, in one or the other, *Omphyma, Spongophyllum, Syringaxon, Pachypora* and *Stelliporella* (Počta, 1902 ; Prantl, 1952). This is the only European Silurian occurrence of *Spongophyllum* known to me. A smaller fauna from Graz in Austria is regarded as $e\alpha_2/e\beta_1$ Lower Ludlow by Flügel (1956a) ; it has *Syringaxon, Entelophyllum, Favosites, Thamnopora, Chætetes* and *Heliolites*. Schouppé (1954c) has considered it uppermost Ludlow. From the Carnic Alps Schouppé (1954a) described a somewhat larger fauna and correlated it with $e\gamma_1$ of Bohemia, and regarded it as topmost Upper Silurian.

Weissermel (1943) described a small Ludlow fauna from west and central Germany mainly from calical moulds.

In Podolia Sokolov (1955) refers to faunas similar to the Bohemian Ludlow. *Pachyfavosites* occurs in the Borshchov horizon of the Ludlow, while in the Skala Stage of Aymestry–Ludlow equivalence, Rozkowska (1946) has described *Mucophyllum eurycalyx, Tryplasma, Microplasma, Rhizophyllum* and *Spongophylloides*. Earlier descriptions were by Eichwald and by Semiradski.

In Asia Minor an important Silurian fauna has been described by Weissermel (1939) and Unsalaner–Kiragli (1958). It contains *Tryplasma*, ? *Polyorophe, Cystiphyllum*, ? *Dinophyllum, Spongophylloides, Entelophyllum, Phaulactis, Fletcheria, Alveolites* (as *Roseoporella*), *Astrocerium, Favosites, Paleofavosites, Halysites, Heliolites* and *Syringopora*. It could well be either Upper Wenlock or Ludlow.

Ludlow faunas are thus almost entirely of genera relict from the Wenlockian. Coral vitality was surprisingly low after the great burst at the top of the Llandovery and in the early Wenlock.

S.W. European Silurian is graptolitic in facies, corals being extremely rare ; '*Cyathophyllum*' and '*Zaphrentis*' are recorded (Sampelayo, 1942).

Asia

In Asiatic Russia rich faunas are now being made known. Russian work on Tabulata has been most active, and a number of generic names new to western research appear in the following review. They suggest a degree of isolation in Siberian faunas, but this may well be more apparent than real, since the Tabulata have been rather neglected in the European and English-speaking world and the new Russian genera may represent groups of species submerged in the west in genera perhaps too broadly defined. In the Sino-Japanese world *Halysites* has recently been subdivided into many subgenera. In India and Burma little Silurian research has been done recently, and in Indochina and Indonesia very little indeed is known of the Silurian.

LLANDOVERY equivalents are widespread in Asiatic Russia, in Kazak A.S.S. (Sokolov, 1955) and on the western (Sokolov, 1946, 1950 ; Kraevskaya, 1955) and northern outskirts of the Siberian platform (Nikolæva, 1955), in the Tunguska River basin (Lindström, 1882 ; Sokolov, 1947, 1955 ; Soshkina in Ivanova *et al.*, 1955), the Taimyr (Chernychev, 1941 ; Sokolov, 1955), Olenek (Lindström, 1882) and Verkhoyansk. A horizon near the boundary with the Wenlock is the richest with the Tabulata *Paleofavosites, Favosites, Multisolenia,* *Agetolites*, *Alveolites*, *Subalveolitella*, *Striatopora*, *Parastriatopora*, *Syringopora*, *Syringoporinus*, *Palæohalysites*, *Cystihalysites* and *Propora* (Soshkina, 1955). The new generic names in these do not necessarily imply endemism, since Russian subdivision of the Tabulata has been carried further than any other. Rugosa are *Dybowskia*, *Streptelasma* (some like *Rhegmaphyllum*), *Pycnactis* and lykophyllinids (including *Cyathactis*).

In China, Japan, Indochina and Indonesia Llandovery coral faunas seem not to have been described, but from Spiti in the central Himalayas, Reed (1912) has figured from beds with *Pentamerus oblongus* halysitids now (Hamada, 1958) referred to *Catenipora* ? and *Schedohalysites*, plus *Favosites*. At a lower horizon *Calostylis* occurs.

WENLOCKIAN faunas, first made known by Lindström (1882) from the Stony Tunguska, have there (Soshkina in Ivanova *et al.*, 1955) *Paterophyllum*, *Pycnactis* and *Holophragma* in the lower parts, and *Rhegmaphyllum whittardi* (Smith), *Pycnactis crassiseptata* (Smith) *Phaulactis* (*Cyathactis*), *Phaulactis*, *Kyphophyllum*, *Micula*, *Dokophyllum* ("*Omphyma*"), *Hedströmophyllum*, *Plasmophyllum* (as *Lamprophyllum*), *Evenkiella* (cerioid ? *Entelophyllum*), *Entelophyllum*, *Favosites* and *Paleofavosites*, with (Sokolov, 1955) *Syringopora* in the upper part. In the Taimyr *Favosites* (*Sapporipora*) and the new genus of favositid *Moyerolites* are reported (Sokolov, 1955). To the south-west of the Siberian platform, in Kazak A.S.S., the multisolenid *Antherolites* and the compact halysitid *Hexismia* occur with *Heliolites* (Sokolov, 1955) while the Australian favositid genus *Hattonia* occurs in South Fergana (Sokolov, 1955).

Chinese Silurian corals are only broadly known as to horizon within the Silurian. Assemblages referred by Wang (1944, 1947, 1948 and 1950) to the Middle Silurian occur in Yunnan. Only the Rugosa have been fully treated by this author, who reports *Amplexoides*, *Pycnactis*, ? *Dinophyllum*, omphymoids, *Entelophyllum* (as *Stereoxylodes*), *Pilophyllum*, *Pseudocystiphyllum*, *Lindstroemophyllum*, *Kyphophyllum*, *Disphyllum* (? = *Weissermelia*), *Cystiphyllum*, *Rhizophyllum*, *Holmophyllum*, *Zelophyllum* and *Gyalophyllum*. Of these *Pseudocystiphyllum* and *Lindstroemophyllum* are not recorded elsewhere, but the material on which they were founded does not seem very satisfactory. Another possibly Middle Silurian fauna is described (Yü, 1956) from West Kansu, with *Ptychophyllum* (*Nanshanophyllum*), *Paleofavosites*, *Favosites*, *Halysites* and *Heliolites*.

A fauna from Szechuan was the first Silurian fauna described from China (Lindström, 1883) and it may be somewhat younger than the Yunnan fauna with which it has one species in common—*Amplexoides appendiculatus* (Lindström); for the rest, it has *Synamplexus*, ? *Ptychophyllum*, *Cystiphyllum*, *Rhizophyllum*, *Teratophyllum*, *Stauria*, *Phaulactis*, *Favosites*, *Somphopora*, *Halysites*, *Heliolites* and *Propora*. A somewhat similar fauna from Hupei (Grabau, 1925; Yü, 1956; Hamada, 1958) is also possibly post-Wenlock, with *Amplexus*, *Pselophyllum*, *Rhabdocyclus*, *Cystiphyllum*, *Teratophyllum*, *Stauria*, *Favosites*, *Heliolites* and *Schedohalysites*.

Amplexoid forms and *Teratophyllum* are the somewhat distinctive features of these Chinese faunas.

Some Manchurian species are referred to the Wenlockian, and to the genera *Pseudomphyma*, *Spongophyllum* and *Favosites* (Yabe and Hayasaka, 1920; Yabe and Eguchi, 1943, 1944, 1945).

A fauna described from boulders in the Mesozoic Kenniho conglomerate in Korea by Ozaki in Shimizu, Ozaki and Obata (1933–5) and by Ma (1956) and regarded as Wenlockian, consists of tryplasmids and cystiphyllids with *Favosites* including *Sapporipora*, *Paleofavosites*, *Heliolites*, *Propora* including *Koreanopora*, *Plasmopora*, *Syringopora* and *Quepora*. The age of the derived fauna is doubted by Hamada (1958), who suggests Ordovician.

The very small faunas described from Indochina by Mansuy (1908, 1913, 1915) are not informative as to horizon or province.

No certainly Wenlockian corals are known from India or Indonesia.

LUDLOVIAN faunas are possibly represented in the Kitakami Mountainland and other parts of Japan (Hamada, 1958), though Hamada continues to refer a lower *Favosites* limestone there to the Wenlockian. The *Halysites* limestone of the Kawauti series, remarkably rich in the characteristic Australian–Asiatic slender halysitid *Schedohalysites*, is, he considers, not Wenlockian, as Sugiyama (1940) thought, but Lower Ludlovian ; it contains some elements not yet known in Europe, such as *Kitakamiphyllum* and *Nipponophyllum* (though *Entelophyllum fasciculatum* Wedekind 1927 may be congeneric with the latter). Other Rugosa are *Spongophyllum*, *Helminthidium*, *Tryplasma*, *Cystiphyllum* and *Rhizophyllum*, while the Tabulata are *Favosites*, *Paleofavosites*, *Thamnopora*, *Alveolites*, *Coenites*, *Heliolites*, *Propora*, ? *Plasmoporella*, *Syringopora* and the halysitids *Halysites*, *Falsicatenipora* and *Schedohalysites*.

In China the *Spirifer tingi* beds of Kueichou were considered by Grabau (1930) to be Upper Silurian, with *Amplexus*, "*Omphyma*", *Cystiphyllum* and *Favosites* ; possibly, as noted above, the faunas from Szechuan and Hupei may be post-Wenlockian. Regnell (1941) refers to the Ludlovian a fauna rather like the *S. tingi* fauna from Tien-Shan, with *Angopora* and *Plasmopora* additional, and considers a small fauna of Tabulata from the same region to be possibly transitional from Silurian into Devonian.

From Asiatic Russia my Ludlovian records are all of Tabulata. In Fergana Chernychev (1951) and Sokolov (1955) record *Favosites* and *Squameofavosites* with the Australian *Hattonia* ; and in the Salair Sokolov (1955) figures *Hattonia* and the favositid *Salairia*. In Turkestan the new tabulatan genera *Cylindrostylus* (*Edwardsiella*) and *Syringoporella* are figured by Sokolov (1955), and in Central Asia *Helioplasmolites*. Chechovich (1955) considers four complexes can be discerned in central Asiatic Ludlow faunas ; two, a *Propora-Multisolenia* and a *Favosites forbesi* complex in the *Pentamerus* zone of the Lower Ludlow, and two, a *Heliolites–Squameofavosites* complex and a *Favosites* complex in the Upper Ludlow.

Australia, New Guinea and New Zealand

In the southwest Pacific region Silurian corals are known only in eastern Australia and western New Guinea ; from the latter Teichert (1928) records the halysitid *Catenipora* ? *wallichi* (Reed), a species originally described from the Llandoverian of Spiti, central Himalayas. None is known from New Zealand.

In eastern Australia LLANDOVERIAN coral faunas are recorded, but require description. From the Orange district of N.S.W., Stevens and Packham (1953) list *Cystiphyllum*, "*Mucophyllum liliiforme*", *Desmidopora*, *Heliolites* and halysitids in the Bridge Creek Limestone Member, which lies 50 feet below shales bearing graptolites they regard as of the *M. gregarius* zone at the top of the Lower Llandovery. Of these only *Desmidopora* has been described (Fitzgerald, 1955). The Quarry Creek Limestone Member, which according to Packham and Stevens (1955) is younger (Upper Llandovery), is, they state, immediately overlain by beds with *Monograptus* cf. *pragensis pragensis* while 20 feet above it *M. marri* occurs. Some of its corals have been described by Etheridge (1904, 1907, 1908, 1909) and these include the large colonial rugosan ? *Arachnophyllum*, the endemic *Mictocystis*, with "*Tryplasma liliiformis*" and *Halysites*, *Schedohalysites* and *Acanthohalysites* (Hamada, 1958).

WENLOCKIAN corals have long been known from the Yass district of N.S.W. Here, in the Yass beds, which are possibly early Wenlockian,? *Hercophyllum*, *Tryplasma*, *Rhizophyllum*, *Holmophyllum*, *Coenites*, *Alveolites*, *Aulopora* and *Syringopora* are known (Etheridge, 1921 ; Hill, 1940 ; Brown, 1941). The younger Bowspring Limestone, *Barrandella* Shale and Hume Limestone possess a rich coral fauna. Endemic genera are the colonial Rugosa *Zenophila* and *Yassia*, and the phaulactid *Hercophyllum*. *Mucophyllum* is very like some Gotland *Pseudomphyma* ; *Baeophyllum* Hill is probably a junior synonym of the Japanese *Nipponophyllum* Sugiyama ; the otherwise Devonian *Disphyllum* is recorded in the Silurian elsewhere only in China. *Entelophyllum*, *Tryplasma*, *Pycnostylus*, *Rhizophyllum*, *Cystiphyllum* and *Streptelasma* occur as in many European countries and North America, and *Spongophyllum* as in Bohemia and Japan. These Rugosa, many of which were first described in short papers by Etheridge or by Jones, were revised by Hill (1940). The endemic *Mazaphyllum* occurs in the Bathurst district of N.S.W. (Crook, 1955). The accompanying Tabulata are cosmopolitan as to genera, with *Favosites* (Jones, 1937), *Hattonia* (a favositid, not a chaetetid as reported Jones, 1927), *Coenites*, *Alveolites* (Etheridge, 1921), *Aulopora* and *Syringopora*, and the heliolitids (revised by Jones and Hill, 1939) *Heliolites*, *Plasmopora* and *Propora*. Very remarkably, no halysitids are known.

This classical Yass fauna may in its younger parts be early Ludlovian, but is probably mainly Upper Wenlockian. Beds with graptolites of the *M. nilssoni* zone overlie it (Brown and Sherrard, 1952). From Quedong Hill (1943) has recorded a similar, smaller fauna that, however, contains *Calostylis*, the only known occurrence for Australia.

A fauna from Yarrangobilly, further south in N.S.W. and somewhat like the Yass fauna, but rich in the halysitids *Hexismia*, *Schedohalysites*, *Falsicatenipora* and *Acanthohalysites* (Hamada, 1958), contains also *Heliolites*, ? *Propora*, *Diploepora*, *Favosites*, *Striatopora*, *Parastriatopora*, *Alveolites* and *Coenites*, with rare Rugosa *Tryplasma* and ? *Neomphyma*. It also is probably Wenlockian, though possibly Ludlovian (Hill, 1954).

An endemic tabulatan genus *Fossopora* Etheridge (1903) possibly related to the northern hemisphere *Thecia* has been described from rocks doubtfully Silurian in the Wellington district of N.S.W.

In Tasmania a few Silurian (? Wenlockian) corals are known. *Hercophyllum* and *Entelophyllum* occur in the Gordon River Limestone (Hill, 1942), and *Falsicatenipora* is recorded (Hamada, 1958).

In North Queensland rich Silurian coral faunas have been collected from the Broken River, Clarke River, Chillagoe and Mungana districts and are at present being worked by the writer.

The oldest fossiliferous limestones here contain *Tryplasma*, ? *Streptelasma* and ? *Paliphyllum* (with dissepiments), *Favosites*, *Heliolites*, *Plasmoporella*, *Plasmopora*, *Propora* and *Catenipora*. *Plasmoporella* in Europe is confined to the Borkholm Beds, now regarded as uppermost Ordovician, and this fauna could possibly be uppermost Ordovician rather than Lower Silurian.

A younger Silurian fauna is much richer, with *Entelophyllum*, *Phaulactis*, omphymoids, *Tryplasma* solitary and fasciculate, ? *Pseudamplexus*, *Cystiphyllum*, *Rhizophyllum*, *Favosites*, *Multisolenia*, *Alveolites*, *Heliolites*, *Plasmopora*, *Propora*, *Diploepora*, halysitids (numerous) and a new syringoporoid genus. This is either Upper Wenlockian or Lower Ludlovian.

North America

In North and Arctic America Silurian strata were deposited in three distinct geosynclinal regions, Appalachian, Innuitian and Cordilleran, and on the craton by shallow seas spreading from these geosynclines.

The best known coral-bearing strata are those of the eastern epicontinental seas in Ontario and Michigan, but the corals collected from these are largely silicified or have had their internal structure obscured by dolomitization, so that it is difficult to draw comparisons between them and the beautifully preserved specimens from Europe. The Canadian corals were revised or described by Lambe (1899–1901) but many of his specimens are now missing (Twenhofel, 1928) and there is doubt about the horizon of others. A further difficulty experienced by the non-American palæontologist in assessing these faunas is the variable stratigraphic connotation, so that a term, *e.g.* Clinton, has different significance for almost every author. In this review I have taken the stratigraphic definitions given by the latest Canadian Memoir on Ontario (Bolton, 1957) since they are clear and since the stratigraphic equivalencies set out in the memoir seem to be broadly based and acceptable to workers in different groups, *e.g.* brachiopods, corals, ostracods and nautiloids.

Possibly the oldest Silurian coral fauna of the eastern seas is that of the Manitoulin dolomite of Ontario (Bolton, 1957) and Michigan (Ehlers and Kesling, 1957). Williams (1919) figures *Palæophyllum* and a cerioid rugosan that he refers to *Acervularia*, together with solitary streptelasmoids and *Paleofavosites*, and lists *Syringopora*, '*Halysites*' and *Chonophyllum belli*. Bolton (1957) lists the small solitary streptelasmoids *Enterolasma*, *Neozaphrentis* and *Kionelasma* (with axial structure), and the Tabulata *Paleofavosites* and *Propora* (as *Lyellia*). A much smaller fauna occurs in the overlying Cabot Head Formation. These two together are equivalent to part of the Medinan of New York, and possibly part of the lower Becsie of Anticosti and the Edgewood and Brassfield of Illinois and Missouri. They are almost certainly Lower Llandovery in equivalence.

The lower Clinton in the sense of Bolton (1957) begins with beds with the brachiopod *Virgiana*, which are widely distributed in eastern Canada and north eastern U.S.A. and are all probably nearly coeval. In Ontario and Michigan these are poor in corals, but in Anticosti the upper Becsie and lower Gun River (Twenhofel, 1928) contain small solitary streptelasmoids (? *Brachyelasma*), two insufficiently illustrated phaceloid rugosans, one possibly allied to *Stauria favosa*, *Syringopora*, *Favosites*, *Paleofavosites*, '*Halysites*' and *Propora* (as *Lyellia*). In Manitoba the Fisher Branch Dolomite at the base of the Interlake group also has small solitary streptelasmoids with *Paleofavosites*, *Favosites* and *Propora*, but with *Multisolenia* and the compact halysitid *Hexismia* making their first appearance.

The upper part of Bolton's (1957) lower Clinton contains the Reynales Formation and its equivalents with bioherms, the coral-rich Fossil Hill of Manitoulin, the Manistique of Michigan, the Thornloe limestone (with *Multisolenia* and *Hexismia*) of the Lake Timiskaming area, the Jupiter of Anticosti, the Attawapiskat of Hudson Bay and the East Arm formation of the Interlake group of Manitoba. The Michigan and Manitoulin fauna was figured by Rominger (1876) but his collection-localities mostly covered more than this formation. From Ehlers and Kesling (1957) and Bolton (1957) this fauna is taken to consist of *Palæocyclus*, *Dinophyllum*, *Arachnophyllum*, *Goniophyllum pyramidale*, *Tryplasma*, *Diplophyllum*, small solitary streptelasmoids and *Kionelasma*, *Amplexus shumardi*, *Ptychophyllum* and "*Omphyma*", together with the tabulatans *Favosites*, *Striatopora*, *Alveolites*, *Coenites*, *Cladopora*, *Halysites*, *Catenipora*, *Heliolites*, *Propora*, *Plasmopora*, *Syringopora*, *Romingerella*, *Thecia* and in the lower beds *Hexismia compacta*. The first four genera suggest correlation with the Upper Llandovery Lower Visby marls of Gotland. The Jupiter formation of Anticosti I. (which has *Pentamerus oblongus* and *Stricklandia*), also has *Monograptus clintonensis*, (like an early *M. priodon*), *Palæocyclus*, *Arachnophyllum*, *Cystiphyllum*, lykophyllinids (solitary "*Cyathophyllum*" with normal dissepimentaria), small solitary streptelasmoids and most of the tabulatan genera of the Fossil Hill–Manistique. The La Veille formation of Chaleur Bay seems to correlate herewith (Alcock, 1935; Northrop, 1939), and the Pike Arm formation of Notre Dame Bay, Newfoundland (Shrock and Twenhofel, 1939) also.

Thus Bolton's upper part of his lower Clinton correlates very well with the Lower Visby marls and the Coralliferous Series of Pembrokeshire, both of which are Upper Llandovery, probably pre-*crenulatus* zone. Iowan corals listed by Rominger (1876) and the small fauna with *Goniophyllum pyramidale*, *Petalocrinus* and *Stricklandia* described by Weller and Davidson (1896) from dolomite surely correlate with the topmost Llandovery.

The Chicotte formation (Twenhofel, 1928) at the top of the Anticosti sequence also may represent topmost Llandovery since it contains ? *Schlotheimophyllum* (as *Chonophyllum canadense*) and *Arachnophyllum*, but if *Entelophyllum* is present it may possibly represent very early Wenlock.

In Manitoba the East Arm Formation of the Interlake group (with *Striatopora*, *Favosites*, *Paleofavosites*, *Corrugopora*, *Multisolenia*, *Alveolites*, *Propora*) is thought to correlate with the Manistique (Stearn, 1956), and above it, from the two topmost members of the group (Chemahawua Member and Cedar Lake Dolomite), Stearn figures two phaceloid Rugosa, *Pycnostylus* and *Synamplexoides*, with the solitary *Dinophyllum* and *Cystiphyllum*, and the tabulatans *Alveolites*, *Corrugopora* and *Striatopora* joining *Paleofavosites*, *Favosites* and *Propora*. The presence of *Dinophyllum* suggests that this is still within the Upper Llandovery, so that the Interlake group might well be wholly within the Llandovery.

The sequence above the Reynales and Manistique in New York, Michigan and Ontario is poor in corals, and in his Upper Clinton (including Irondequoit, Rochester and Decew) Bolton (1957) lists only small solitary streptelasmoids with *Aulopora*, *Favosites*, *Striatopora* and *Coenites*. On the corals it is thus not possible to say whether his Upper Clinton is Llandovery or Wenlock.

In Ohio the small fauna of the West Union formation is said by Foerste (1917) to contain *Holophragma calceoloides*, '*Zaphrentis*', '*Cyathophyllum*', and *Acervularia*, while the possibly equivalent Laurel limestone has *Calostylis*. This may be uppermost Llandovery. *Grabauphyllum* (? a cerioid *Spongophyllum*) occurs in 'Niagaran' dolomite in Illinois.

The Silurian of Alaska (Buddington and Chapin, 1929) and of the Cordillera of Western Canada (including the Ronning Formation, Hume, 1954) is poorly known, but lists without illustrations indicate *Palæocyclus*, *Arachnophyllum*, '*Zaphrentis*', '*Cyathophyllum*', '*Disphyllum*', *Favosites*, *Alveolites*, *Syringopora* and *Halysites*. Horizons within the Silurian are not clear, but from the first two genera lower Clinton and Upper Llandovery strata appear to be represented. This north-western fauna has been compared with the Silurian coral fauna of the western U.S.A., which (Duncan, 1956) includes *Tryplasma* (solitary and fasciculate species), *Palæocyclus*, *Cystiphyllum*, *Pycnactis*, solitary '*Cyathophyllum*', phaceloid *Entelophyllum* and *Circophyllum*, *Cystihalysites*, *Halysites*, *Catenipora*, *Alveolites*, *Favosites* including squamulate types, *Cladopora*, *Syringopora* and *Heliolites*, all of which remain to be investigated by modern techniques. *Entelophyllum*, *Circophyllum* and squamulate *Favosites* suggest that faunas younger than Upper Llandovery are also represented, and descriptions will be awaited with interest.

Arctic American corals are on the whole, poorly known. Reefs are reported (Fortier in Stockwell, 1957) in the Read Bay Formation of Cornwallis Island, now in part dolomitic. Possibly the oldest Silurian fauna is in the Offley Island Formation (Poulsen, 1941) and of the *M. sedgwicki* zone at the base of the Upper Llandovery, and here *Palæophyllum*, ? *Cystiphyllum* and small solitary Rugosa occur with *Paleofavosites*, *Favosites*, ? *Proheliolites*, *Propora*, ? *Nyctopora* and halysitids. On Brodeur Peninsula at the northwest end of Baffin Island, and at

Kuk at the north tip of Southampton Island on the northwest of Hudson Bay, Teichert (1937) has described a few corals including small solitary Rugosa, *Favosites* and *Halysites* that are probably Llandoverian. From King William Land he has described *Paleofavosites* and halysitids referable to *Quepora*, ? *Catenipora* and ? *Eocatenipora*. From unknown horizons in the Arctic Silurian are the rugosan *Naos* (=? *Craterophyllum*) *pagoda* from Melville Island (Lang, 1926) and the tabulatan *Boreaster* from Beechy Island in Lancaster Sound (Sokolov, 1955).

Where one should draw the base of the WENLOCKIAN in the Ontario–Michigan–New York sequences it is difficult to say, but probably the Wenlockian includes Bolton's (1957) Lockport there, and the Amabel which he regards as equivalent to the Lockport. In the Wiarton member of the Amabel he lists, but does not figure *Cystostylus*, small solitary streptelasmoids (*Enterolasma* and '*Zaphrentis*') '*Omphyma*', *Pycnostylus*, *Favosites*, *Striatopora*, *Coenites*, *Thecia*, *Heliolites*, *Syringopora* and *Halysites*. From the Lockport (shale) of New York (restricted) Hall (1852) figured *Striatopora* and *Astrocerium*.

In Britain the Wenlockian is called Middle Silurian, but in North America the Niagaran is commonly called Middle Silurian. As seen above, in Bolton's usage the Niagaran includes the Upper Llandovery Clinton group as well as his Albemarle, which includes both Lockport and overlying Guelph dolomites. According to some the Guelph is equivalent to part of the Lower Ludlow. Thus Niagaran fully corresponds neither to the Wenlockian nor to the British Middle Silurian, a fact that must be borne in mind in reading coral faunal papers.

The Louisville of Kentucky may conceivably be Wenlockian. It contains *Entelophyllum* (Smith, 1933) and *Rhizophyllum* (Lindström, 1883), *Tryplasma*, *Thecia*, *Heliolites*, and *Propora* (as *Lyellia*, Rominger, 1876) plus *Amplexus shumardi*, *Blothrophyllum*, *Chonophyllum*, '*Cyathophyllum*', '*Diphyphyllum*', '*Eridophyllum*', '*Hallia*', '*Heliophyllum*', *Omphyma*, *Ptychophyllum*, *Streptelasma*, *Arachnophyllum*, *Alveolites*, *Cladopora*, *Coenites*, *Favosites*, *Halysites*, *Plasmopora*, *Romingeria*, *Striatopora* and *Syringopora* (Butts, 1914–15). This fauna requires revision.

In Tennessee the coral fauna of the Brownsport formation has been investigated by modern thin section methods (Amsden, 1949). It is quite rich, and contains several solitary non-dissepimented Rugosa showing a peculiar rejuvenescence, the corallites expanding and contracting in diameter rhythmically, giving angular projections and concave surfaces between; other forms are *Anisophyllum*, *Ditoecholasma* and non-dissepimented ? *Spongophylloides waynense* (Safford), *Tryplasma*, *Rhizophyllum*, *Cystiphyllum*, lykophyllinids with wide, normal dissepimentaria, solitary entelophyllids such as '*Naos*' *sewellensis* Amsden, and the compound *Entelophyllum rugosum* and *Arachnophyllum*, with the tabulatans *Favosites*, squamulate *Favosites*, ? *Pleurodictyum*, *Striatopora*, *Alveolites*, *Planalveolites* and *Coenites*, ? *Dendropora*, ? *Cladopora*, *Romingerella* and *Thecia*, *Heliolites*, *Stelliporella* (as *Cosmiolithus*), ? *Propora*, ? *Plasmopora* and *Cystihalysites*. This fauna has little in common with the Llandovery Clinton faunas, and it resembles European Wenlockian and early Ludlovian faunas. Amsden correlates it with the Louisville of Kentucky, the Bainbridge of Missouri (from which *Syringaxon* (*Laccophyllum*) is known) and the Henryhouse of Oklahoma. But Freeman (1950) shows the Louisville as lying immediately below the Brownsport. Berry (1958) reports Lower Ludlovian *M. nilssoni* zone graptolites in the Henryhouse of Oklahoma, and suggests the Brownsport therefore is Lower Ludlovian.

In the Arctic the *Atrypella* beds with the *Atrypella scheei* fauna (formerly the *Lissatrypa phoca* fauna) are now considered to be Middle and Upper Silurian and possibly later, and contain a long list of corals (Foerste, 1929) nearly all of which require elucidation. The fauna is widespread in the Arctic (including

Vaigach I.). It is found on King William Island, in Boothia Peninsula and in Victoria Strait Basin to at least Scoresby Bay near the eastern margin of the central Ellesmere belt.

The Lower LUDLOVIAN may possibly be represented by the Guelph dolomite of the Niagaran escarpment, from which Bolton (1957) lists *Amplexus shumardi*, *Arachnophyllum*, "*Cyathophyllum*", "*Omphyma*", *Ptychophyllum*, *Pycnostylus elegans* and *guelphensis*, *Coenites*, *Favosites* and *Halysites*. The New York Guelph also contains *Diplophyllum* Hall (1876). The two *Pycnostylus* species are recorded from the Silurian of Great Slave Lake (Hume, 1926). As mentioned above, the Brownsport fauna of Tennessee may be Lower Ludlovian.

Higher Silurian strata contain extremely few corals.

South America, Africa and Antarctica

Records of Silurian corals are remarkably rare in South America. A doubtfully Silurian collection from Bom Jesus de Lapa in the Amazon Valley of Brazil contains *Favosites niagarensis* (Reudemann in Maury, 1929). In Cerro del Fuerte, San Juan, in the Argentine, *Favosites argentinus* occurs in probably Clinton (Upper Llandovery) strata (Clarke, 1913).

In Africa graptolitic Silurian beds are known from Morocco and Algeria, but corals are extremely rare; Termier and Termier (1950) figure *Favosites tachlowitzensis*, *Columnopora* sp., *Streptelasma* cf. *aggregatum* Nich. and Eth., and *Spongophyllum fritschi* Novak from Morocco from ? Ludlovian horizons, and Barbier, Termier and Termier (1948) mention *Favosites gothlandicus* from Ludlovian limestones of western Algeria, in Grande Kabylie. As in Spain and France, in N.W. Africa and French Guinea the Silurian facies is graptolitic except in the Ludlovian, where calcareous beds with *Cardiola interrupta* appear.

No Silurian corals are recorded from Antarctica.

III. CORAL REEFS.

Small coral-stromatoporoid-algal reefs are characteristic of epicontinental shelf regions in the Silurian from late Upper Llandovery to early Ludlow times. They are most beautifully displayed in the Islands of Gotland and Oesel in the Baltic sea (58° N), on Wenlock Edge in Great Britain (52° N) and less well on Vaigach I. south of Novaya Zemblya (70° N). Excellent descriptions in English are available for the Gotland reefs (Hadding 1956, 1950, 1941). In North America similar reefs are well known in the Great Lakes area (Lowenstamm, 1950) and Hudson Bay. Others occur in Alaska, on Cornwallis I. (75° N, Fortier in Stockwell, 1957) and further south in Nevada (*B.A.A.P.G.*, 1959). In Japan (Ma, 1956; Hamada, 1958) no bioherms appear to have been described, but in Siberia on the Stony Tunguska R. (Soshkina in Ivanova *et al.*, 1955) (63° N) small masses occur. In southern Europe and North Africa graptolitic facies predominate, possibly reflecting depths of water too great for reef growth. In South America, Africa and Antarctica no reefs (and very few corals) are known, but in Australia reefs occur in north Queensland (19° S) and in N.S.W. at Yass (35° S) and Yarrangobilly (35° 40′ S). Talent and Philip (1957) consider topmost Silurian or early Devonian reefs occur in Victoria at 37° S.

Ma (1956) to explain this distribution invoked sudden total displacements of the solid earth shell and accompanying drift of continents. But it seems to me that a rise in sea temperatures is a more likely explanation.

IV. WORLD FAUNAL SEQUENCE AND DISTRIBUTION.

Generalising from these sequences in the various continents, we may obtain a working understanding of the world sequence and distribution.

The LOWER (AND MIDDLE) LLANDOVERIAN faunas are so far known only in the Northern Hemisphere, and are still very similar to the Upper

Ordovician faunas. They are perhaps richest in Estonia, where the first normally dissepimented genus *Paliphyllum* (that arose in the Upper Ordovician) is accompanied by solitary, non-dissepimented streptelasmids and by the tabulatan *Palæohalysites*. In Great Britain *Calostylis* (earlier found in the Upper Ordovician of Estonia) and small columellate *Dalmanophyllum* accompany the streptelasmids, with *Paleofavosites*, *Pinacopora* (=? *Propora*) and *Heliolites*. In eastern North America the Manitoulin dolomite contains *Palæophyllum*, small solitary non-dissepimented streptelasmids and a doubtful *Acervularia*, *Chonophyllum belli*, *Paleofavosites*, *Propora* (as *Lyellia*), *Syringopora* and halysitids. These faunas are too small to establish whether they are divisible into geographic provinces or not.

It was in the Upper Llandoverian that the great burst of Silurian coral vigour occurred, numerous new families, genera and species entering, the number increasing rapidly from a quite vigorous first appearance in the *M. turriculatus* zone of Shropshire. Small coral reefs were present in Northern Europe at the time, especially in Gotland and Estonia.

In Europe, amongst the Streptelasmatina, small non-dissepimented Streptelasmatinæ (*Streptelasma*, *Rhegmaphyllum*, *Brachyelasma*, *Dalmanophyllum*) are joined by *Dinophyllum* and the characteristically Silurian large and wide-bordered solitary chonophyllinid *Schlotheimophyllum*, by a wealth of solitary Lykophyllinæ, both non-dissepimented (*Pycnactis*, *Onychophyllum*, *Holophragma*) and dissepimented (*Phaulactis*) and by the colonial Arachnophyllinæ *Arachnophyllum* and *Petrozium*, while the aberrant *Calostylis* continues. Amongst the Columnariina, *Strombodes* and *Cyathophylloides* continue ; of the Cystiphyllina, *Tryplasma* continues and is joined by *Cystiphyllum*, *Hedströmophyllum*, *Polyorophe*, *Palæocyclus*, *Cantrillia* (these last two disappearing below the top), *Rhabdocyclus* and *Goniophyllum*. The tabulatans *Paleofavosites*, *Protaræa*, *Propora*, *Heliolites* and halysitids are joined by *Mesofavosites*, *Favosites*, *Alveolites* and *Syringolites*, *Striatopora* and *Pachypora* (at the top), *Thecia*, *Angopora* and *Planalveolites*, *Multisolenia* and the heliolitids *Heliolites*, *Stelliporella*, *Pycnolithus*, *Cosmiolithus*, *Plasmopora* and *Propora* and halysitids.

This fauna becomes richer from bottom to top of the Upper Llandoverian, but enough elements are common to Great Britain, Gotland and Estonia to show that we are here dealing with one zoogeographical province.

The Siberian fauna regarded as Upper Llandoverian has far fewer Rugosa, and could possibly be early rather than late Upper Llandovery as at present supposed. But its tabulatan fauna is rich with *Paleofavosites*, *Favosites*, *Multisolenia* *Agetolites*, *Alveolites*, *Subalveolitella*, *Striatopora*, *Parastriatopora*, *Syringopora*, *Syringoporinus*, *Palæohalysites*, *Cystihalysites* and *Propora*. This includes newly described genera that may yet be recognised within genera as presently known from Northern Europe. It is too soon, therefore, to know whether the Siberian fauna is of a zoogeographical province distinct from that of northern Europe.

The Australian Upper Llandovery fauna is small, but contains at least one endemic Rugosan, *Mictocystis* ; its halysitids however are *Halysites*, *Acanthohalysites* and *Schedohalysites*, and according to Hamada (1958) indicate that the ‘ Gotlandian ’ sea of Asia and Australia constituted a distinct faunal province.

In North America the “ lower Clinton ” in the sense of Bolton (1957) probably correlates with the Upper Llandoverian. It includes the famous Manistique fauna of Michigan made known by Rominger, and its generic list seems to indicate that eastern North America was co-provincial with northern Europe at this time. Some elements, the streptelasmid ‘ *Kionelasma* ’ with spongy axial structure and ‘*Amplexus* ’ *shumardi*, appear endemic, and the compact halysitid *Hexismia* seems to have entered here earlier than elsewhere. Western and Arctic North American faunas are smaller but similar.

Though in Britain WENLOCKIAN faunas are richer than the British Llandoverian in general, elsewhere in Europe they simply represent a weakened further development from the Upper Llandovery burst. Some Llandovery genera die out before or early in the Wenlockian, *e.g.* the Rugosa *Palæocyclus*, *Cantrillia*, *Dinophyllum*, *Aræopoma*, *Schlotheimophyllum* and *Holophragma*, and some new Rugosa enter early (*Acervularia*, *Kyphophyllum*, '*Omphyma*' (=*Ketophyllum*), *Kodonophyllum* and *Pseudomphyma*); *Zelophyllum* is restricted to the early Wenlockian, *Helminthidium*, *Circophyllum* ,*Stauria* and *Rhytidiophyllum* (the latter endemic to Gotland) enter later in the Wenlockian, as does *Entelophyllum* and *Micula*; Lykophyllinæ proliferate. Of the Tabulata *Coenites*, *Nodulipora* and *Diploepora* appear within the Wenlockian and in Estonia *Subalveolites*, *Mastopora* and *Jaaremolites* have recently been split off from broader genera. *Heliolites* is a dominant reef builder. The Asiatic (Stony Tunguska) Wenlockian fauna is smaller than that of northern Europe, but it does not contain many endemic genera and there is little reason for thinking it of a separate province from that of Europe, though some new favositid genera and subgenera have recently been distinguished—*Sapporipora*, *Moyerolites* and *Antherolites*, with *Hexismia* (earlier known in the Clinton of North America) and the otherwise Australian favositid *Hattonia*. Hamada (1958) considers the Halysitidæ indicate an Asio-Australian province separable from the European in 'Gotlandian' times. Chinese Wenlockian lists contain some generic names not found elsewhere, but on the whole they are like the European.

The Australian Wenlockian fauna has a few endemic elements (*Zenophila*, *Crinophyllum*), shares a few genera only with Asia [*Bæophyllum* (=? *Nipponophyllum*), *Hattonia*, *Schedohalysites*], but otherwise is very similar to the northern European fauna. *Rhizophyllum* may have made its earliest appearance herein. The North American Wenlockian faunas are mostly poorly known, except for that of the Brownsport formation of Tennessee, though this indeed might be early Ludlovian; mostly its genera are as in Europe, but a few may prove endemic.

One must, I think, be more impressed by the cosmopolitan nature of the Wenlockian coral genera than by the few evidences of geographical differentiation, such as the weakly defined Asio-Australian subprovince and the even more weakly defined North American subprovince.

LUDLOVIAN faunas are cosmopolitan, show few new genera (*Gyalophyllum*, *Weissermilia* and *Rhizophyllum* in Gotland, *Squameofavosites*, *Salairia*, *Syringoporella* and *Helioplasmolites* in Asia) and are on the whole poorer than the Wenlockian; everywhere they can only be regarded as a weakening development from the Wenlockian. The number of genera is radically reduced in the Gedinnian, and it is not until the Coblenzian that the Devonian fauna proliferates.

Of the Silurian genera mentioned above only *Rhizophyllum*, *Cystiphyllum*, *Pseudamplexus*, *Entelophyllum*, *Spongophylloides* and *Spongophyllum* amongst the Rugosa, and *Favosites*, *Hattonia*, *Squameofavosites*, *Alveolites*, *Coenites*, *Striatopora*, *Thamnopora*, *Heliolites*, *Plasmopora* and *Syringopora* amongst the Tabulata, commonly proceed into the Gedinnian. The subsequent development of the coral faunas in the Devonian and Upper Palæozoic has already been reviewed by Hill (1957).

V. CONCLUSION.

We conclude therefore, that the 'Silurian' coral fauna began cautiously in the uppermost Upper Ordovician, gained evolutionary speed a little during the Lower Llandovery, then very rapidly increased its rate of development from early until late Upper Llandoverian, and, though it did develop some new genera in the Wenlockian and fewer in the Ludlovian, began to weaken from early Wenlockian times, so that by latest Silurian and earliest Devonian times it was reduced to but a fraction of its former self. Also, though there are suggestions of Asio-Australian and North American subprovinces, on the whole the Silurian fauna of the world is cosmopolitan, with its richest and best known development in the Upper Llandovery and early Wenlockian of northern Europe (Gotland). Further, the richest developments are always associated with coral-stromatoporoid-algal reef growth, especially in northern Europe and North America, as far north as 70° N. To me this suggests that at least the northern oceanic temperatures were higher in the Silurian than now.

Southern Europe, Africa, South America, Antarctica and New Zealand are extremely poor or lacking in Silurian corals ; for southern Europe and northern Africa the widespread graptolitic facies may indicate a deeper-water environment not suitable for coral growth.

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RECORD OF *BOTHRIOLEPIS* AND *PHYLLOLEPIS* (UPPER DEVONIAN) FROM THE NORTHERN TERRITORY OF AUSTRALIA.

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Professor of Geology and Mineralogy in the University of Melbourne.

(With Plate VIII.)

Two small collections of fragmentary remains of placoderm fishes recently referred to me by the Commonwealth Bureau of Mineral Resources, Geology and Geophysics and by Frome–Broken Hill Pty. Ltd. are derived from the Dulcie Sandstone in the Dulcie Ranges some 200 miles north-easterly of Alice Springs, in the Northern Territory. The beds are somewhat silicified quartz sandstones, ranging in colour from white to red, and no fossils other than the fish plates are present in the specimen examined by me. The three plates of the Bureau collections are all referable to *Bothriolepis*, while the samples supplied by Frome-Broken Hill contain two *Phyllolepis* plates together with small fragments having *Bothriolepis*-like ornament. I am informed by the Chief Geologist, Bureau of Mineral Resources, Geology and Geophysics, that the two collections were derived from outcrops approximately half a mile apart and probably separated 300–400 feet stratigraphically.

Geological Age and Facies.—*Bothriolepis* is of very wide geographical distribution in the Upper Devonian, but is also reported to occur in the Middle Devonian of the Baltic region. The association *Bothriolepis–Phyllolepis* is, however, known only from the Upper Devonian, not only in Europe and Greenland but also in south-eastern Australia.

In the absence of indications to the contrary, it may be reasonably assumed that the Dulcie Sandstone is of continental and presumably of fresh-water origin, analogous with the Old Red Sandstone of Europe. This discovery of continental Upper Devonian fish beds in Central Australia, over 1000 miles from the localities, which are now numerous, where they are known in the south-east, vastly extends the geographical range of *Bothriolepis* and *Phyllolepis* within Australia, and opens new horizons as to palæogeographic and tectonic concepts.

DESCRIPTION.

Genus **Bothriolepis**.

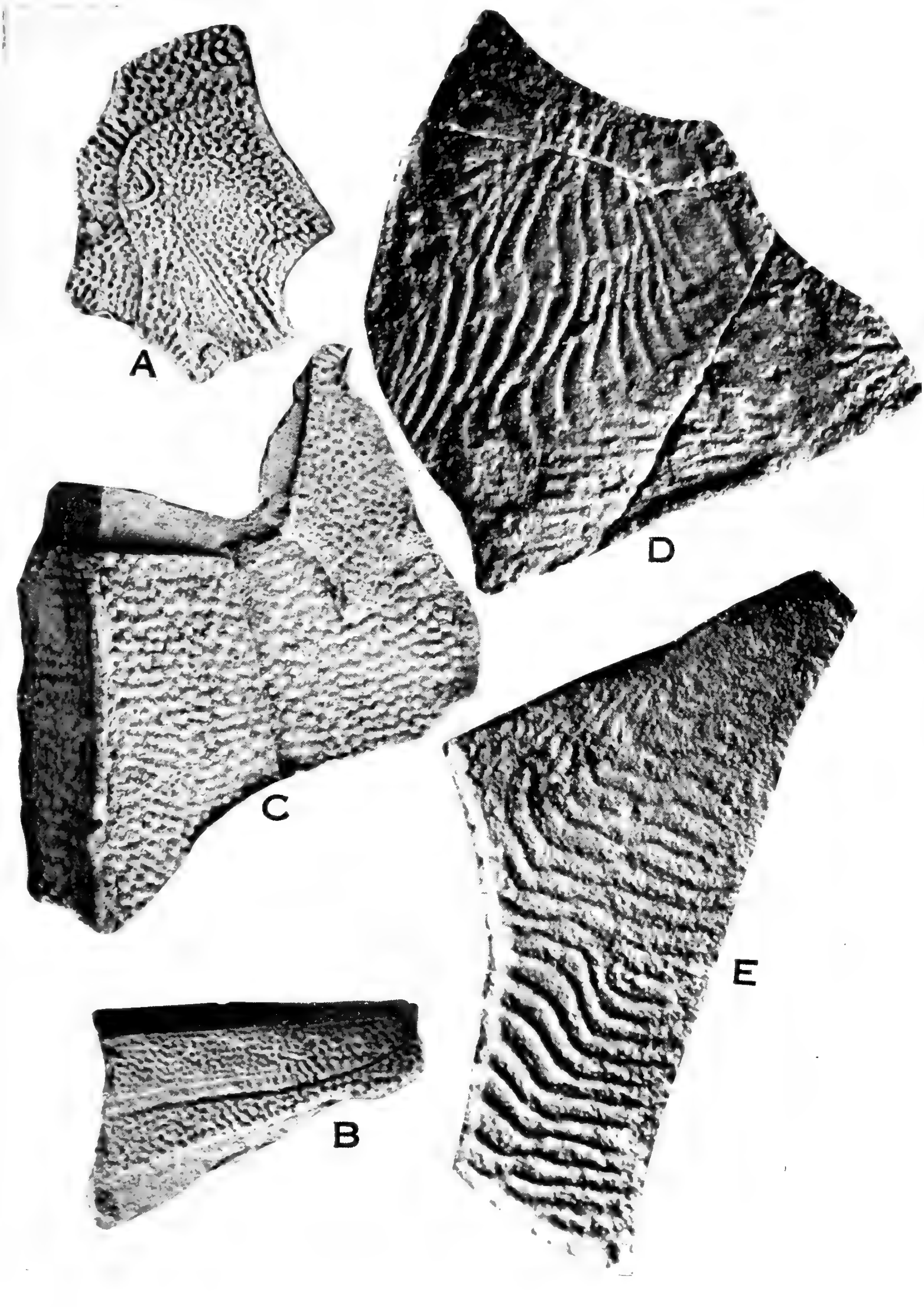
F21,135, Bureau of Mineral Resources (Pl. VIII, A).

A left lateral plate of the head, preserved almost entire. In all respects this plate conforms with *Bothriolepis*. Its proportions lie within the range of variation of several described species, but the rather delicate ornament of tubercules linked by short ridges to form either a reticulate or vermicular pattern suggests a comparison with *B. cellulosa* from Europe and Australian forms such as *B. gippslandiensis* and various fragmentary remains, not specifically determinable, from Victoria and south-eastern New South Wales.

F21,136, Bureau of Mineral Resources (Pl. VIII, B).

An imperfect right anterior dorso-lateral plate showing the anterior angle, the descending lamina with lateral line canal passing upwards anteriorly, the overlap area against the anterior ventro-lateral, and the fractured dorsal lamina of the bone. This plate belongs to a smaller individual than F21,135.

F21,134, Bureau of Mineral Resources (Pl. VIII, C).


A
D
C
E
B

This specimen consists of the broken remains of a right posterior ventro-lateral plate, against which an indeterminate fragment of another individual lies. The ornament is of tubercles which are larger and less strongly linked by ridges than in the other two plates described. The angle of the plate is marked by a strong ridge.

It is clear that the remains of several individuals are represented even in this small collection, and that the plates were strewn after the death and disintegration of the fishes, although they are scarcely worn and were not carried far by current-action.

Genus **Phyllolepis.**

The two examples described are both imperfect and are referred to *Phyllolepis* because the ornament, general proportions and thinness of the bones conform with plates of this genus, which has few close allies.

Specimen No. 1, Frome–Broken Hill Pty. (Pl. VIII, D).

This may doubtfully be referred to a posterior lateral angle of an anterior ventro-lateral plate.

Specimen No. 2, Frome–Broken Hill Pty. (Pl. VIII, E).

This may doubtfully be referred to the anterior median angle of a posterior ventro-lateral plate.

Permission to submit these records for publication has been kindly granted by Frome–Broken Hill Pty. Ltd., and by the Director, Bureau of Mineral Resources, Geology and Geophysics. I am indebted to Miss Cecily Finlay, B.Sc., for the photographs reproduced in the Plate.

Explanation of Plate VIII.

(All Illustrations are X2.)

Bothriolepis sp.

A. Left lateral plate of head.
B. Right anterior dorso-lateral plate.
C. Remains of right posterior ventro-lateral plate.

Phyllolepis sp.

D. (?) Posterior lateral angle of an anterior ventro-lateral plate.
E. (?) Anterior median angle of a posterior ventro-lateral plate.

QUEENSLAND EARTHQUAKES AND THEIR RELATION TO STRUCTURAL FEATURES.

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It may at first sight seem inappropriate that a paper the major interest of which is seismological rather than geological should be included in a volume which is a memorial to the late Professor Sir Edgeworth David; but David's interests were extremely wide and certainly included the relation of seismic effects to geology, for while it was Woolnough who first suggested that some suitable instrument be installed at the Burrinjuck reservoir to ascertain whether any deflection of the earth's crust would take place as the result of the increased loading as the reservoir filled, it was David, who, after Woolnough was appointed to the Chair of Geology at Perth, suggested to Mr. (later Professor) L. A. Cotton that he undertake the investigation (Cotton, 1915; 1921).

A glance at a map showing the recorded epicentres of earthquakes in Australia (Burke-Gaffney, 1951, fig. 1, p. 50) suggests that not only is Queensland much more stable than New South Wales, Victoria, Tasmania and South Australia, but that its freedom from earthquakes is only surpassed by that of the Northern Territory and of Western Australia. Such deductions, however, are not entirely reliable, for prior to 1937 there was not one seismological station in the whole of Queensland's vast area (Bryan, 1938), while the Northern Territory is still lacking in such an installation. And, since highly sensitive instruments were first operated at the University of Queensland Station in 1942, twenty-eight Queensland earthquakes and six aftershocks have been recorded at that station. That one station, especially one situated in the south-east corner of the State, is insufficient adequately to record the seismicity of an area the size of Queensland, is demonstrated by the fact that, since a second station was established at Charters Towers in September, 1957, as part of the Australian International Geophysical Year programme,[1] twelve local shocks have been recorded there in addition to one of those recorded also at Brisbane. Many of these tremors were too slight to be felt (or reported in this sparsely populated State) and there is not the slightest doubt that, were additional stations established, records would be obtained of many more shocks originating within the boundaries of the State.

The earthquakes of April 12th, 1935, (large for Queensland) and recorded in Sydney, Melbourne and Adelaide, and its numerous aftershocks were thoroughly investigated in the field by Bryan and Whitehouse (1938) and all later shocks which were reported felt were investigated by the writer by means of widely distributed questionnaires (based on the Modified Mercalli Intensity Scale). The information available on three earlier earthquakes and deductions from the information collected as above are set out in Table I, while Table II gives the small amount of information available about tremors which have been recorded, but not reported felt; all these were almost certainly smaller than all of those in Table I except perhaps Nos. 10, 16, 20 and 22.

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[1] This station was at the end of the I.G.Y. presented to the University of Queensland by the Australian Academy of Science, and will continue to be operated by the Department of Geology of the University.

TABLE I.

SOME DETAILS OF RECORDED QUEENSLAND EARTHQUAKES.

(Nos. 1–4 were recorded at Riverview; the remainder, except No. 23, at Brisbane.)

Number and Date	Time (G.M.T.) of P at the recording station.	Epicentre Lat. S.	Epicentre Long. E.	Quality.	Magnitude M. or Intensity.	General Locality and Remarks
	H M S					
1. 1913 May 1st	16–20–17	27	152·5	c	M.4	Kilcoy
2. 1913 Dec. 18th	13–54·0	20	147	b	M.4	40 miles east of Charters Towers. Epicentre determined by Gutenberg.
3. 1918 June 16th	18–14–15	24	154	c	M.6	About 200 M. east of Gladstone. Epicentre determined by Pigot; but its position is doubtful (see Bryan 1946, pp. 49–50).
4. 1935 April 12th	01–32–34	26	151·1	c	M.5	60 m. S.W. of Gayndah. Epicentre by Bryan and Whitehouse. More than eighty aftershocks including strong ones on May 23rd 1935, July 19th 1935 and Oct. 7th 1937.
5. 1947 June 11th	10–03–13	25·5	152·7	c	V	Maryborough
6. 1950 April 5th	19–50–52	21·1	149·2	c	V	Mackay
7. 1950 June 19th	About 09–00	17·5	145·5	d	III	Epicentre probably S.E. of Atherton near the edge of the Tableland.
8. 1951 Dec. 30th	20–34–44	25·8	150·9	c	IV	Mundubbera. Recorded aftershocks at 21.41.08; 21.42.23; 21.44.29 and at 22.40.49 on the same day.
9. 1952 June 24th	01–34–39	25·5	152·8	c	V	Maryborough. Epicentre very close to that of No. 5.
10. 1953 Feb. 6th	17–50–30	near 24·5	150·7	d	II	Monto. Epicentre near Dawes.
11. 1953 Dec. 3rd	15–43–43	24·5	151·5	c	IV	Many Peaks.
12. 1954 May 4th	07·1	17·7	146	d	III	Mourilyan. Surface waves only recorded.
13. 1954 Sept. 19th	10–38–11	28·5	148·5	d	IV	St. George. Felt also in north-central N.S.W.
14. 1954 Sept. 21st	20–29–59	25·5	152	d	III	Biggenden
15. 1955 Feb. 1st	11–09–55	26·2	151·2	c	IV	Murgon.
16. 1955 April 10th	22–36–36	26·7	152·2	d	II	Mt. Stanley near Nanango
17. 1955 Sept. 10th	06–13–31	26	151	d	III	Mundubbera.
18. 1955 Dec. 1st	05–34–37	25·2	151·7	d	III	Mt. Perry.
19. 1956 Jan. 29th	03–49–13					Not reported felt. (1.45 a.m. local time.) $\Delta_{S\text{-}P} = 3\cdot7°$.
20. 1956 Nov. 30th	21–51–56	near 27·5	153·7		II	Felt at Pt. Lookout, Stradbroke Island and in Moreton Bay. Epicentre perhaps a few miles east of Pt. Lookout near 27·5S; 153·7E.
22. 1957 April 1st	15–50–39	25·5	150·7	d	II	Mundubbera. $\Delta_{S\text{-}P} = 2\cdot6°$.
23. 1957 April 29th	16·5	near No. 18				Mt. Perry. Not recorded.
44. 1958 Dec. 1st	10–38–33	16·5	145·5	c	V	Cairns. Aftershock at about 10.38.30 not recorded; aftershocks recorded at Charters Towers at 18.05.18 on December 1st and at 19.44.13 on January 2nd.

The probable accuracy of the determination of the epicentre is indicated by: a — very good, b — good, c — fair, d — poor.

On the map (Figure 1) all known epicentres and such well established structural features[2] as seem pertinent to the problem under discussion, have been plotted.

A glance at the map shows an obvious fact—all epicentres except two Nos. 3 and 13 are in the region between the Main Divide and the coast, the main area in which highly folded and faulted rocks occur.

The shocks near Maryborough, Nos. 5 and 9, among the largest recorded, lie within the Maryborough Basin, the strata of which were strongly folded in Upper Cretaceous times, and these shocks may well be related to readjustments connected with that folding or faults associated with it. It is in the area to the west of this Basin to as far as 130 miles west of it that the majority of the earthquakes have occurred (Nos. 4, 8, 10, 11, 14, 15, 17–19, 22 and 23) including

TABLE II.

Additional Tremors not Reported Felt and from which the P Phase only was Recorded.

B = Brisbane. C.T. = Charters Towers where regular recording began on September 15th 1957.

Number and Date	Time (G.M.T.) of P	Station and Remarks	Number and Date	Time (G.M.T.) of P	Station and Remarks
	h m s			h m s	
21. 1957 March 3	20–20–15	B	33. 1958 Feb. 20	10–17–13	C.T.
24. 1957 Sept. 10	08–30–16	B	34. 1958 May 31	16–16–22	C.T.
			35. 1958 June 20	06–41–21	B
25. 1957 Oct. 10	22–04–36	C.T.			$\Delta_{S\text{-}P}=4\cdot 8^{\circ}$
26. 1957 Nov. 9	21–23–41	C.T.	36. 1958 July 2	00–33–08	B
				00–33–23	C.T.
27. 1957 Nov. 26	05–06–11	C.T.	37. 1958 July 7	17–07–52	C.T.
28. 1957 Nov. 26	23–38–37	B. (Probably	38. 1958 July 30	02–12–13	C.T.
		slightly	39. 1958 Sept. 8	06–26–26	B
29. 1957 Nov. 26	23–41–28	B. (deep	40. 1958 Oct. 4	02–10–54	C.T.
30. 1958 Jan. 18	20–39–21	B	41. 1958 Nov. 5	05–16–33	C.T.
31. 1958 Jan. 18	21–10–47	B	42. 1958 Nov. 11	06–12–54	C.T.
32. 1958 Feb. 20	08–22–44	C.T.	43. 1958 Nov. 30	10–20–33	C.T.

The times of phases set out in the above tables have been taken from the Stations Bulletins prepared by O. A. Jones, O. A. Jones and J. P. Webb or J. P. Webb.

the largest recorded in Queensland, No. 4. These are perhaps related to structures parallel to and associated with the margin of the Maryborough Basin, although the more westerly seem too distant for such a relationship. One of this group, No. 10 near Dawes, is not far west of the north-north-westerly prolongation of a well established fault which brings the Triassic down against the Palæozoic rocks.

One of the largest of the shocks, that near Kilcoy, No. 1, and one of the smallest No. 16, near Mt. Stanley, lie on the east and west side respectively of the rift valley immediately west of the D'Aguilar horst.

In the north of Queensland the typically drowned coast line and many of the features immediately inland suggest extensive recent faulting, most spectacular structures being the Mulgrave Corridor and the scarp of the Atherton Tableland. The structures are illustrated in Figure 2 (after Sussmilch, 1936, section C, fig. 2, p. 111). The positions of the faults are however, not sufficiently well established for them to be plotted on the structural map. The small shocks centred near the eastern edge of the Atherton Tableland (No. 7)

[2] These structural features have been taken from the Structural Map of Queensland, prepared by the Tectonic Map Sub-Committee of the Queensland Division of the Geological Society of Australia.

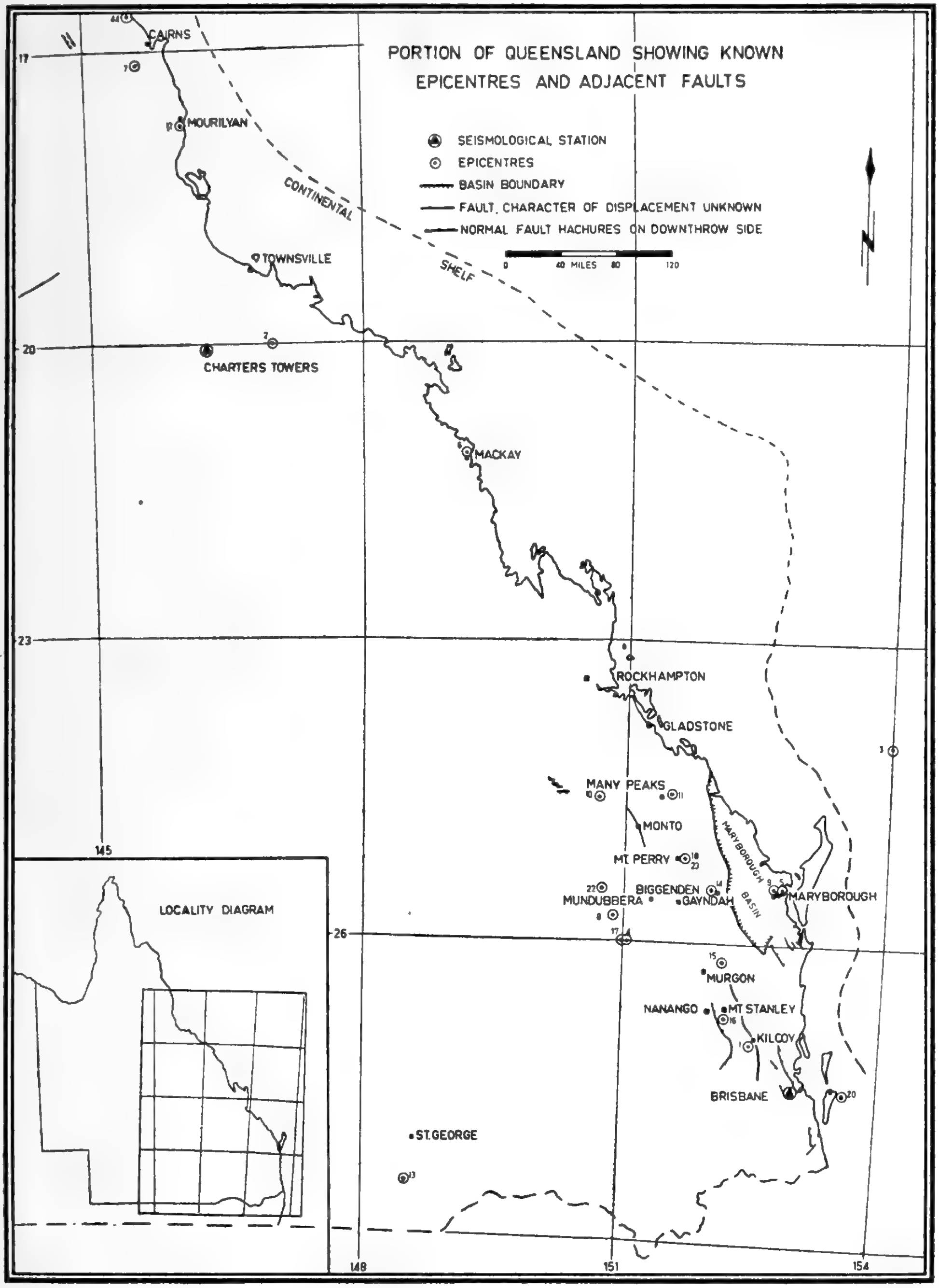
PORTION OF QUEENSLAND SHOWING KNOWN
EPICENTRES AND ADJACENT FAULTS
SEISMOLOGICAL STATION
EPICENTRES
BASIN BOUNDARY
FAULT, CHARACTER OF DISPLACEMENT UNKNOWN
NORMAL FAULT HACHURES ON DOWNTHROW SIDE
0
40 MILES 80
120
N
CAIRNS
MOURILYAN
CONTINENTAL
SHELF
TOWNSVILLE
CHARTERS TOWERS
MACKAY
ROCKHAMPTON
GLADSTONE
MANY PEAKS
MONTO
MT PERRY
BIGGENDEN
MUNDUBBERA
GAYNDAH
MARYBOROUGH BASIN
MARYBOROUGH
MURGON
NANANGO
MT STANLEY
KILCOY
BRISBANE
ST.GEORGE
LOCALITY DIAGRAM
17
20
23
26
145
148
151
154

Figure 1.

and near Mourilyan (No. 12) and the much larger one near Cairns (No. 44) with its three after-shocks may well be related to readjustments on one or the other of these faults. A number of the small shocks recorded at Charters Towers, but not felt (Nos. 26, 27, 34, 37, 38, 40, 41 and 42) may be related to the southern margin of this same faulted area. The S phase as well as P was recorded for some of these and the S–P interval gives a distance of 120 miles from Charters Towers but in an unknown direction; others for which S was not recorded show a pattern on the records identical with those of the former and almost certainly from the same locality. The distance of 120 miles in a north or north-easterly direction brings one to the southern edge of the tableland area or the coast respectively.

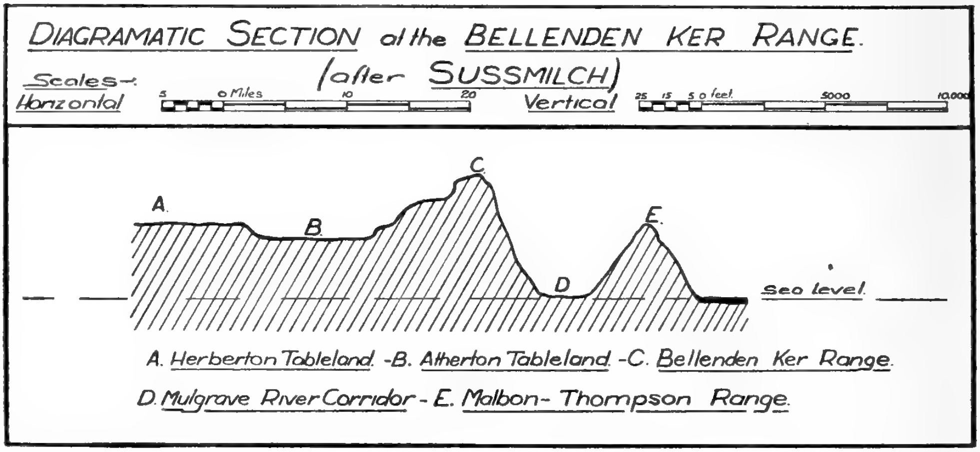

Figure 2.

Between the Charters Towers Tableland and the coast Sussmilch (1936, pp. 116–188, section H, fig. 2) has described the Ross River Corridor, the Townsville Corridor, and the Marine Corridor with any or all of which faulting may be associated, although it has not been demonstrated.

Coming southward a structure similar to, but less well established than, the Mulgrave Corridor has been described by Sussmilch (1936, pp. 118, 119) as the Sarina Corridor. Again faulting has not been proved, but may be present. The epicentre of the small shock recorded from near Mackay (No. 6) lies not far from the northern end of this Corridor.

This leaves three isolated epicentres. That near St. George (No. 13) does not seem to be related to any structure with a known surface expression. It is, however, interesting that the area within which it was felt had a markedly linear shape, extending northward to Roma and Mitchell and southwards to Moree in north-central New South Wales, but to only a short distance to either east or west. This distribution of intensity, approximately north-south suggests a relationship to the trend of the basement rocks, which, by analogy with their trend where they are exposed, would be north-north-west. The epicentre of this tremor is situated near one of the deepest parts of the Great Artesian Basin (see Whitehouse, 1954, fig. 19, section along latitude 28° S.).

The position of the epicentre out to sea near Pt. Lookout on Stradbroke Island (No. 20) is very doubtful; the tremor was felt quite strongly at Pt. Lookout and its effects were noted in Moreton Bay; the position suggested agrees with the distance calculated from the Brisbane seismogram. Could the shock be related to the Tasmantides (David, 1933, p. 14 and figs. 5, p. 15) or to some fracture in the ocean floor, associated with these astonishing submarine volcanic peaks? There remains Queensland's largest earthquake on record, that of June 16th, 1918, (No. 3), which was felt as far away as Brisbane (about 260 miles). It was recorded at Riverview Observatory, but Bryan (1936, pp. 49, 50) writes " The position of the focus of this earthquake cannot be fixed with precision. According to the several possible interpretations of the seismograph records at Riverview College Observatory, Sydney, the distance from the epicentre varied from 980 to 1180 kilometres (a difference of over 120 miles), while the exact direction from that observatory was also uncertain ". The position shown on the map is well to seaward (east) of the edge of the continental shelf, whereas Hedley (1925, p. 151) suggested that it was situated on that edge.

It has been possible to say little concerning the earthquakes listed in Table II, but two are worthy of further mention—Nos. 28 and 29, both on November 26th, 1957. These were recorded at Brisbane only and although the records are brief (no S phase was recorded) in both cases the record has the appearance of a deep focus earthquake.

Deep focus earthquakes have never been recorded in Australia and their occurrence would be most unexpected.

Perhaps the point which emerges most clearly from this brief paper is how little we know as yet of the detailed structure of this State.

Addendum.

Referring again to epicentre No. 3, June 16th, 1918, since the above was written, Mr. P. S. Upton has drawn my attention to the shape of the profile of the edge of the continental shelf in that area. Taking the edge of the continental shelf in the usual position—the 100 fathom line, the bottom descends in two clear cut steps—the first to a depth of 200–400 fathoms and then after a more or less steady slope to 800–900 fathoms some 100 miles eastward there is a second abrupt descent to 2000 or more fathoms. The position in which I have tentatively placed the epicentre is close to the top of the second step, a likely location for an earthquake.

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THE GEOLOGICAL STRUCTURE OF VICTORIA

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(With two Text-figures and Bibliography).

Abstract.

Three major belts of folding and thrust-faulting are recognized—the Stavely Heathcote and Wellington Belts—all with roughly meridional trends, and all characterized by inliers of Cambrian thrust over Ordovician, Silurian and Lower Devonian rocks. Structurally Victoria is broadly symmetrical about the median Heathcote line. Between it and the Stavely line is a series of brachyanticlinoria and brachysynclinoria, with faulting. East of the Heathcote line the folds are arcuate about Melbourne as a centre.

In the far west, beyond the Grampians, are Cambrian and Lower Ordovician beds, whose detailed structure is not known. Beyond the Wellington line, in the Mt. Wellington Highlands and the country to the east, the older rocks are thrown into anticlinoria and synclinoria, while the younger rocks are as a rule only gently folded. Unconformities reveal evidences of three Palæozoic epochs of folding—Benambran, Bowning and Tabberabberan—in this region.

In contrast to the older rocks, Mesozoic and Tertiary beds outcropping in the south of the State have a general E–W disposition and have been much faulted. The thickest Tertiary deposits, in the west, exceed 5,000 feet.

1. Introduction

Apart from general accounts of the structure of Victoria as part of Australia, of whose area it forms a very small fraction, there has been no attempt to treat this subject as a whole or to show how recent researches affect the published work. In the following notes an attempt to remedy this deficiency is made but only major aspects can be dealt with.

Three major thrust-belts, whose importance is becoming more apparent, are recognized in the State (Fig. 1), from west to east the Stavely, Heathcote and Wellington belts. Along all these belts outcrop Cambrian rocks, including the igneous suite referred to as diabases or greenstones. The median or Heathcote line, the most continuous of the three, separates the State into an eastern and a western part, which are characterized by broad similarities of structure.

2. The Major Thrust-Belts.

(i) *The Stavely Belt.* In western Victoria the Grampians, a mountainous region of red sandstones, shales and conglomerates of Upper Devonian to Lower Carboniferous age, with acid igneous rocks at the base, are flanked on the east by a discontinuous arcuate thrust-belt, the Mt. Waverly–Mt. Drummond (Stavely) belt. So far no fossils have been found, but cherts and black slates associated with the greenstones can be correlated with similar fossiliferous Cambrian rocks elsewhere. The axis shows marked curvature, trending northerly near Mt. Stavely, then turning north-easterly, then north-westerly on the eastern edge of the Grampians. This belt has been shown by drilling in search of underground water to extend north as a shallow ridge beneath the younger deposits of the Murray Plains.

(ii) *The Mt. William–Colbinabbin (Heathcote) Belt.* No additional information is available apart from the detailed parish plans of Thomas (1940–1941). There is no doubt, however that better exposures would prove that the structures are more complicated than at first thought. The general pattern is a fault belt thrusting Cambrian over Silurian and Lower Devonian rocks. On the western side there is the normal sequence of Lower and Middle Ordovician rocks, but to the east the Upper Ordovician, Silurian and Lower Devonian sediments in the synclinal fold are overthrust by the Cambrian.

In the Heathcote area no Upper Ordovician rocks outcrop flanking the Lower Ordovician, but they are present as small infaulted lenses about 100 feet wide and several hundred feet long, surrounded on all sides by the Cambrian diabases. South of the Cobaw granite the major structure has apparently only one major fault-zone, but in the Heathcote area the belt of Cambrian rocks is confined by two sub-parallel lines of faults, which eventually become lost beneath the younger rocks of the Murray Plains. That the faults continue north-west is, however, to be seen north of Echuca on the flanks of the Cadell Tilt Horst, as described by Harris (1939).

The rather abrupt trend-changes of this belt and the presence of oblique faults between the major boundary ones are characteristic. South of the Cobaw granite the belt trends west of south, then runs southerly for several miles before turning abruptly to the south-west to disappear beneath the Upper Ordovician rocks, in which the major structure cannot be found. It may be that the epidiorites of the Dog Rocks near Geelong are the continuation of this structure. The belt of Cambrian rocks plunges steeply near Monegetta, where pitches of between 70° and 80° to the south-west have been measured on some of the minor folds.

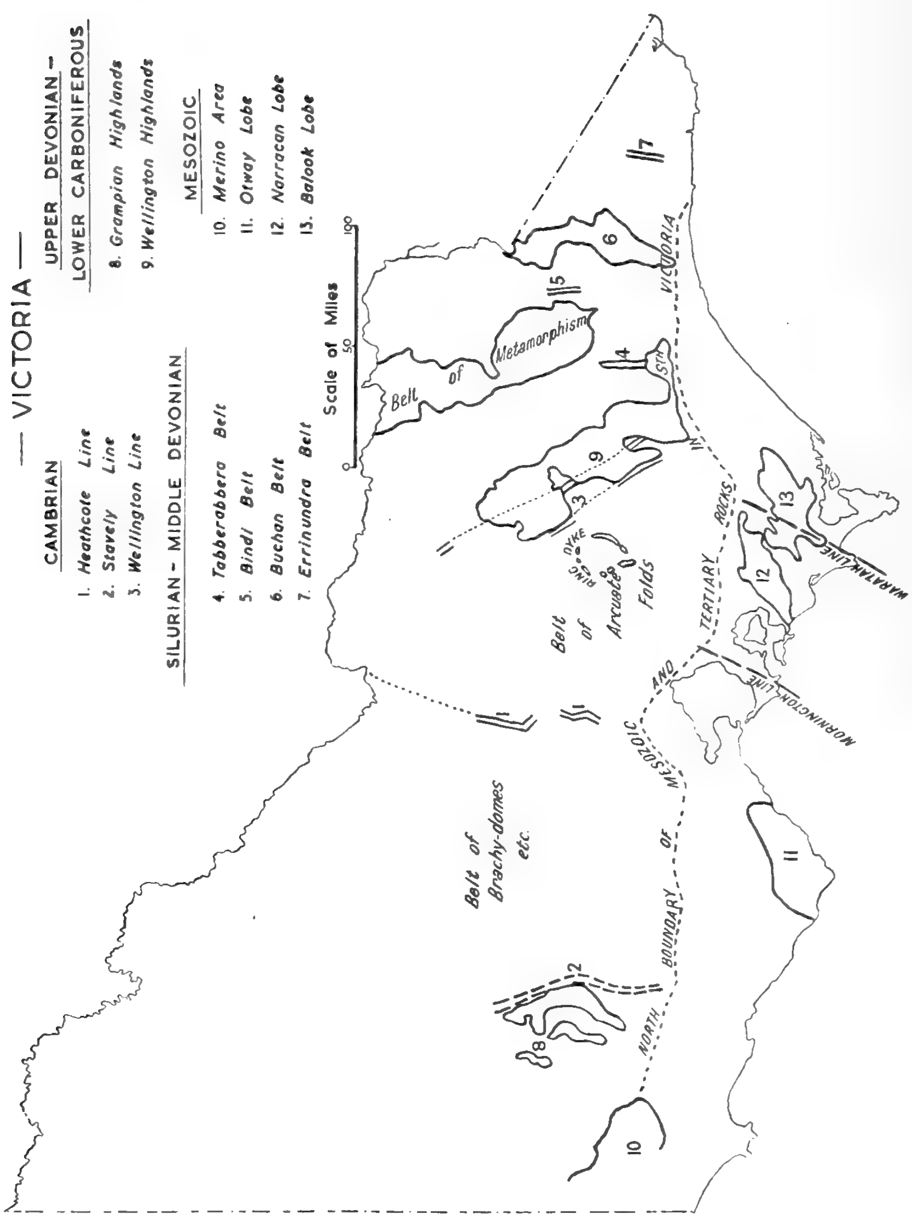
North of the granite at Tooboorac the faulted belt trends north-westerly as far as Heathcote, where it suddenly changes to a northerly direction. In this belt occur narrow infaulted strips of Upper Ordovician and three triangular-shaped areas of Lower and Middle Ordovician age. The east-west trending Ordovician rocks in each one of these triangular areas can be traced to a sharp angle where they change their strike direction to west of north.

(iii) *The Wellington Belt.* Eighty miles east of the Heathcote belt are the Mt. Wellington Highlands, another area of Upper Devonian to Lower Carboniferous terrestrial deposits with acid volcanics near the base. These are broadly folded and rest unconformably upon the closely-folded older rocks. On their western margin the highlands are bounded by a series of thrusts along which Cambrian beds outcrop. This Wellington belt is the most easterly yet recognized in Victoria. It does not outcrop continuously and may bifurcate to the south. At Dookie the Cambrian greenstone belt has been mapped by John Andrews, Ph.D. (unpublished report), and at least one small patch containing Lower Ordovician (Castlemainian) graptolites has been found. The continuation south-east is in the Tatong area first described by Summers and now being remapped by F. Brown of the University of Melbourne.

Phosphate Hill (Howitt, 1923) on the eastern side of the Upper Ordovician rocks is the next occurrence. Although no diabases are known there are (?) Cambrian and several zones of Lower, Middle and Upper Ordovician rocks in close proximity in a badly crumpled belt. Farther to the south-east are equally complex belts along the Howqua and Jamieson Rivers described by Teale (1920) and Harris and Thomas (1938, 1940). Here evidence is available of the possible bifurcation of the axial belt, the more easterly branch reappearing from beneath the Upper Devonian belt along the Wellington River (Teale, 1920; Harris and Thomas, 1954). The other line occurs on the western edge of the Wellington Highlands mass and up to the present only reconnaissance work (Harris and Thomas, 1954) has been carried out here.

3. Structures Between the Major Axial Belts.

(i) *Area west of Heathcote Belt.* Where studied in detail the rocks are found to be sharply folded into brachy-anticlinoria and brachy-synclinoria with innumerable high-angle faults and many major thrusts.



Text-Figure 1.

Where graptolite bands occur the structure is well-known, but where these are absent even the major structures cannot be determined although the regional structural pattern apparently remains constant. The major domes and troughs have been named and described, although detailed work in the Bendigo area (F. Chambers, unpublished) shows the need of minor adjustments. Detailed mapping of the Stawell goldfield by The Gold Mines of Australia is proceeding. This work has established a dome structure trending north-westerly, with a thrust fault developed along its flanks with a downthrow to the east. The N.W. trend of this structure continues to Ararat. One important result of all this work has been to prove that our major goldfields are on the flanks of major domes and that the gold mineralization is not determined by the major faults (Thomas, 1953).

(ii) *Area between the Heathcote and Wellington Belts.* In this area are to be found a series of arcuate folds curving around Melbourne as a centre. Apart from igneous masses the rocks are mostly Silurian and Lower Devonian, with Upper Ordovician beds outcropping in the anticlinoria. In the southern part of two of these structures older rocks occur, on the Mornington Peninsula (Keble, 1950) and at Waratah Bay as mapped by Ferguson (Parish Plan) and later by Lindner (1953). Most of these structural lines have been named. It is not proposed to enter into details here, but mention may be made of the famous Walhalla Synclinorium on the eastern side of the belt. Mapping has been proceeding on the northern extension of this belt, and it is evident as the Wellington Highlands are approached the rocks become more sheared and crushed.

4. Area West of the Grampians

To the west of the Grampians there are granites and Upper Palaeozoic deposits, and a belt of Cambrian greenstones and black shales is exposed along river-valleys cut into the Dundas Tableland. There are also fine sandstones and shales similar to undoubted Ordovician rocks. No major structural lines have been determined; according to Wells (1956) the structural trends near Dergholm run N.W. and dip to the N.E., then swing northerly near Casterton with predominant westerly dips. Recent mapping by D. Spencer-Jones has disclosed that rocks of similar type outcrop in the Black Range between strike-ridges of massive Grampian sandstones. These basement rocks trend north to north-east in the southern outcrops and then swing to the north-west.

5. Area East of the Wellington Belt.

(i) *The Mt. Wellington Highlands.* This mountainous area extends from Briagolong in the south, 80 miles northward to the Mansfield district, with a width of about 25 miles. It is bounded on the west by the Mansfield–Barkly Thrust, while the eastern boundary is mainly a normal unconformity with minor faulting. In its general structure the belt consists of several broad anticlinoria and synclinoria of Silurian and Lower Devonian rocks, beginning on the west with the Macalister synclinorium showing a northerly pitch and followed to the east by the Wellington anticlinorium, which has been breached by erosion to expose Lower Palaeozoic rocks. The overlying Upper Devonian and Lower Carboniferous rocks are only gently folded.

Farther east is the Avon synclinorium, which extends to the Wonnangatta River, and east of it is the Freestone Creek anticlinorium, which has a southerly pitch. Only a narrow belt of the older rocks is preserved in the Freestone Creek area. From Freestone Creek to Yellowman's Nob the boundary of the younger (Upper Devonian) rocks is an unconformity, but at Yellowman's Nob these are displaced by an E–W fault and most of the basal lavas are missing.

From Cobbannah Creek to Tabberabberra the boundary is faulted, cutting out the lavas and giving steep dips in the adjacent sediments. East of Yellowman's Nob the dips are very low, and the basal lavas are exposed on some of the minor rolls. Dips eastward to Mt. Taylor are almost horizontal.

A number of minor N. to N.E. trending folds complicate the general picture. Across the Barry Mountains near The Viking the Upper Devonian rocks are apparently truncated by a north-westerly trending major fault, which may form the boundary of this belt.

The Mansfield Basin is flanked by acid igneous rocks on the western side and associated with these are conglomerates and sandstones which contain Upper Devonian fish remains. This basal belt swings easterly on the northern side of the Howqua River to form the southern margin of the Mansfield Basin.

(ii) *The Area east of the Mt. Wellington Highlands.* Although marked on the geological maps as Ordovician and from the few fossil localities as Upper Ordovician, much of the area contains beds lithologically similar to those of known Silurian and Lower Devonian age. The older strata are closely folded, the younger, occupying synclinal areas, only locally so. In this part of the State there are evidences of three major epochs of Palaeozoic folding.

The following summary has been taken from notes prepared by J. Talent, M.Sc., who has been carrying out much detailed work in this area :

" On the Mitchell and Wentworth rivers a complex sequence of Lower and Middle Devonian sediments, the Wentworth Group, was folded during the Tabberabberran orogeny (Upper Devonian) into a north-south synclinal structure, the Tabberabbera Synclinorium, which has been traced for about 25 miles. The axis of this structure does not coincide with the fold-axes of the Ordovician sediments but transgresses them at 10° to 30°, showing clearly that the Ordovician sequence was strongly folded at least once (Benambran and/or Bowning orogeny) prior to the inception of sedimentation during the Lower Devonian. The Wentworth Group, and to a less extent the adjacent Ordovician rocks, were intruded by a swarm of intermediate dykes prior to deposition of the Iguana Creek Group in the Upper Devonian."

"At the headwaters of the Indi and Buchan rivers a sequence of Middle and Upper Silurian sediments, the Cowombat Group, has been shown to be overlain with marked angular unconformity by the Snowy River Volcanics, a sequence of comparatively flat-lying Lower Devonian rhyodacites. These are overlain, with apparent conformity, by remnants of the Buchan Caves Limestone. The Snowy River Volcanics and the remnants of the Buchan Caves Limestones are bounded on the west by a major north-south normal fault which brings them down against Cowombat Group sediments. Further to the west the Cowombat Group is separated by a fault from schists, gneisses and granitic rocks which form an easterly extension of the Omeo Schists. This fault has been traced for over 20 miles along the west fall of Limestone Creek and the Indi River."

" In the Buchan area the Buchan Group has been shown to be folded into a synclinorium with partly normal contacts and partly faulted boundaries with the Snowy River Volcanics (Teichert and Talent, 1958). On the east, the Snowy River Volcanics are faulted down against Ordovician sediments, but their western boundaries west and north of Buchan have not yet been mapped."

" Three major periods of folding can be distinguished in the Silurian and Devonian of eastern Victoria, namely the Benambran, Bowning and Tabberabberan orogenies. The first is indicated by the major unconformity between Upper Ordovician graptolite-bearing sediments and the Wombat Creek Group (Middle to Upper Silurian) exposed in Wombat Creek, a tributary of the Mitta Mitta River. The Bowning orogeny is indicated by the major unconformity between the strongly folded Cowombat Group (Middle to Upper

Silurian) and the weakly folded Snowy River Volcanics (Lower Devonian) outcropping in the headwaters of the Indi and Buchan rivers. The Tabberabberan orogeny is indicated by the unconformity between the strongly folded Wentworth Group (Lower to Middle Devonian) and the Iguana Creek Group (Upper Devonian) outcropping on the Mitchell River, just downstream from Tabberabbera."

"Major intrusions of granitic rocks accompanied each of these orogenies. It is generally agreed that the formation of the Omeo schists and the emplacement of the associated grey granites is to be correlated with the Benambran orogeny. The Berridale granite outcropping in the watersheds of the Suggan Buggan and Ingeegoodbee rivers can be seen to have metamorphosed Cowombat Group sediments in the same area, but is overlain unconformably by the Snowy River Volcanics, thus permitting its dating within comparatively narrow limits (Late Upper Silurian or early Lower Devonian). Similarly the Ellery granite has metamorphosed late Lower and early Middle Devonian limestones, siltstones and tuffaceous sediments at Errinundra, yet the overlying, nearly flat Devono-Carboniferous sandstones are unaffected. This proves the emplacement of the granite to have been connected with the Tabberabberan orogeny (early Upper Devonian). The Gabo Island Granite intrudes the Upper Devonian Merimbula Formation near Mount Carlyle, showing that still younger granites occur in eastern Victoria."

Of great interest are the Upper Devonian sediments overlying the Snowy River Volcanics, but no recent work has been carried out on these. Many of the faults in this area are of fairly recent dating, and affect the present topography.

(iii) *The Belt of Metamorphism.* To the north-east of the Wellington Belt is the highly metamorphosed region described by Tattam (1929) and mapped in part by Easton. The general geology of this area has been described by Edwards and Easton (1937). The belt of metamorphic rocks is about 100 miles long and 30 miles wide, extending across the Murray from New South Wales as far south as Cassilis. The marked constriction in this belt is probably caused by the Towonga Fault Zone.

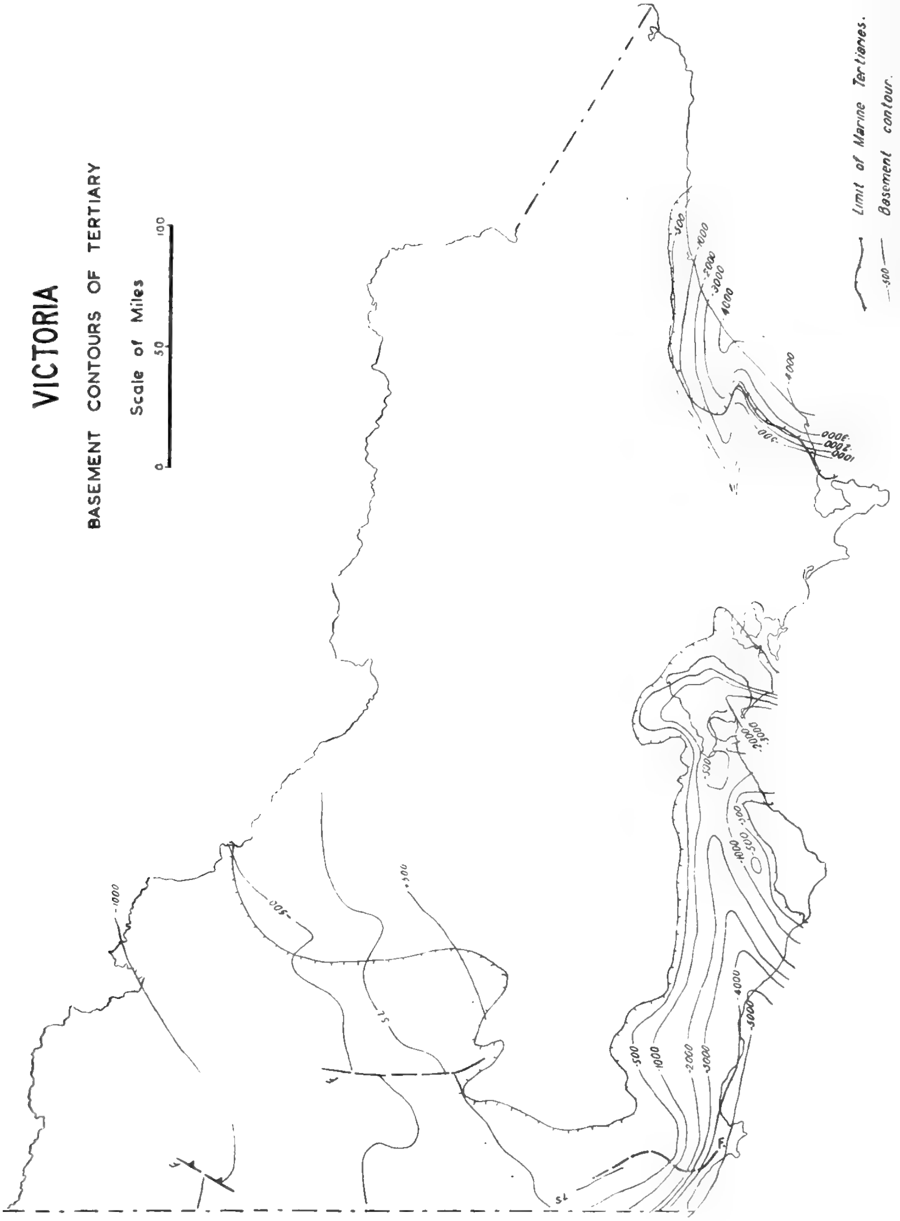
6. Areas of Upper Palaeozoic and Younger Rocks.

(i) Scattered over Victoria are rocks of Permian or Permo-Carboniferous age, chiefly glacial deposits, which have been preserved by downfaulting, though it is seldom that the actual fault contacts are to be seen. Further details may be obtained from "The Geology of Campbelltown" (Harris and Thomas, 1948). The sequence near Bacchus Marsh has been re-examined by Bowen (1958).

(ii) In the Mesozoic rocks a marked change of structure pattern is evident, the belts having a general east-west trend, corresponding to that of Gregory's "Great Valley of Victoria" in contrast to the roughly meridional strikes of the older rocks. Block-faulting makes structural studies exceedingly difficult. The Mesozoic rocks (Jurassic and Cretaceous) occur in three main areas—in the far west about Coleraine, Casterton and Merino ; in the Otway Ranges : and in South Gippsland.

Where examined in detail they are seen to be faulted in complex fashion and broken up into fault blocks. They are also affected by broad structures running slightly north of east. No details are known of the belt around Coleraine but the Mesozoic beds of the Otways extend in an easterly direction, plunging beneath younger Tertiary deposits south of Geelong. The Barabool Hills, also of Mesozoic rocks, owe their preservation to faults (Coulson, 1938).

The outcrops in South Gippsland form two lobes, the Narracan and Balook Lobes, plunging easterly, around which the Older Volcanics and younger Tertiary



Text-Figure 2.

sediments curve. The pattern as worked out in the Wonthaggi Mines (Edwards, Baker and Knight, 1944) is applicable to all of these areas. Work in recent years (Cookson, Duigan, Baker, Kenley and Medwell) has proved the existence of rocks of Cretaceous age in a sequence previously regarded as entirely Jurassic. The recent discovery of ammonites, shelly fossils and foraminifera in one of the deep wells at Port Fairy has proved beyond doubt the presence of rocks of this age in western Victoria also.

(iii) An east-west trend is also visible in the disposition of the Tertiary deposits. In general two major subdivisions of these can be recognized—estuarine, ligneous sands with brown coal-seams, and later marine beds. In the southern part of the State forming a part of the " Great Valley " of Gregory are the deepest of the Tertiary basins (Fig. 2). From the meagre information available it appears that the basin in the Western District plunges westerly and attains a depth of over 5,000 feet, while that in Gippsland plunges easterly and contains over 4,000 feet of Tertiary sediments. A smaller meridionally-trending structure along Port Phillip Bay is also indicated on the map.

There seems little reason to believe that the Tertiary beds deposited in the Murray Gulf in the north-west of the State attain a great thickness and it is doubtful whether they are much over 1,500 feet thick.

7. Acknowledgements.

Grateful acknowledgement is made to the many members of the Geological Survey of Victoria, who have helped in the preparation of this paper.

I wish to thank in particular Messrs. J. A. Talent, P. Kenley, D. Spencer-Jones, J. L. Neilson and J. J. Jenkin, who kindly supplied details of their incompleted work.

8. Bibliography.

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TECTONIC EVOLUTION OF NORTH-EASTERN NEW SOUTH WALES, AUSTRALIA

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With three Text-figures.

ABSTRACT.

Tectonic movements within a eugeosynclinal belt developing through Palæozoic times are considered in detail only for the Carboniferous and Permian, but are recognised as having affected various parts of the belt with different intensities from Pre-Cambrian to Recent times. The orogen is characterised by border thrusts, a central heavily deformed and slightly metamorphosed core intruded by granite and lying between two sub-parallel eastward-dipping thrusts containing serpentine, upthrust blocks bordered in part by transcurrent faults, a belt of basins and a belt of domes. It is almost surrounded by Mesozoic sediments derived in part from the belt itself, which moved up isostatically after the mountain-building of Permian times. The remnants of Tertiary basalt flows remain on the terraced New England Plateau in the centre of the old denuded orogenic tract.

INTRODUCTION.

This paper deals with the tectonic evolution of north-eastern New South Wales comprising the southern portion of an orogenic belt which continues northward into Queensland (Osborne, 1950, p. 77–78). The area shown on the map (Figure 1) is bounded on three sides by Mesozoic sediments and is separated by them from the northern portion of the belt.

The region studied possesses a number of features which characterise orogenic belts throughout the world. It has a central complex of tightly folded and somewhat metamorphosed beds which is intruded by granites and porphyries and lies between two parallel belts of ultra-basic intrusives. It is bounded on the west and south by thrust faults dipping inwards. Transcurrent faults, along which a number of upthrust blocks have moved, occur together with tightly folded and thrust faulted strata. No nappe or nappe-like structures have yet been recognised and, indeed, the steep dips of many of the thrusts emphasise dominant vertical rather than horizontal components of the thrusts.

A large number of igneous rocks ranging from ultra-acid to ultra-basic are present and they vary from plutonic to volcanic types. Spilites characterise Devonian and older rocks and in places are associated with keratophyres (Benson, 1913, *et seqq.*). During the Carboniferous and Permian periods there were great outpourings of rhyolitic and andesitic lavas, together with the ejection of much fragmental material. Teschenite sills and alkaline intrusives in the form of plugs and laccoliths were followed by flows of basalt in Tertiary times.

The sedimentary pile consists of a great variety of types in a wide range of textures, and includes greywackes, cherts, jaspers and phyllites of Lower and Middle Palæozoic age, limestones, arkoses, glacial and normal marine deposits intercalated with coal measures of Upper Palæozoic age and well-washed terrestrial Mesozoic sediments. The depression in which they were all laid down may be termed a typical eugeosyncline (see Kay, 1950).

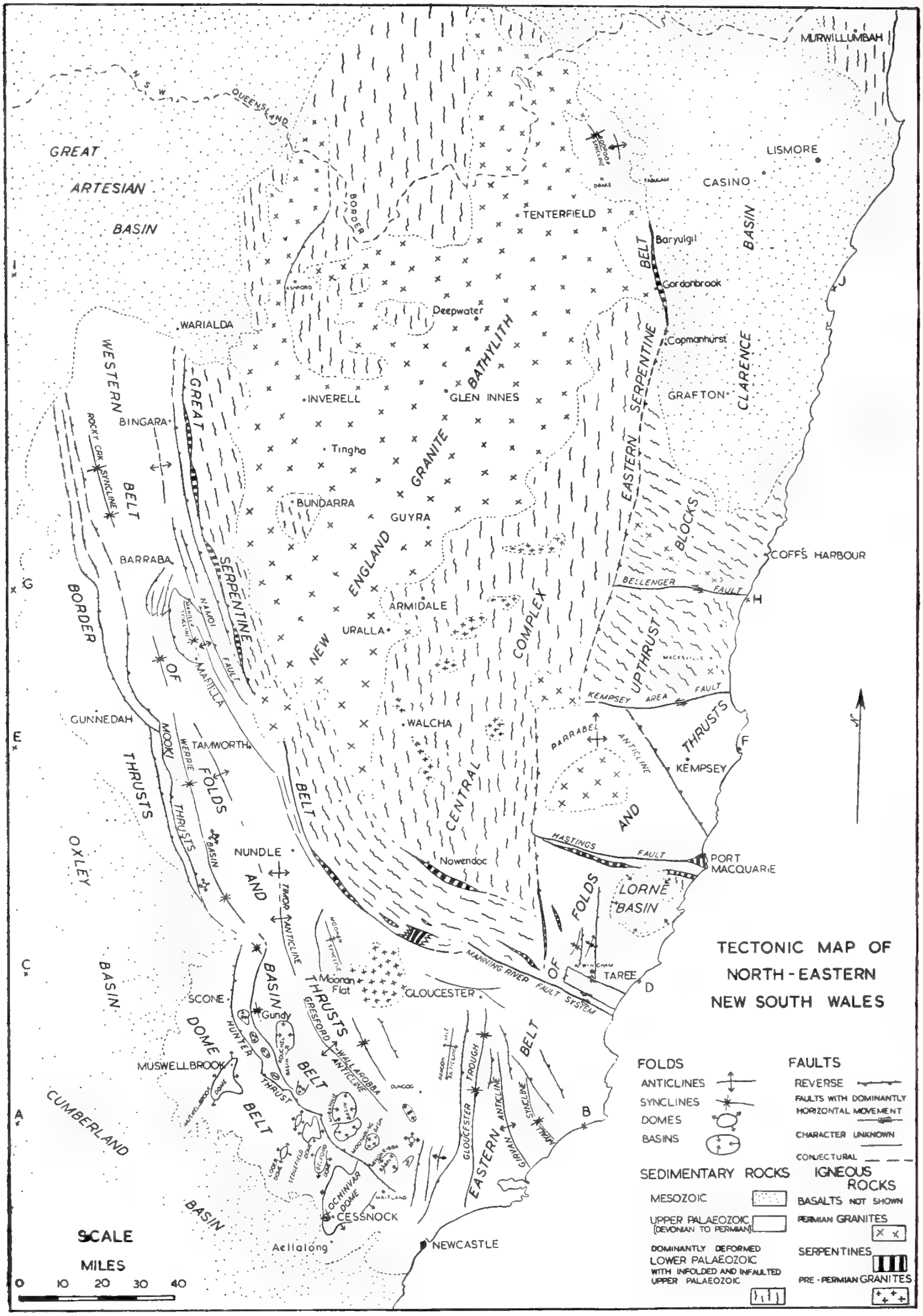

Fig. 1.—Tectonic Map of North-eastern New South Wales.

Previous Literature.

E. C. Andrews (1908) drew attention to the importance of Upper Palæozoic tectonic movements in north-eastern New South Wales. We are indebted to T. W. E. David (1911, p. 54) for the concept of a great warp development running north from near Sydney to Townsville, Queensland. This was intermittently separated from land to the west by Permo-Carboniferous lakes and seas. H. I. Jensen (1912) detailed contemporary views of his time in discussing the tectonic history of eastern Australia.

W. N. Benson (1913 *et seqq.*) in an important series of papers dealt with the geology of north-eastern New South Wales emphasising Carboniferous movements and suggesting that the serpentine intrusions were of that age.

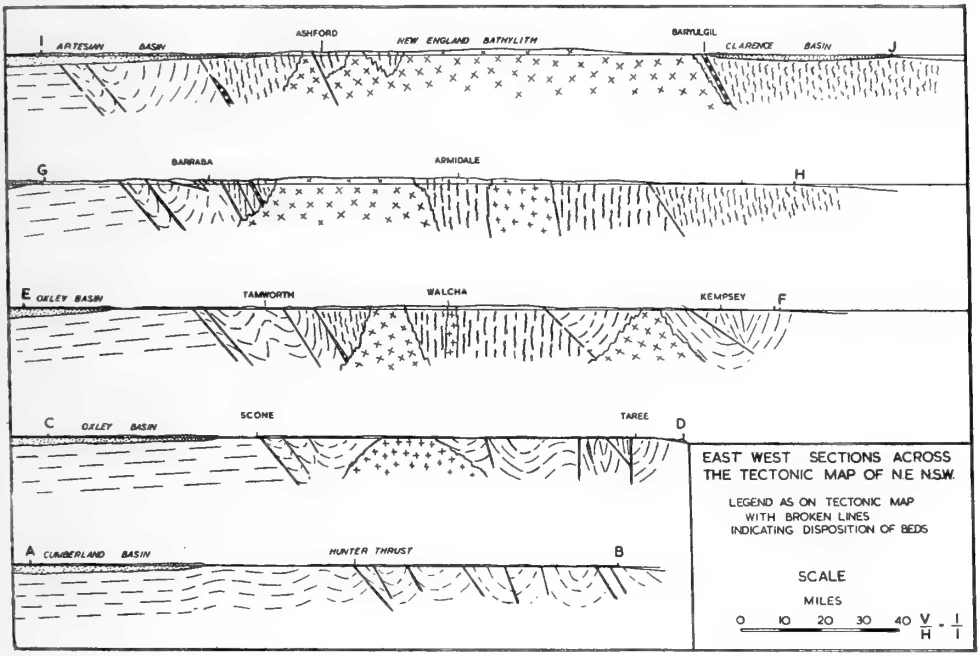

Fig. 2.—East-West Sections Across Tectonic Map of North-eastern New South Wales.

Queensland geologists have not been so impressed with the view that the main Upper Palæozoic orogeny was of epi-Permian age and have alternative ideas regarding the origin of many of the structures.

Bryan (1925, p. 67) opposed the idea that orogenic movements occurred in "Permo-Carboniferous" times, regarding the phenomena observed as being explained by epeirogenic movements only. It has long been recognised, however, that the Permian rocks at Gympie have suffered very low grade metamorphism and are intruded by granite plutons (Hill, 1955).

Detailed work in New South Wales by G. D. Osborne (1920, 1950), H. G. Raggatt (1929, 1938), S. W. Carey (1934a), J. A. Dulhunty (1940), F. Hanlon (1947a–1948c), the writer (Voisey, 1934 *et seqq.*) and others contributed to the acceptance of the importance of post-Palæozoic orogenic movements as summarised by David (1950, p. 386). Osborne (1950) discussed the structures in the Hunter-Manning-Myall-Province in detail and this paper should be regarded as supplementing his work and emphasising the characteristics of the central and northern areas of the New South Wales portion of the orogenic belt.

Stratigraphy.

The stratigraphy of the area has been summarised by David (1950) and by the present writer (Voisey, 1958a), and the names of the rock units may be determined readily from these works and the articles listed in their bibliographies.

The Structural Elements.

The structures may be classified into a number of groups each of which has received some attention from previous workers.

1. The *Border Thrusts* include the Hunter-Mooki system, which forms the western and south-western boundary of the orogenic belt. They are of great significance in that they separate the region of intense folding and faulting from the relatively undisturbed areas to the west. Although the Permian rocks in the Belt of Domes have also suffered some deformation, this is much less than that on the opposite side of the Hunter Thrust.

2. The *Western Belt of Folds and Thrusts* parallels the Border Thrusts and is bounded on the east for most of its length by the Great Serpentine Belt, which follows the Peel Thrust. It averages thirty miles in width and runs for some 200 miles until it merges with the more complex Basin Belt in the Hunter Valley. It is characterised by a series of meridional folds and faults, most of which appear to be thrusts. Although there are a number of irregularities the belt could be said to contain two synclinal and one anticlinal axis. The most western downfold is known as the Rocky Creek Syncline in the north. This becomes the Werrie Basin in the south, a reversal in pitch taking place to the west of Manilla. The Werrie Basin (Carey, 1934a) is a canoe-shaped fold possessing a number of subsidiary flexures such as the Quipolly Dome, Jacob and Joseph Basin and Castle Mt. Dome.

The corresponding upfold to the east is extensively fractured in the north but takes form between Currabubula and Tamworth and is recognisable as the Timor Anticline (Osborne, Jopling, Lancaster, 1948) near Nundle, becoming Gresford-Wallarobba Anticline in the south.

The eastern down-fold has not been recognised in the extensively fractured area west of Bingara, but the *schuppen* structures near Barraba pass into the Manilla Syncline near the town of that name (Voisey, 1958b). The change in pitch south of Manilla is accompanied by faulting, and the fold is not well formed until Nundle is passed and the Moonan Syncline could be said to be a remnant of the fold.

A large number of major faults approximately parallels the Peel Thrust. One of the larger and more persistent of these is the Namoi Fault (Voisey, 1958b).

As pointed out by Benson (1917a) there is a belt of isoclinal folds between Bingara and Manilla just west of the Peel Thrust. In this belt faults are very numerous and the strata are sub-vertical for a considerable distance.

Alongside the Thrust beds younger than those further to the west are commonly present. A thin strip of fossiliferous Lower Carboniferous strata was mapped by Benson in this position. Furthermore, slivers of Permian beds occur in the region of the Thrust itself as at Anderson's Flat, near Nundle, (Benson, 1913b, p. 586).

The increase in the intensity of the deformation moving east from the Border Thrusts to the Great Serpentine Belt is the outstanding feature of the Belt of Folds and Thrusts. The beds lying between these two fracture zones range from Middle Devonian to Permian—the last-named being preserved mostly in the central zones of the down-folds.

3. The *Great Serpentine Belt* was first mapped by W. N. Benson (1913a). It lies in the fractures which separate the Middle and Upper Palæozoic rocks from those believed to be Silurian and older lying to the east.

The main fault can be observed in the field near Nundle to dip to the east at an angle of 60°. Wherever it is encountered dips of this order are indicated. The belt with some minor offshoots runs from Warialda to Nundle and beyond into the Manning River District. The change in direction south-east of Nundle is in sympathy with but more marked than that of the Border Thrusts.

4. The *Basin Belt*, which is adjacent to the Hunter Thrust in the Hunter Valley, was analysed by Carey and Osborne (1939) and attributed to the operation of rotational and possibly torsional stresses resulting from the active advance of the Hunter-Bowen orogen in relation to the relatively immobile area to the south. It would appear that early development led to the production of domes probably with sigmoidal axes in association with the basins. Further compression led to the fracturing of the domes and their replacement by the thrusts necessary to take up the extra crustal shortening involved.

5. The *Dome Belt* contrasts markedly with the Basin Belt to the north. In the first place the rocks are in general very much less competent, and had they been compressed to the same extent as the beds north of the Hunter Thrust they must surely have developed even more complex structures. They have, however, only been arched up into domes with relatively slightly deformed tracts between them. Although the dips are steep in places and some folding has taken place, the amount of compression is obviously very much less than that to the north. Even so, Osborne (1920) has shown that there was a crustal shortening of about 7 miles in 70 or approximately 10 per cent.

6. The *Eastern Belt of Folds and Thrusts* includes Rawdon Vale Anticline, Gloucester Trough, Girvan Anticline and Myall Syncline and subsidiary structures, the descriptions and possible origins of which have already been given by Osborne (1950). To these may be added the Taree and Wingham synclines and associated faults and the Parrabel Anticline (Voisey, 1934, 1938). The area has in it many more faults and minor structures than have been mapped. The structures are complicated and the outcrops of the rocks are poor in the coastal areas. The meridional strike of the belt persists to the south and Osborne (1950, pp. 73–74) has commented upon the conflict between this belt and the north-westerly trend of the western belt.

The folds in the Wingham-Taree area and the Parrabel Anticline all pitch to the north. The last-named is a large structure with a steep eastern limb, with subsidiary folds and faults. (Voisey, 1934, 1936a). The western limb was not studied because of the difficulty of the terrain, so its very existence has had to be assumed. The granite shown in the centre of the anticline was reported by the Geological Survey of N.S.W. and its boundaries are largely conjectural.

The common features which the two belts of folds and faults share lie chiefly in the nature of the rocks which have been deformed. Both range from Middle Palæozoic to Permian and there are big differences in the competency of the various units.

7. The *Central Complex*. East of the Great Serpentine Belt the rocks are vertically disposed for many miles and in many places are dominantly siliceous. Benson (1912) gave the name Woolomin Series to the cherts, jaspers and quartzites east of Tamworth. Associated with the siliceous beds are greywackes and phyllites lithologically similar to those included in the Brisbane Metamorphics by Queensland geologists.

As work proceeds more different rock types and more fossil beds are being discovered from strata ranging in age from Silurian to Permian, and it is very difficult indeed to separate the beds in which they occur from rocks which previously were all regarded as Lower Palæozoic (Whiting, 1950 ; Voisey, 1958a ; Crook, 1958).

The high degree of deformation and the silicification of the beds of the central complex make it a distinct structural unit in spite of the differences in the age of the strata involved.

8. The *New England Granite Bathylith* lying within the Central Complex is made up of a wide variety of rocks including granites, granodiorites, porphyries, etc. It extends from a point east of Nundle in New South Wales into Queensland in the neighbourhood of Warwick, a distance of some 200 miles. Its maximum width through Glen Innes is about 100 miles. Large roof pendants are common and have been recognised in the Bundarra, Tingha, Deepwater and Tenterfield areas. The igneous rocks lie almost midway between the two serpentine belts and are surrounded by the rocks of the Central Complex. Associated with the granite are many mineral deposits (Voisey, 1953).

A number of small intrusions, gneissic in part, and generally showing concordant relationships with the surrounding sediments, are found in the Walcha-Hillgrove area east of the main bathylith. While the possibility that they may be earlier phases of the main body has not been entirely discounted, they have, in the past, been regarded as being possibly Silurian in age. Lithologically, they are quite distinct from any of the other rocks of the bathylith.

Osborne (1950) made reference to the presence, in the Gundy–Moonan Flat area, east of Scone, of a granite inlier towards which there was a thinning of the Lower Carboniferous beds. The apparent interruption in sedimentation is inferred as indicating a large island in the Lower Carboniferous seas. The granite, if of pre-Lower Carboniferous age, would probably be Tabberabberan and possibly related to the granodiorite which outcrops on Mount View, near Cessnock (Browne and Walkom, 1911) and that at Winder's Hill near Gosforth (Browne, 1927).

The influence which this rise in the basement implied by the presence of the granite, may have exerted on the major structure may be seen from an inspection of the tectonic map (Figure 1). The Great Serpentine Belt swings to the north of it and could possibly mark the western and southern edges of the region of maximum total deposition of the main geosyncline. The Border Thrusts swing to the south of it and are deflected slightly to the west. It also separates the western belt of folds and thrusts from the eastern belt lying close to the position where there is a marked change in the directions of trends of the main belts.

9. The *Eastern Serpentine Belt.* Serpentine outcrops in the vicinity of Baryulgil in the Clarence River Valley, where it is being mined for asbestos. Once more it appears to occupy an important thrust, which separates Lower Palæozoic rocks on the east from Upper Palæozoic rocks on the west, with a displacement as great as that of the Peel Thrust. Once again the dip seems to be steep. The northern continuation of the belt beneath the Mesozoic cover is suggested by the reappearance of serpentine in the Brisbane Valley, Queensland. Its southern continuation south of Copmanhurst is not known with certainty, but the line of the fault is continued on the map in order to explain the juxtaposition of Upper Palæozoic rocks on the west with more disturbed Lower Palæozoic beds on the east.

10. The *Transcurrent Faults.* A number of transcurrent faults, striking approximately east-west, characterise the coastal belt. They comprise the Manning River Fault System, the Hastings Fault, the Kempsey Area Fault and the Bellinger Fault. All of them have apparently large throws, which can only be accounted for by the tearing movement. The Kanghat Fault of the Manning River Fault System separates Devonian from Permian and Carboniferous beds ; the Hastings Fault, Carboniferous from Devonian ; the Kempsey Area Fault, Permian from Lower Palæozoic, and the Bellinger Fault, the Lower Palæozoic Nambucca Beds from the Fitzroy Beds. They would appear to

separate up-thrust blocks of strata which were pushed westward by varying amounts. Unfortunately, the difficulties of the terrain between the New England Plateau and the Coast have prevented detailed investigation of the belt, which should show the up-thrust edges of these blocks. The conjectural fault shown on the map represents the writer's interpretation of the structure and is substantiated only by the fact that the Permian and Carboniferous rocks are known to occur sporadically in the belt from Nowendoc to Drake, east of Tenterfield. The eastern rocks are, for the most part, stratigraphically lower than these.

11. The *Upthrust Blocks*. The oldest rocks in north-eastern New South Wales lie in the coastal belt between the Nambucca and Tweed rivers. They appear to be a more highly metamorphosed than the beds higher in the sequence as a general rule, but it must be admitted that this could have come about through deep burial in the eugeosynclinal trough. No sequence which shows clearly the relationship between the Woolomin Group, regarded as being at the top, and the Devonian rocks has yet been found. The writer now prefers to think of these older rocks as being the lower ones in a sedimentary pile which suffered intermittent deformation culminating in the uplift of the region at the end of Palæozoic times.

The coastal blocks are structural highs, and have come upwards quite considerable distances. As mentioned above they are bounded by the transcurrent faults on both the north and south, and on the west probably by thrust faults. In the Baryulgil area serpentine has been introduced into the thrust. The southern extension of this thrust is conjectural. The junction between what are probably Upper Palæozoic rocks exposed on the Glen Innes–Grafton Road and the older phyllites on the east of the Clarence River near Buccarumbi (west of Grafton) suggests its presence in this area. Around Coffs Harbour the Coffs Harbour beds of the writer (Voisey, 1934) later called the Fitzroy Series by Kenny (1936) depart from the general meridional strike and in places strike east-west. They are comparable in rock-type with the Neranleigh-Fernvale Group of the Brisbane metamorphic rocks of the Queensland geologists and on account of the lithology are correlated in part with the Woolomin Group of New South Wales. They are separated from the Nambucca Beds, corresponding to the Bunya Beds of Queensland, by the Bellinger Fault. The evidence for this fault depends partly on recognition of this relationship and the change in strike and partly upon the disturbed character of the beds as seen in the road cuttings between Bellingen and Dorrigo. The northern block is largely covered by Triassic and Jurassic sediments belonging to the Clarence Basin. The older rocks are generally obscured, appearing only around the margins. They are well exposed, however, between Ballina and Murwillumbah and continue into the Queensland type area. It is possible that other transcurrent faults are obscured in this region, the rocks in the north probably being much older than the Coffs Harbour beds.

12. *Mesozoic Basins*. Mesozoic sediments almost surround the outcrops of older rocks in north-eastern New South Wales, except for a portion of the coast in the south. The Cumberland Basin occurs in the south, merging north-eastwards into the Oxley Basin and from this sediments swing northward into the Great Artesian Basin and, passing through to Warwick in Queensland, turn southward into the Clarence Basin. The Lorne Basin is a much smaller one than the others, and lies between the Manning River Fault System and the Hastings Fault on top of what appears to have been a relatively down-sunk block. The dominant rocks are well-washed sandstones, which are associated with shales containing, in places, the remains of plants. Coal seams, some of which appear to have economic possibilities, occur in the Clarence Basin. It is not proposed here to discuss the detailed structures of these Basins. Raggatt

(1938) has given a full account of the Cumberland Basin, Dulhunty (1940) has named and described the broad features of the Oxley Basin, Lloyd (1946) has worked in the Clarence area, and the writer has dealt with the Lorne Basin (Voisey, 1939b). It would appear from the presence of the encircling Mesozoic rocks that the New England region has been more or less consistently rising since Permian times, and that sediments derived from the mass have contributed largely to the deposits in the basins. Much of the sand must have been derived from the granites which were exposed from early Triassic times onwards. The positive tendency of New England follows from the presumed low density of the granite core, which may have moved up isostatically. Marshall and Narain (1954, fac. p. 24) show a regional Bouguer gravity anomaly beneath north-eastern N.S.W., their traverse having been taken through the central portion of the region. The lowest value obtained was —78 mg. at Armidale. They suggest (pp. 49–50) that, if the region is in isostatic equilibrium, as appears likely, it should have a root of about 5·5 kms.

The tendency for the region to move upward in the past is indicated by the terraced character of the highlands (Voisey, 1957b).

Age Relations of the Geological Structures.

The gradual emergence above sea level of the sediments of the eugeosyncline has already been discussed (Voisey, 1945, 1957a). It was suggested that the New England region had risen, possibly forming an island arc, which changed its shape and size during Carboniferous times. This arc was a volcanic one characterised by a wide variety of lavas and tuffs including andesitic types. It is believed by the writer that although earth movements occur more or less continuously in certain belts in the earth, and that though they may occur more rapidly on occasions in certain places, they do not necessarily reach their culminations at the same times. (See Gilluly, 1949.) Thus, it is hard to say what movements should be included in the Hunter-Bowen Orogeny. David (1904) placed those which started immediately after the deposition of the Muree Beds as being the first in the Upper Palæozoic diastrophism and Raggatt (1938, p. 126) and Osborne (1950, p. 72) followed him.

Raggatt's maps showing the isopachs of the Permian sediments indicate a westerly movement of depressions and elevations in the floor of the deposition area from Lower Marine times onward as shown in figure 3C. There does not seem to be any way of determining whether these folds moved uniformly or spasmodically but, as the diagrams show, the axis of the depression moved a distance of approximately 25 miles during Permian times. An upfold or rise in the basement similarly migrated from the vicinity of Newcastle to the west of Maitland, a distance of approximately the same amount, before becoming stabilised as the Lochinvar Dome. Apart from the evidence of the isopachs, David (1904) showed that there had been some erosion of the dome before the deposition of the Triassic sediments at Aellalong.

Osborne (1950, p. 72) gave his views on the Hunter–Bowen orogeny, placing the various movements into four episodes—the first at the end of the Muree Stage, producing broad folds in the Lochinvar area and initiating the Stroud–Gloucester Trough ; the second at the end of the Upper Marine, emphasising the previous folding and producing large faults on a meridional strike ; the third at the close of the Permian, producing strong thrusting with the intrusion of the ultra-basic rocks ; and the fourth, with the development of the border thrusts, with consequential rotation in the Hunter region as previously interpreted by Carey and Osborne (1939).

As this southern area was at the end of the main belt it is likely that the folding commenced earlier further to the north and later became more intense there. This is indicated firstly by the fact that the area commenced to rise in the Carboniferous and secondly by the extreme deformation of the beds. Strata younger than Lower Marine have not been found in the coastal belt north of the Manning River, and this may indicate that the region was emerging above the sea after deposition of the Lower Marine beds. The folding of the Carboniferous and Lower Marine sediments probably commenced then, and because of the large scale of the uplift it is possible that the serpentine was intruded at this time. It must have post-dated the Lower Marine sediments of the Manning River District (Voisey, 1939d) and Anderson's Flat (Benson 1913b, pp. 586–587). It must be older than the Triassic strata which overlie it near Port Macquarie (Voisey, 1939b). As most students of tectonics accept the views of Hess (1939) that the tapping of the lower layers of the crust is more likely to take place in the early stages of orogenesis the writer is inclined to place the introduction of the serpentine at the earliest time consistent with its structural relationships, but there is no proof in its field-relationships that it was not later still. As the writer (1939, p. 405) has previously pointed out, however, the sequence of events in the Manning River is :

(1) Folding and faulting of lower Permian.
(2) Injection of serpentine into faults which cut earlier folds.
(3) Truncation of earlier structures by the transcurrent faults of the Manning River Fault system.
(4) Deposition of Triassic sediments unconformably on the upturned edges of the Palæozoic sediments.

The Triassic sediments were folded by later movements into the Lorne Basin structure and faulted to the extent that Carboniferous strata appear in the centre of the Basin (Voisey, 1939b).

Hanlon (1947a, p. 285) showed that Triassic and Lower Jurassic beds are faulted against the Carboniferous and are dipping vertically in the Murrurundi area.

It is apparent from a consideration of the observations made on the rocks of north-eastern New South Wales that both compressional and tensional movements have occurred at a number of places at different times and with varying intensity.

Tectonic Evolution of the Region.

The Lower Carboniferous strand-line is regarded as having been situated some miles west and south of the Border Thrusts. It marked the margin of a thick pile of eugeosynclinal sediments which may well have been accumulating since Pre-Cambrian times. Deposition, while generally more or less continuous, had been interrupted from time to time by tectonic movements and igneous rocks, notably granites, were intruded in places.

Lying off the coast were islands, at least one group between Nundle and Cessnock being in part granitic. They were probably the remnants of former more extensive epi-Middle Devonian land. Elsewhere in the north and east Devonian sedimentation had suffered little interruption and generally comparable conditions of sedimentation had continued into Lower Carboniferous times.

Renewal of the earlier tectonic movements towards the end of the Lower Burindi saw the commencement of the rise of the New England ridge, which was a northward extension of the earlier Devonian land, and this eventually caused a separation of the later deposition areas. In its earlier stages it appeared above sea level as an island archipelago or island arc, on the inside of which appeared a number of volcanoes ejecting material of rhyolitic and andesitic type. As a result the later Carboniferous (Kuttung) sediments are found to be in part terrestrial and in part marine, (Carey and Browne, 1938), and, as might

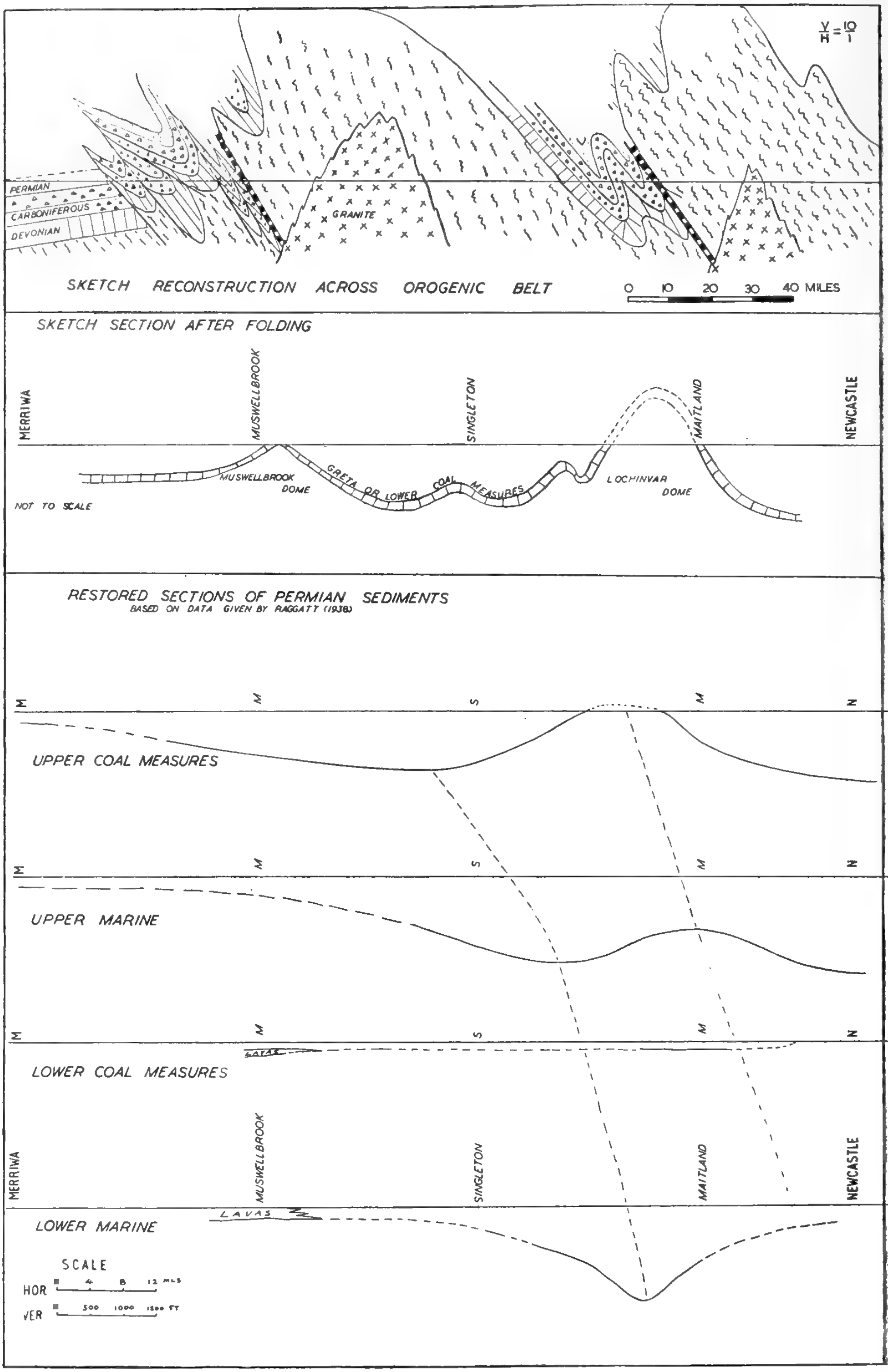

Fig. 3 (a).—Sketch reconstruction across orogenic belt.
(b).—Sketch section after folding.
(c).—Restored sections of Permian sediments.

be expected, the relationships between various units in the sequence are not consistent. However, no violent angular unconformities have been recognised.

The instability of the region at this time as evidenced by the nature of the deposits suggests that earthquakes were prevalent and the eastern Australian region might be compared with eastern Asia today, the Japanese islands corresponding with ancestral New England.

A more complete picture of the earth movements can be obtained for Permian times owing to the large amount of work done in the Hunter Valley.

The isopachs determined for the various groups and formations by Raggatt (1938) enable one to determine movements in the floor of deposition (see Figure 3). These show the western progression of undulations, interpreted here as forming furrows and welts on the sea floor. These may have had their extensions northward as peninsulas or islands separated by arms of the sea in the early stages, and ranges and valleys later.

Considering the Hunter Valley area, it can be seen that in the position of greatest deposition of the Lower Marine sediments the Lochinvar Dome rose later, appearing above sea level in Upper Coal Measure times.

It was during Permian times that the compression increased—being more intense to the north. Thus, it is likely that many of the structures in the Macleay and Manning districts commenced to form soon after the close of Lower Marine time and that some emergence above sea level occurred at this stage, two major folds developing, one along the present coast and the other in New England. Upper Permian deposition continued in places alongside them, possibly in the neighbourhood of Drake and Inverell, as they rose.

The acceleration of the movements and the onset of the main deformation of the whole orogenic belt leading to the fracture of the sub-stratum and the introduction of the ultrabasic rocks on the east and west of the New England fold may have occurred between Lower Marine and Upper Coal Measure times. Although there is a strong temptation to correlate these events with the later appearance above sea level of the top of the Lochinvar Dome it must be admitted that this is really a fortuitous occurrence as movements of the sea floor were in progress throughout Permian times.

Increasing intensity of compression led to the development of the upthrust blocks with their bounding transcurrent and thrust faults in the north and the wrinkling, folding and thrusting of the Western Zone culminating in the formation of the Border Thrusts.

This westerly progress of the orogen north of the Hunter Valley and the relative stability of the southern block produced the torsional structures—the belts of Basins and Domes together with the Hunter Thrust between them, as described by Carey and Osborne (1939).

Arbitrary limits would have to be determined in any description of an Upper Palæozoic Diastrophic Epoch because, as can be seen from the above account of events, they were spread out over much of Palæozoic time and were of varying intensity from place to place. Hence the expressed differences of opinion as to its timing have depended largely upon the particular area which has been studied.

Tectonic movements continued into Mesozoic times and involved the folding of Triassic sediments in the Cumberland Basin and elsewhere.

Both compressional and tensional movements have occurred in places up to the present day. No doubt some of these are related to the isostatic rise of blocks lightened by the presence of granite. Some of the movement has taken place in the neighbourhood of the older lines of faulting, thus increasing the difficulties in their interpretation.

Conclusion and Acknowledgement.

This description of the tectonics of north-eastern New South Wales might be regarded as an account of our present knowledge relating to this area as interpreted by the writer, following over twenty years' work in the region. A great deal more work has yet to be done and members of the Department of Geology of The University of New England are engaged on the systematic mapping of the region, concentrating in the first place upon the western belt of folds and thrusts.

Collaboration with the Geological Survey of New South Wales in connection with the preparation of the tectonic map of the state and also assistance from time to time from the Science Research Funds of the Government of the Commonwealth of Australia are gratefully acknowledged.

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THE OCCURRENCE OF SOME FUSED SEDIMENTARY ROCKS AT RAVENSWORTH, N.S.W.

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With Plates IX and X.

The occurrences described herein all lie within the Hunter River Valley, a district with which the name of the late Professor Sir T. W. Edgeworth David will long be associated in connection with his survey of its coal resources. It is thought fitting, therefore, that this paper should be included in the volume published in commemoration of the centenary of his birth.

A number of small outcrops of black slag-like material, which closely resembles basalt in appearance, were noted some years ago during the course of the geological survey of the Singleton–Muswellbrook region, and they were tentatively mapped as volcanic necks or minor igneous intrusions.

Upon microscopic examination of thin sections of specimens from these occurrences the rocks proved to be so unlike any basaltic rocks known to the writer that doubts at once arose as to the correctness of their original classification as igneous intrusions. Arrangements were made to visit the locality to study them in the field and to collect further specimens for systematic study.

A close examination of the field association of the outcrops in conjunction with a study of thin sections of further specimens indicates that the slag-like material is the result of fusion of clayshales and sandstones caused by the burning of a coal seam. No positively identifiable igneous material could be found in any of the localities visited.

Occurrences of this type are somewhat rare except in the vicinity of collieries in which the working of the coal seams has caused accidential fires, and descriptions of the effects of such fires on the surrounding rocks are few. The present paper places on record the peculiar types of mineral assemblages and microscopic structures observed to result from the fusion of fairly common sedimentary rocks subjected to the intense heat generated by the combustion of a seam of coal, and also indicates how such occurrences may be distinguished from igneous intrusions. It is obviously of great importance in the survey of coal-bearing sedimentary basins to be able to make this distinction, as the effect of igneous intrusions on underlying seams is likely to have been widespread, whilst the effect of fires is much more localised and can have had little effect on seams of coal lying below the level of the fire zone.

David (1907) noted the fusion of sediments along the burned outcrop of the Greta seam near Cessnock, and stated that the melting had been so complete that he at first mistook the material for contemporaneous basalt. No references, however, are to be found concerning the Ravensworth exposures.

Location of the Occurrences.

The principal outcrops of slag are in the vicinity of Ravensworth in the Singleton district, on Portions 150 and 226, Parish Liddell, County Durham. They are all close to the New England Highway, near the overhead bridge crossing the railway line, some three miles north of Ravensworth. Five are on the eastern side of the road a few hundred yards north of the bridge, and a sixth lies about ¾ mile west of the road, near the site of the old Bayswater Colliery. All lie within an area of two square miles.

They are all within the Tomago beds of the Main Permian Coal Basin and lie some 30 to 50 feet above the Bayswater coal seam, which is exposed nearby in a railway cutting. The enclosing rocks are freshwater shales and sandstones containing thin bands of sideritic material, which on weathering yield beds of concretionary limonite. The sandstones are somewhat clayey and contain some sideritic cement.

The countryside is flat to gently rolling, with little stream erosion, and there is a fairly deep mantle of soil, so that rock exposures are few. The slag outcrops are all small, most of them under 50 feet in diameter, and, as they are harder and more resistant than the surrounding rocks, form the tops of low rounded hills. Neither the exact size nor shape of any one outcrop can be determined, as their margins are hidden by soil. All of them are thin, not more than about 2 feet of material being visible in most of them.

Although the various outcrops have not been accurately levelled, inspection suggests that they all lie on, or nearly on, the same plane and that they are part of a connected whole.

General Description of the Outcrops.

In a typical exposure angular fragments of light-coloured, hardened clayshale are to be seen embedded in a black and generally vesicular slaggy matrix, which branches and invades the surrounding sediments. The whole mass has the appearance of a volcanic agglomerate. The shale fragments vary in size from about 6 inches in diameter downwards to pea-sized pieces. They are sharply irregular in shape and show no preferred orientation. They are fairly closely packed and greatly exceed in volume the amount of slaggy matrix. In places the slag is present only as thin stringers an eighth of an inch or less in width invading cracks in the shales. (See Plate X, Fig. 7).

Associated with this agglomerate-like material are sandstones which have been affected by heat, all stages from slight baking, through partial fusion to complete melting, being visible within the space of a few inches. The fusion of the sandstones has yielded a grey vesicular glassy mass in which some white unfused sand-grains are still to be seen, and traces of the original bedding remain even where fusion appears to have been complete. The clayshales and sandstones immediately above any of the fused material have been hardened and have developed a pale pink to terra-cotta-red coloration as a result of heating. The volume of such baked shale and sandstone is greatly in excess of the amount of fused material.

There is no evidence that any of the fusion of the sedimentary material is due to igneous action and abundant evidence to the contrary is present. This contrary evidence may be summarised as follows:

(1) No definitely recognisable igneous rock could be detected in any of the exposures.

(2) The amount of fused and semi-fused sandstone and baked shale is far greater than is normally to be found surrounding any minor intrusions into sedimentary rocks. In the undoubted doleritic sills and dykes of dolerite in the nearby districts of Muswellbrook and Jerry's Plains, the contact effect on the surrounding sediments is negligible, no fusion at all being visible and only a thin zone of mild "baking" a few inches thick being visible in the surrounding sediments.

(3) Specimens of sandstone and shale from the vicinity of the slag outcrops were submitted to fusion tests by heating in a muffle furnace. These specimens were virtually unchanged at 1100°C, the first signs of softening were noted at about 1250°C, whilst marked softening took place only at temperatures in excess of 1350°C, and complete fusion at about 1370°C. These temperatures are well

above those which have been recorded in open volcanic craters and basaltic lava flows, the usual figures for which are quoted as about 1000°C. to 1100°C. Such temperatures would therefore not result in the fusion of the sandstones in the area.

(4) The specimens of sandstone and shale heated experimentally all assumed a pale pink or red colour, identical with that of the rocks around the slaggy outcrops. This colour is due to oxidation of iron-bearing minerals under the action of heat, and is similar to that produced in bricks and tiles during firing in kilns. Typically such oxidising conditions are lacking during igneous intrusions and the sedimentary rocks surrounding igneous bodies do not assume a pink or red colour.

(5) At the "Burning Mountain" at Wingen some 20 miles N. of Muswellbrook, where a seam of coal is still on fire and has been burning for a period estimated by David (1907) as some centuries, the strata above the burned-out seam have assumed the same pink to red coloration as the rocks at Ravensworth. No definite slaggy material, however, is to be seen at Wingen, either on account of a more refractory rock-cover to the seam, or to the fact that the seam is burning under a very thick cover, and erosion has not yet uncovered the material immediately over the remains of the seam.

(6) The reddening of sediments over a wide area by the burning of a seam of coal in Wyoming has been described by Bastin (1905), who also noted the presence of fused slaggy material. His description of the occurrence could aptly be applied to the Ravensworth rocks, although the amount of completely fused material in the Wyoming area is far less than here. He described the slag veins in the reddened shales as only $^{1}/_{10}$ inch thick, whilst at Ravensworth individual veins are several inches in thickness.

(7) Workings in the Muswellbrook open-cut colliery some 10 miles to the North have exposed portions of the Greta seam which have been on fire, and in which large masses of black, slaggy material have been formed. This material is similar in most respects to the Ravensworth slags. The formation of clinker during the combustion of coal in a furnace is too well known to be worthy of comment, but gives further indication that the heat of combustion of coal is sufficient to melt sedimentary rocks which contain fluxes, principally iron, lime, magnesia and alkalis in amounts which are not uncommon.

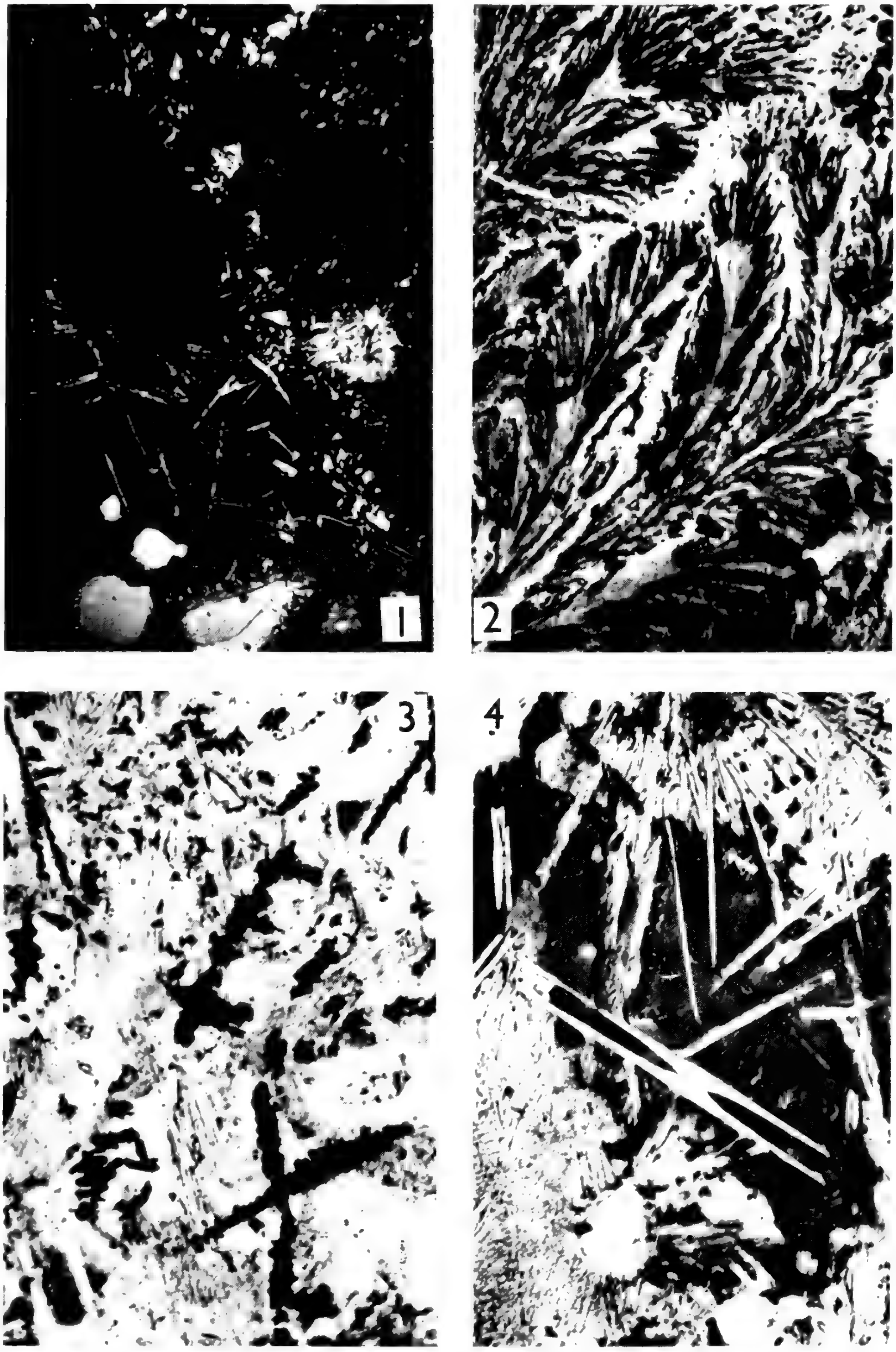
It can now be stated beyond all reasonable doubt that the slag outcrops are the result of fusion of sediments by a fierce fire. The fire covered a fairly wide area, as evidenced by the prevalence of reddened rocks. The isolated outcrops of slag may be remnants left by the erosion of a large area, but may represent "chimneys" or fissures through which flames and hot gases escaped from an underlying fire and about which intense heating was localised.

Whether the fire originated in the underlying Bayswater seam cannot be stated in the absence of openings or test borings in the immediate vicinity of the slag outcrops. It is considered, however, in the light of evidence offered by the relatively large area of reddened material, that the heat did not come from an underlying source, but that the outcrops represent the sole remains of a seam which has been completely destroyed by fire and subsequent erosion.

Microscopic Structures in the Slags.

Examination in hand-specimen shows slight variations in colour between different pieces of slags and also differences in the amount of vesicular material present, but microscopic examination reveals the presence of extremely diverse mineralogical assemblages and structures.

The two principal types of slag are: (1) those which can be seen to have been derived from the partial or complete fusion of sandstones, and are still in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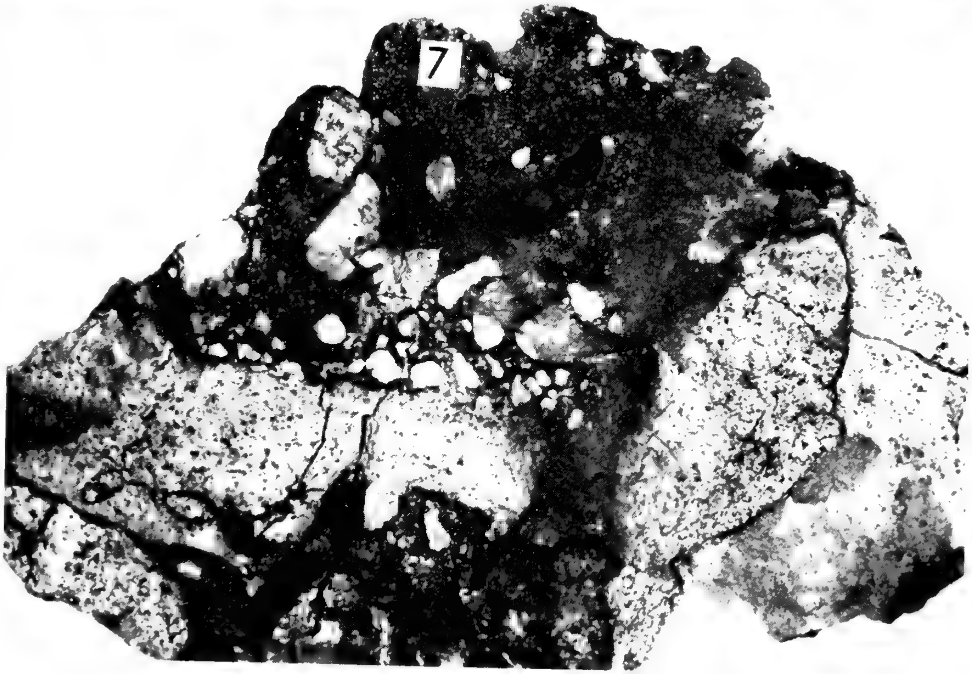
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the position in which they were formed, and (2) those which have melted completely and flowed into cracks in the more refractory aluminous clayshales. The former are composed chiefly of quartz grains and more or less glass, chiefly dark brown in colour, whilst the latter are finely crystalline and closely resemble basalts.

The fused sandstones might be described as buchites and they bear many resemblances to similar rocks described by Thomas (1922) occurring in xenoliths of sedimentary rocks enclosed by Tertiary intrusives in the island of Mull. The most completely fused ones are composed almost entirely of dark brown glass containing only a few residual grains of badly corroded quartz, many of which are fringed with small, platy crystals of quartz, which have the typical shape of tridymite crystals. These represent actual plates of tridymite formed during the heating of the quartz, which have, on cooling, inverted back to quartz. (Plate IX, Fig. 1).

Many of the specimens of buchite examined show beautifully formed plumose and dendritic crystallites of pyroxene and magnetite, tiny needles of felspar and rare hollow, pseudo-hexagonal very small crystals of cordierite (Plate IX, Figs. 2–4). Mineralogically these rocks are much less complex than the buchites of Mull which Thomas describes as containing, in addition to the above minerals, sillimanite, corundum and spinel, and which he considered to have derived certain constituents by contamination or exchange with the surrounding basalt. Certain specimens contain indefinite spherulitic masses of poorly differentiated material, which so far is unidentified, but which may be mullite.

The finely crystallised slags are far more basic than the buchites and at first sight under the microscope might readily be mistaken for basalts. They are composed largely of a pale green feebly pleochroic pyroxene, with abundant magnetite, some cordierite, tiny needles of felspar and a small amount of dark brown residual glass, in which magnetite, chiefly in the form of skeletal crystallites, is abundant. (Plate X, Figs. 5–6).

The pyroxene is present largely in the form of elongated prisms but equant-shaped grains are also developed. The pale green colour and elongated form are not characteristic of the pyroxene of basalts, but the pyroxene often developed in furnace slags commonly is of this type.

Some of the cordierite is poorly crystallised and closely resembles the nepheline found in many of the Tertiary basalts of eastern Australia, but in some of the specimens the mineral is well-crystallised in short, stumpy prisms averaging about 0·2 m.m. in length, and pseudo-hexagonal twins are common. Most of the crystals are colourless, but the largest of them, if favourably oriented in the section, show a pale blue or lilac tint and are markedly pleochroic. Some 'H'-shaped crystallites of cordierite are to be seen in some specimens, and hexagonal hollow box-like forms filled with brown glass are also to be seen.

Felspar needles comprise only 1 or 2 per cent. of the rock. They are very small, averaging less than 0·1 mm. in length and 0·01 mm. in diameter. Multiple twinning is just detectable and extinction angles of up to 20° can be measured, indicating a probable composition of around $Ab_{50}An_{50}$, a fairly basic andesine.

The basic slag is somewhat similar to some of the Wyoming material described by Thomas, and to some of the sediments fused by igneous action in Scotland and the nearby islands of the West Coast, where the development of cordierite, pyroxene and magnetite has been noted by several writers.

It is unlikely that the basic slag could have been formed from fusion of either sandstone or the typical clayshales of the area, as they are not rich in fluxes and contain insufficient iron to have formed the large amount of pyroxene and magnetite present. The coal seams in the district, however, contain bands in which siderite and iron pyrites are abundant. These bands are most prevalent near the tops of the seams and during working of the coal are a constant source of danger, as oxidation of the pyrites is a common cause of heating, which has resulted in numerous mine fires. It is considered that fusion of such bands has provided the material for the basic slags, especially as in brickmaking operations using clayshales from both the Wianamatta beds in the Sydney area and from the Coal Measures in the Newcastle district, the presence of sideritic bands gives rise to clinkering troubles during the firing of the bricks.

Beds of sideritic material occurring in the clayshales at Ravensworth could have provided the material for the slags, but as no such beds are observable within many feet of the present position of the slags, it is thought that the slags originated within the material of the coal seam itself.

The source of the magnesia in both the cordierite and the pyroxene may possibly be questioned, but the presence of magnesia in the Permian sediments of the district is indicated by the fairly common occurrence of nodular masses of magnesite in the overlying soils.

Conclusion.

It is hoped that the foregoing description of the field-occurrence of these basic slags and their mineralogical composition and peculiar micro-structures will be of some assistance in the recognition of similar occurrences elsewhere and will help in distinguishing between basic intrusive rocks and fused basic sediments.

Acknowledgements.

Acknowledgements are due to Dr. F. W. Booker and to Mr. P. McKenzie for bringing the slag outcrops under notice and for helpful discussions during field-examinations of them, and to the Under-Secretary for Mines for permission to submit this paper for publication.

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Explanation of Plates.

Plate IX.

Fig. 1.—Plates of tridymite in dark brown glass resulting from fusion of sandstone. Grains of corroded and partially absorbed quartz are to be seen at the lower end of the field. × 120.

Fig. 2.—Plumose crystallites of pyroxene in siliceous glass resulting from fusion of sandstone. ×500.

Fig. 3.—Dendritic crystals of magnetite in light coloured glass resulting from fusion of sandstone. ×500.

Fig. 4.—H-shaped crystallite of felspar in dark brown glass resulting from fusion of sandstone. A corroded grain of quartz surrounded by tridymite can be seen in the bottom left corner of the field. ×500.

Plate X.

Fig. 5.—The typical " pseudo basaltic " slag consisting of green pyroxene showing well-marked cleavage, cordierite (the light coloured stumpy crystals, tiny felspar laths and small areas of dark brown glass heavily charged with magnetite dust). × 120.

Fig. 6.—Cordierite crystal from the same slide as Fig. 5, showing well-marked pseudo-hexagonal form. ×500.

Fig. 7.—Hand specimen of brecciated light coloured shale traversed by veinlets of black slaggy material. ½ natural size.

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On Some Aspects of Integral Transforms*

JAMES L. GRIFFITH

It has been traditional in the Royal Society of New South Wales for the retiring President to tell members of the Society something of the subject in which he is most interested.

For some years, I have been carrying out research on Integral Transforms and I will attempt in the short time at my disposal to indicate the main trends and the present state of this topic.

1. Introduction

The subject of Integral Transforms reduced to its bare essentials is the study of the integral mappings

$$F(s)=\int K(s,x)f(x)dx \quad \ldots . \quad (1.1)$$
$$=T[f(x)]$$

and

$$F(s)=\int K(s,x)df(x) \quad \ldots . \quad (1.2)$$
$$=T_1[f(x)],$$

where the definite integrals may be n-dimensional if required.

The variable s may be a complex number or a real number, or in a few cases be restricted to be a positive integer.

The definition of the subject as the study of integrals of the type (1.1) and (1.2) is rather too wide. However, as in many fields of Mathematics the boundaries are rather ill defined.

It is rare to include a discussion of a general Kernel $K(s,x)$ over a general function space.

In order that the mappings (1.1) and (1.2) should be included in our subject, I would restrict the kernel by at least one of the following conditions :—

(i) it must be one of the classical kernels—e^{-sx}, e^{isx}, $\cos sx$, $\sin sx$, $xJ_\nu(xs)$, x^{s-1}., $(x+s)^{-1}$ or $(x-s)^{-1}$;

(ii) it must be a kernel which occurs in Applied Mathematical problems ;

(iii) it must be a generalization of one of the above kernels.

The use of the Dirac δ-function and pseudo-functions in Applied Mathematics and Engineering has forced the definitions (1.1) to be modified to include the generalized functions of Schwartz (1946, 1948). It has also been found profitable to consider Fourier and Laplace transforms over generalized measures (Mautner (1955), Hewitt (1943), Cameron (1945)).

Since I do not intend to treat the topics in great detail, I will restrict the definition to the form in (1.1). The greater part of the literature considers the integrals in the definition to be L^p-integrals, simple L-integrals, Cauchy principal value integrals, (C,k)-summable integrals and Gauss summable integrals.

It must be emphasized at this point that even though the subject has a considerable bulk of Mathematics in its own right, the main driving force behind the research in Integral Transforms comes from the needs of the Applied Mathematician.

Some of the engineering fields using Integral Transforms can be found from the chapter heading and examples in standard text books (Carslaw and Jaeger (1947), Churchill (1944), Sneddon (1951), Muskhelishvili (1953), Gardner and Barnes (1942)).

2

2.1. *A Classification of the Main Fields of Research*—It is clear that any classification of the research fields could be modified since there is again no sharply marked boundary line.

I would divide out four main classes :—

(i) The Basic Theorems—Existence Theorems, Representation Theorems, Inversion Formulae and Uniqueness Theorems.

(ii) Analysis of the Properties of Transforms—Operational Calculus associated with the applications.

(iii) Construction of Tables of Transforms.

(iv) Generalization of Transforms—Classification of Transforms.

There are many minor topics not yet fully developed. Of these I will comment on three :—

(v) Self Reciprocal Functions.
(vi) Characterization of Transforms.
(vii) Dual Integral Equations.

* Presidential Address delivered before the Royal Society of New South Wales, April 1, 1959.

2.2. *The Basic Theorems*—We suppose that the meaning of the integral in

$$F(s)=\int K(s,x)f(x)dx \quad \ldots. \quad (2.1)$$

is made clear, i.e. whether it is an L^1-integral, L^2-integral, etc.

We then come to the four main types of basic theorems.

(i) *Existence Theorems*—By an existence theorem we understand a theorem which defines a class of functions $f(x)$ for which an $F(s)$ exists.

(ii) *Representation Theorems*—A representation theorem is a theorem which defines a set of functions $F(s)$ for which it is known that an $f(x)$ exists so that equation (2.1) holds.

(iii) *Inversion Theorems*—An inversion theorem states a set of functions $f(x)$ for which $F(s)$ exists and also states a rule by which $f(x)$ can be obtained from $F(s)$.

(iv) *Uniqueness Theorems* — A uniqueness theorem is a theorem which states a set of functions $f(x)$ and a corresponding set $F(s)$ connected with $f(x)$ by equation (2.1) so that the relation between the two classes is (1—1).

It is obvious, first of all, that some kind of existence theorem is necessary since otherwise the definition (2.1) would be a waste of time. Additionally, it is desirable that the theorem should be stated so that it covers all the functions on which the transform will operate. In order to apply the Laplace transform in Electrical Engineering, a theorem somewhat as follows would be satisfactory :—Assuming that

$$\int_0^\infty e^{-sx}f(x)dx$$

is defined to be a Cauchy-Riemann integral, then it is sufficient for the integral to exist that $f(x)$ would be sectionally continuous and be $O(e^{ax})$ for some finite a and $x\to+\infty$.

A representation theorem has two purposes. The first is seen in the situation when attention is directed to the $F(s)$. The engineer has some reason to believe that $F(s)$ may be expressed in the form (2.1). The representation theorem will confim this belief.

Now suppose that we are mainly interested in $f(x)$, but are working with $F(s)$. The representation theorems will confirm in the steps of our work that we are dealing with genuine transforms.

In recent times it has become usual to indicate representation theorems immediately after the definition of a new transform.

One must distinguish between the set of functions $f(x)$ for which it is known that $F(s)$ exists and the set of $f(x)$ which can be determined from the corresponding $F(s)$, by a specific inversion formula.

The Hankel transform and its inversion formula are

$$F(s)=\int_0^\infty xJ_\nu(sx)f(x)dx \quad .. \quad (2.2a)$$

and

$$f(x)=\int_0^\infty sJ_\nu(sx)F(s)ds \quad .. \quad (2.2b)$$

The well-known L^1 theorem demands that $x^{\frac{1}{2}}f(x)$ should belong to $L^1(0,\infty)$ and that the integral in (2.2b) should be a Cauchy limit at the upper end.

However, it is clear that $F(s)$ exists if we merely demand that $x^{\frac{1}{2}}f(x)$ belongs to $L^1(1,\infty)$ and that $x^{1+\nu}f(x)$ belongs to $L^1(0,1)$.

Now referring to Erdelyi (1954), p. 25 (30) and p. 35 (5), we observe that if

$$f(x)=2^{-1-\nu}\pi^{-\frac{1}{2}}a^{-1}\Gamma(\nu-\tfrac{1}{2})x^{-\nu}\sin(ax)$$

then

$$F(s)=s^{-\nu}(s^2-a^2)^{\nu-3/2}, \quad s>a$$
$$=0, \quad s<a.$$

For this pair (2.2a) holds when $\nu>\frac{1}{2}$ and (2.2b) holds only when $\frac{1}{2}<\nu<2\frac{1}{2}$.

The existence theorem holds over a larger range of functions than does the inversion formula.

Before proceeding further, we should observe the table of transforms with the corresponding inversion formulae (Table 1).

It will be noted that the inversion formulae may be written as series, integrals, limits, derivatives or combinations of these. The methods of dealing with integrals and series are familiar to everyone but the methods of dealing with the limits of derivatives have not been developed. In fact I cannot recall any paper which gives a method of dealing with such limits. Theorems expressed in terms of infinite derivatives are not at the moment of much help to the Applied Mathematician.

When we are in the unfortunate position that we cannot apply our inversion theorems because they are too difficult or are non-existent, we have to examine our uniqueness theorems.

The uniqueness theorem shows that to every $F(s)$ there is one and only one $f(x)$ so that $T[f(x)]=F(s)$. If this were not so there would exist a function $g(x)\not\equiv0$ so that $T[g(x)]=0$.

The finite Hilbert transform furnishes a neat example. Here

$$F(s)=\pi^{-1}\int_{1}^{+1}(x-s)^{-1}f(x)dx \quad .. \quad (2.3a)$$

where s is restricted to the interval $-1<s<1$.

It is not difficult to show that if $f(x)=(1-x^2)^{-\frac{1}{2}}$ then $F(s)=0$.

Tricomi's inversion formula for this transform is

$$f(x)=-\pi^{-1}\int_{-1}^{+1}\frac{(1-s^2)^{\frac{1}{2}}F(s)}{(1-x^2)^{\frac{1}{2}}(s-x)}ds+C(1-x^2)^{-\frac{1}{2}} \quad .... \quad (2.3b)$$

where C is an arbitrary constant.

With L^1-theory the function $f(x)$ is not uniquely determined by $F(s)$, but if we are dealing with L^2-theory $f(x)$ is unique (see also Griffith (1956)).

It is immediately clear that the set of functions for which a uniqueness theorem can be found must include those functions for which an inversion formula can be found. This indicates that the preferable uniqueness theorems should be constructed independently of the inversion theorems. The well-known Lerch's theorem of the Laplace Transform is proved without reference to an inversion formula.

As soon as a set of functions $F(s)$ has been determined by a uniqueness theorem, an applied mathematician merely required a suit-

TABLE I

Name	*Definition*	*Inverse*	*Reference*
Laplace (one-sided)	$\int_0^\infty e^{-sx}f(x)dx$	$(2\pi i)^{-1}\int_{c-i\infty}^{c+i\infty} e^{sx}F(s)ds$	(*a*)
Laplace (two-sided)	$\int_{-\infty}^\infty e^{-sx}f(x)dx$	$(2\pi i)^{-1}\int_{c-i\infty}^{c+i\infty} e^{sx}F(s)ds$	(*a*)
Mellin	$\int_0^\infty x^{s-1}f(x)dx$	$(2\pi i)^{-1}\int_{c-i\infty}^{c+i\infty} x^{-s}F(s)ds$	(*b*)
Whittaker	$\int_0^\infty e^{-\frac{1}{2}sx}(sx)^{-k-\frac{1}{2}}W_{k+\frac{1}{2},m}(sx)f(x)dx$	$\frac{\Gamma(1-k+m)}{2\pi i\Gamma(1+2m)}\int_{c-i\infty}^{c+i\infty} e^{\frac{1}{2}sx}(sx)^{k-\frac{1}{2}}M_{k-\frac{1}{2},m}(sx)F(s)ds$	(*c*)
Cosine	$(2/\pi)^{\frac{1}{2}}\int_0^\infty \cos sx\, f(x)dx$	$(2/\pi)^{\frac{1}{2}}\int_0^\infty \cos sx\; F(s)ds$	(*b*)
Sine	$(2/\pi)^{\frac{1}{2}}\int_0^\infty \sin sx\, f(x)dx$	$(2/\pi)^{\frac{1}{2}}\int_0^\infty \sin sx\; F(s)ds$	(*b*)
Hankel	$\int_0^\infty xJ_\nu(sx)f(x)dx$	$\int_0^\infty sJ_\nu(sx)F(s)ds$	(*b*)
Complex Fourier	$(2\pi)^{-\frac{1}{2}}\int_{-\infty}^\infty e^{isx}f(x)dx$	$(2\pi)^{-\frac{1}{2}}\int_{-\infty}^\infty e^{-isx}F(s)ds$	(*b*)
Hankel Y	$\int_0^\infty xY_\nu(sx)f(x)dx$	$\int_0^\infty s\mathbf{H}_\nu(sx)F(s)ds$	(*b*)
Hilbert	$\pi^{-1}\int_{-\infty}^\infty \frac{f(x)}{x-s}dx$	$-\pi^{-1}\int_{-\infty}^\infty \frac{F(s)}{s-x}ds$	(*b*)
Finite Cosine	$\int_0^\pi \cos sx f(x)dx$	$\pi^{-1}F(0)+2\pi^{-1}\sum_{n=1}^{\infty}F(n)\cos nx$	(*e*)
Finite Sine	$\int_0^\pi \sin sx f(x)dx$	$2\pi^{-1}\sum_{n=1}^{\infty}F(n)\sin nx$	(*e*)

TABLE I—*continued*

Name	*Definition*	*Inverse*	*Reference*
Stieltjes	$\int_0^\infty (s+x)^{-1}f(d)dx$	$\lim_{\eta\to 0}\frac{1}{2\pi i}[F(-x-i\eta)-F(-x+i\eta)]$	(*d*)
Weierstrass	$(4\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty} e^{-\frac{1}{4}(s-x)^2}f(x)dx$	$\lim_{n\to\infty}(1-D^2/n)^nF(x)$	(*f*)
		$\lim_{n\to\infty}\left(\sum_{p=0}^{n}\frac{(-1)^pD^{2p}}{p!}\right)F(x)$	(*f*)
Laplace (one-sided)	$\int_0^\infty e^{-sx}f(x)dx$	$\lim_{n\to\infty}\frac{(-1)^n}{n!}\left(\frac{n}{x}\right)^{n+1}F^{(n)}\left(\frac{n}{x}\right)$	(*d*)
——	$\int_0^s \sin(s-x)f(x)dx$	$\int_0^x F(t)dt+F'(x)+F(0)$	(*g*)
Finite Hilbert	$\pi^{-1}\int_{-1}^{+1}(x-s)^{-1}f(x)dx$	$-\pi^{-1}\int_{-1}^{+1}\frac{(1-s^2)^{\frac{1}{2}}F(s)}{(1-x^2)^{\frac{1}{2}}(s-x)}ds+C(1-x^2)^{-\frac{1}{2}}$	(*h*)

Notes

(*a*) Widder (1951).
(*b*) Titchmarsh (1948).
(*c*) Meijer (1941).
(*d*) Hirschmann and Widder (1955). $F^{(n)}$ indicates nth derivative.
(*e*) The ordinary Fourier Series.
(*f*) Rooney (1957–58). $D=d/dx$.
(*g*) An example easily verified by substitution.
(*h*) Tricomi (1951). C is a constant.

able set of tables of images and properties of transforms. In engineering and elsewhere there may never be need to use an inversion formula.

2.3. *Analysis of the Properties of Transforms*—The principal feature of a large group of transforms is the algebraization of certain mathematics situation. In order to do this the transform is used to construct an operational calculus. Each transform deals with its own particular set of problems.

I will show two very simple examples from the Laplace Transform.

In almost every text book on this subject will be found the following entries

Table of Images of Functions

$f(x)$	$F(s)$	
e^{-x}	$(s+1)^{-1}$	.. (2.4)

Table of Images of Operations

$f'(x)$	$sF(s)-f(0)$	.. (2.5)

Table of Images of Relations

$\int_0^x f(x-t)g(t)dt$	$F(s)G(s)$	.. (2.6)

We will now solve the differential equations

$$\frac{df}{dx}+f=g(x),\ \text{with } f(0)=0 \quad .. (2.7)$$

Apply the Laplace transform to each side of the equation (2.7), using the transform pair (2.5). Thus

$$sF(s)+F(s)=G(s)$$
$$(s+1)F(s)=G(s)$$
$$F(s)=(s+1)^{-1}G(s).$$

Then using pairs (2.4) and (2.6) we find the result

$$f(x)=\int_0^x e^{-(x-t)}g(t)dt.$$

This trivial example contains most of the essential mathematical notions for working out a vast number of electrical engineering and radio problems. With a set of tables and a knowledge of elementary algebra it is possible to obtain solutions to problems without any notions of the underlying mathematical concepts.

Consider now a differential equation of the Volterra type

$$f(x)=g(x)+\int_0^x h(x-t)f(t)dt. \quad .. \quad (2.8)$$

We wish to find $f(x)$ in terms of the other functions.

Applying the Laplace transform again we obtain

$$F(s)=G(s)+H(s)F(s)$$

that is

$$F(s)=G(s)/(1-H(s)) \quad \ldots\ldots \quad (2.9)$$

The engineer now looks through his set of tables to find $f(x)$.

There are obviously now two possibilities. Either he finds the answer or he does not. Both alternatives need examination.

Without going into all the alternatives, we could say that in applying the Laplace transform to equation (2.8) we are assuming that $g(x)$, $h(x)$ and $f(x)$ are all $O(e^{ax})$ as $x \to \infty$ for some finite a and all belong to $L^1(0,n)$ for all finite n.

Thus if a result is found it has these properties. There may be further solutions for which one of the properties does not hold.

If a result is not found the fault may lie in the incompleteness of the tables (which would be the case for equation (2.8)). A check through representation theorems would be called for. After this an application of an inversion formula.

However, it may happen that the equation has no solution. For example

$$\cos x=\int_0^x \sin(x-t)f(t)dt \quad .. \quad (2.10)$$

which when " solved " by the Laplace transform leads to $F(s)=s$.

Each integral transform creates its own operational calculus over a suitable restricted class of functions with suitable boundary conditions. The Zero-th Order Hankel transform converts

$$\left[\frac{d^2}{dx^2}+\frac{1}{x}\frac{d}{dx}\right]^n y(x) \to (-1)^n s^n Y(s)$$

(see also Griffith, 1956*b*).

The second section of this analysis of transforms consists of determining the manner in which a property of $f(x)$ affects the behaviour of $F(s)$ and the manner in which a property of $F(s)$ allows us to discover some property of $f(x)$.

In our equation (2.10) above it is known that for all $f(x)$, $F(s) \to 0$ as $s \to +\infty$, thus $F(s)=s$ is not the transform (Laplace) of any function.

As an illustrative example we consider the example

$$F(s)=s^{-3}J_4(as)=(2\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty} e^{isx}f(x)dx$$

(Erdelyi (1954), p. 69 (9)).

Our analysis would proceed as follows :—

(i) $F(s)$ is an integral function of exponential type a. This shows that $f(x)$ is zero for $|x|>a$ (Boas (1954, p. 103)).

(ii) $F(s)$ is odd in s, then $f(x)$ is odd in x.

(iii) $sF(s)$ belongs to $L^1(-\infty.\infty)$, so that $f(x)$ is differentiable for all x.

In fact $f(x)=Cx(a^2-x^2)^{2\frac{1}{2}}, \quad |x|<a$
$=0, \quad |x|>a,$

where $C^{-1}=2^{1\frac{1}{2}}\pi a^3\Gamma(3\frac{1}{2})$.

Sometime later in the year, I hope to submit a paper which shows how to find the discontinuities of $f(x)$ when $F(s)$ has been defined by

$$F(s)=\int_0^\infty xJ_\nu(xs)f(x)dx.$$

It is not surprising that a section of the subject has a very large literature (Franz (1950), Zemanian (1957), Harmann and Wintner (1951) as examples).

There is associated with this type of work also a great deal of work on Tauberian and Abelian Theorems. Much of this is based on the work of Karamata (1931) and Wiener (1933).

The analysis of transform properties is a continuing program with naturally no limit.

2.4. *Construction of Tables of Transforms*—It is seen from the remarks made above that in order to make applications easy there must be suitable tables prepared. Erdelyi (1954) lists approximately 900 entries for the Laplace transform. There is no limit to the number of transforms which can be tabulated. Any transform-pair useful to an engineer is a welcome addition.

The method of construction of the tables must be directed at the user. The tables for a Mathematician would not suffice for a person whose knowledge is restricted to a year of University Mathematics.

3. Generalization of Known Transforms

The topics mentioned in the previous section are all directly of the utilitarian type. They are all related to the solution of specific problems which come from Applied Mathematics.

We will have a look at a few topics which have developed without reference to applications.

3.1. *The Whittaker Transforms — Meijer Transforms*—Meijer (1940) found that the transforn

$$F(s)=(2/\pi)^{\frac{1}{2}}\int_0^\infty (sx)^{\frac{1}{2}}K_\nu(sx)f(x)dx \quad \ldots (3.1)$$

reduces to the Laplace transform when $m=\frac{1}{2}$.

He later found that (Meijer (1941*a*))

$$F(s)=\int_0^\infty (st)^{-k-\frac{1}{2}}e^{-\frac{1}{2}st}W_{k+\frac{1}{2},m}(st)f(t)dt \quad \ldots\ldots\ldots\ldots (3.2)$$

also reduced to the Laplace transform when $k=m$.

The bulk of periodical literature on this transform is very large. It does not appear to have been collected in any reference book. Almost every paper involves very heavy algebra. Much of the work is formal and doubtful, which makes an accurate estimation of the value of the research rather hard. It is probable that the major contribution is the construction of tables of integrals involving Whittaker Functions and other Confluent Hypergeometric functions (Saksena (1953)).

3.2. *The Convolution Transforms*—We class a transform as a convolution transform when it is expressed as

$$F(s)=\int K(s-x)f(x)dx. \quad \ldots\ldots (3.3)$$

It is easily observed that all of our transforms mentioned can be expressed this way.

Any analysis of equation (3.3) without heavy restrictions cannot get anywhere.

A development which will no doubt have a very great influence on future work is due to Pollard, Hirschmann and Widder in U.S.A. This work started about 1946 and was summarized in 1955 by the book by Hirschmann and Widder.

The two-sided Laplace Transform (Van der Pol and Bremmer (1950) and Widder (1941)) is defined by

$$L_{11}[f(x)]=F(p)$$
$$=\int_{-\infty}^\infty e^{-px}f(x)dx \quad \ldots\ldots\ldots (3.4)$$

and has the following two properties

$$L_{11}[D^nf(x)]=p^nF(p), \quad D=d/dx \quad \ldots\ldots (3.5)$$

and

$$L_{11}\left[\int_{-\infty}^\infty g(x-t)f(t)dt\right]=G(p)F(p) \quad \ldots (3.6)$$

(we have used p as a variable to avoid confusion in the next few lines).

The operational form of the Taylor series is

$$e^{aD}f(x)=f(x+a). \quad \ldots\ldots\ldots\ldots (3.7)$$

These writers now consider the transform

$$\varphi(s)=\int_{-\infty}^\infty g(s-x)f(x)dx \quad \ldots (3.8)$$

where $g(x)$ has a two-sided Laplace transform $[E(p)]^{-1}$ of the special form

$$E(p)=e^{bp}\prod_{k=0}^\infty (1-p/a_k)e^{p/a_k} \quad \ldots (3.9)$$

where the b and a_k are *real* and $\sum_k a_k^{-2}$ converges.

Formally, applying the two-sided Laplace transform (with regard to s on equation (3.8) we obtain

$$\Phi(p)=(E(p))^{-1}F(p)$$

i.e.

$$F(p)=(E)p\Phi(p).$$

So using equation (3.5), we obtain

$$f(x)=e^{bD}\prod_{k=0}^\infty (1-D/a_k)e^{D/a_k}\varphi(x) \quad \ldots\ldots\ldots\ldots (3.11)$$

which is interpreted in light of equation (3.7).

The inversion theorem indicates to us immediately that in order that a transform should be collected in this general group that the image function must be infinitely differentiable. With some change of variable, the one-sided Laplace, the Stieltjes and the Meijer transforms can be expressed as convolution transforms of this type. On the other hand, it is clear that the Fourier and Hankel transforms cannot be included.

An examination of the research shows that much of the work has a statistical basis and there is no doubt that there will be further applications in this field.

One indirect result of this study of convolution transforms is the stimulus it has given to workers to look for inversion theorems expressible in terms of infinite derivatives.

Unfortunately, there is no literature on the subject of how to deal with these infinite derivatives.

It would seem that the next step in the research on this transform could be to examine the situation when the a_k were complex. In particular, they could possibly be restricted to lie in strips along the real axis. However, whether this has been examined and found to be unprofitable I do not know. Research seems to be directed to examining other types of kernels (Pollard (1945), Blackman (1957). Sumner (1953), Calderon and Zygmund (1955)),

3.3. *The Contributions of E. C. Titchmarsh*—E. C. Titchmarsh, with two books "*Fourier Integrals*" and "*Eigenfunction expansions associated with second order Differential equations*" and a large number of papers, has had a profound influence on the modern work on integral transforms.

Eigenfunction expansions is concerned with providing a method for obtaining inversion formulae for a large class of kernels. These kernels satisfy a differential equation of the type

$$\frac{d^2y}{dz^2}+[\lambda-q(z)]y=0 \quad \ldots\ldots \quad (3.12)$$

together with certain boundary conditions.

If a transform has occurred with a Kernel $K(s,x)$ and this Kernel with some change of variable $x=x(z)$ and $s=s(\lambda)$ can be put in the form where it satisfies an equation of the type (3.12), there is some possibility that an inversion theorem can be obtained (i.e. at least formally).

The equation

$$\frac{d^2y}{dx^2}+\left(s^2-\frac{\nu^2-\frac{1}{4}}{x^2}\right)y=0$$

leads to the inversion formulae for the Hankel, Weber, Generalized Weber (Griffith (1956*b*)) and the Finite Hankel Transforms.

The subject of the "*Eigenfunction Expansions*" is closely related to the subject of Operators in Hilbert Space. All the transforms discussed possess a real scalar product or Parseval formula of the type

$$\int f(x)g(x)dx=\int F(s)G(s)dw(s) \quad (3.13)$$

Fourier Integrals was first published in 1937. This book collects in an easily accessible form much of the work connected with Fourier integrals. We will only mention two chapters.

Chapter VIII deals with General Transformations or Watson Transforms. Here he finds that

$$F(s)=\int_0^\infty K(sx)f(x)dx \quad \ldots \quad (3.14a)$$

has an inverse of the form

$$f(x)=\int_0^\infty H(xs)F(s)dx \quad \ldots \quad (3.14b)$$

provided that

$$\bar{K}(s)\bar{H}(1-s)=1$$

where $\bar{K}(s)$ and $\bar{H}(s)$ are the Mellin transforms of $K(x)$ and $H(x)$ respectively.

This result again allows a general method for finding inversion formulae (Bochner and Chandrasekharan (1949), Guinand (1950)).

Chapter IX provides the notations and methods of much of the later work on self reciprocal functions (see later).

4. Some Minor Topics

4.1. *Self Reciprocal Functions*—The integral equation

$$p(x)=q(x)+\int K(x,s)p(s)ds$$

when solved for $p(x)$ will have one solution only if

$$f(x)=\int K(x,s)f(s)ds \quad \ldots\ldots \quad (4.1)$$

has no solutions.

This (amongst other considerations) has led to determinations of functions which satisfy (4.1). Such functions are said to be reciprocal with regard to the Kernel $K(x,s)$. The problem is clearly a specialized form of the eigenvalue problem for the Kernel $K(x,s)$.

Titchmarsh treats only the sine, cosine and Hankel transforms. However, the subsequent literature is extremely extensive, the greater part being connected with the Hankel transform and its generalizations (for example, Bhatnagar (1953), Bose (1954)). A few other transforms have been considered (Stankovic (1953), Guinand (1938–39)).

4.2. *Characterization of Transforms*—This is a section of the subject which has received little attention and in my opinion is exceedingly important.

There are two aspects of the problem. The first is what properties of a transform uniquely determine the transform, and the second is what is the set of transforms which have a certain property.

To illustrate the second problem, we note that the two-sided Laplace transform and the Fourier transform (slightly modified) satisfy the equations

$$T\left[\int_{-\infty}^{\infty} f(x-t)g(t)dt\right]=T[f(x)]\,T[g(x)] \qquad \ldots\ldots\ldots (4.2)$$

(Kunze (1959)). The problem would be to find are there other transforms satisfying this equation. The solution would possibly provide a set of new transforms which could be of assistance to the engineer and the applied mathematician. These transforms may operate on *different* sets of functions from known transforms.

We know that the most important property of the zero-th order transform $\int_0^\infty xJ_0(xs)f(x)$ is

$$\int_0^\infty xJ_0(xs)[f''(x)+x^{-1}f'(x)]dx=-s^2F(s)$$

i.e.

$$T[f''(x)+x^{-1}f'(x)] \;=-s^2T[f(x)] \qquad \ldots\ldots\ldots (4.3)$$

It is quite trivial to show that provided the $f(x)$ satisfy certain boundedness conditions that this is the only transform of the type

$$\int_0^\infty xQ(sx)f(x)dx$$

which satisfies this equation.

This would be a solution of the first type of problem. The Hankel transform of order zero is the only transform of the type (4.4) which satisfies equation (4.3).

For related problems, see San Juan (1941) and Jaeckel (1957).

4.3. *Dual Integral Equations*—This section of the work is usually extremely difficult, and the problems require rather ingenious methods of solution. These equations arise from the translation of boundary value problems in physics into transform formulae.

An example from the recent literature is (Gordon (1954)) to solve

$$\int_0^\infty y^a f(y)J_\nu(xy)dy=g(x), \quad x>1$$

$$\int_0^\infty f(y)J_\nu(xy)dy=k(x), \quad x<1.$$

The equations satisfy one transform over part of a range and a related transform over a second part of the total range.

There does not appear to be any general method, and most examples are of the Hankel type.

5. Future Developments

As mentioned earlier, the major driving force in the subject of integral transforms is the supply of problems coming from engineering and applied mathematics. Without an intimate knowledge of applied mathematics one could not anticipate a transform as

$$F(s)=\int_0^\infty f(x)K_{ix}(s)dx$$

which is inverted by

$$f(x)=2\pi^{-2}x\sinh(\pi x)\int_0^\infty F(s)K_{ix}(s)s^{-1}ds$$

(the Kontorovich-Lebedev transform, see Erdelyi (1954)). There is no doubt that as research continues more problems will be provided.

It is clear that, as in Statistics, where much of the work is being considered over generalized measure spaces, Integral Transforms will include more work with generalized measures and generalized functions.

5.1. *The Multidimensional Fourier Transforms*—One of the surprising features of our subject is the smallness of the literature on the multidimensional Fourier Transforms. There are many applications in journals on applied Mathematics, but it is easy to see that these are mostly formal. There is the need for an encyclopaedic work of the nature of Doetsch (1950–56).

Very few properties of the transforms which are not trivial extensions of the one-dimensional case are known. The non-trivial extensions are those related to radially symmetric functions, and these are developable from Hankel Transforms.

Reference to Sneddon (1951) shows the need for an examination of the situation where the original transform is defined by

$$F(s,t,u)=\lim_{p\to 0}\iiint e^{-pr}e^{i(sx+ty+uz)}dxdydz.$$

This problem will probably be treated by means of a generalized measure theory.

Possibly one of the reasons for lack of progress in research of the multidimensional Fourier is the difficulty of obtaining literature on the theory of functions of more than one complex variable. There is no comprehensive text book available.

The major problem of crystallography, that of determining $f(x,y,z)$ from $| F(s,t,u) |^2$, has not been solved. There has been a fairly complete study of the problem, for the one-dimensional case has been given by Akutowicz (1956, 1957), but the corresponding problem for the two and three dimensions has not been completed.

5.2. *Numerical Methods and Inequalities*—With the extended use of integral transforms in engineering, there has developed a number of methods for evaluating transforms by numerical methods. The major problem is the following: If $F(s)=G(s)+H(s)$ and we approximate $F(s)$ by $G(s)$, what is the error made in $f(x)$?

We need three separate answers to this question. These are (i) is $g(x)$ essentially the same as $f(x)$ i.e. do the graphs look alike? (ii) what is the maximum error?; (iii) what is the error for the extreme values, say 0 and $+\infty$?

Most of the literature appears to be connected with the sine- and cosine-transforms (Zemanian (1957), Boas and Kac (1945)).

There is a large field of work yet to be covered in this section.

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Minor Planets observed at Sydney Observatory during 1958

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The following observations of minor planets were made photographically at Sydney Observatory with the 13-inch standard astrograph until July 8 and from then on with the 9-inch Taylor, Taylor and Hobson lens. Observations were confined to those with southern declinations in the *Ephemerides of Minor Planets* published by the Institute of Theoretical Astronomy at Leningrad.

On each plate two exposures, separated in declination by approximately 0′·5, were taken with an interval of about 20 minutes between them. The beginnings and endings of the exposures were recorded on a chronograph with a tapping key.

Rectangular coordinates of both images of the minor planet and three reference stars were measured in direct and reversed positions of the plate on a long screw measuring machine. The usual three star dependence reduction retaining second order terms in the differences of the equatorial coordinates was used. Proper motions, when they were available, were applied to bring the star positions to the epoch of the plate. Each exposure was reduced separately in order to provide a check by comparing the difference between the two positions with the motion derived from the ephemeris. The tabulated results are means of the two positions at the average time except in cases 664, 696, 698, 713, 714, 751, 760, 773 where each result is from only one image, due to a defect in the other exposure or a failure in timing it. No correction has been applied for aberration, light time or parallax but in Table I are given the factors which give the parallax correction when divided by the distance. The serial numbers follow on from those of a previous paper (Robertson, 1959). The observers named in Table II are W. H. Robertson (R), K. P. Sims (S) and H. W. Wood (W). The measurements were made by Mrs. M. Wilson, who also assisted in the computation.

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Sydney Observatory
Sydney

Table I

No.	1958 U.T.		Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
640	Aug.	27·65240	28 Bellona	0 08 48·14	— 5 48 08·4	—0·01	—4·1
641	Sep.	9·62544	28 Bellona	0 00 44·91	— 7 24 42·1	+0·04	—3·9
642	Sep.	25·57851	28 Bellona	23 48 46·83	— 9 23 27·6	+0·05	—3·6
643	July	28·55388	52 Europa	19 35 24·51	—19 12 34·7	+0·02	—2·2
644	Aug.	11·47869	52 Europa	19 25 55·50	—19 58 53·5	—0·08	—2·1
645	July	31·60217	87 Sylvia	20 29 32·56	—31 32 18·0	+0·09	—0·4
646	Aug.	18·53859	87 Sylvia	20 16 17·28	—32 24 23·2	+0·07	—0·2
647	July	31·56188	93 Minerva	19 52 58·71	—34 24 18·7	+0·04	+0·1
648	July	21·69789	116 Sirona	22 03 30·81	—17 07 02·4	+0·09	—2·6
649	Aug.	18·60564	116 Sirona	21 42 08·91	—19 14 32·6	+0·09	—2·2
650	Sep.	9·53211	116 Sirona	21 25 14·26	—20 25 04·6	+0·09	—2·1
651	July	28·60737	127 Johanna	21 08 46·52	—29 26 10·5	—0·02	—0·7
652	Aug.	27·61528	128 Nemesis	22 39 48·20	—19 32 02·3	+0·07	—2·2
653	Sep.	25·51660	128 Nemesis	22 18 05·15	—21 06 02·6	+0·06	—1·9
654	May	29·54118	134 Sophrosyne	15 26 41·66	—36 36 51·1	+0·01	+0·5
655	June	18·50874	134 Sophrosyne	15 09 30·96	—35 03 36·1	+0·13	+0·1
656	May	27·65752	145 Adeona	17 16 43·89	—22 15 45·5	+0·12	—1·8
657	July	2·54060	145 Adeona	16 42 47·04	—23 38 05·1	+0·14	—1·6
658	Feb.	26·64040	172 Baucis	11 53 40·33	— 5 13 31·3	—0·01	—4·2
659	Mar.	20·55428	172 Baucis	11 31 52·25	— 4 26 19·8	—0·04	—4·3
660	Mar.	31·63732	186 Celuta	14 00 35·84	—16 14 38·4	—0·01	—2·6
661	Apr.	29·52730	186 Celuta	13 28 42·11	—16 12 28·3	—0·04	—2·6

TABLE I—*continued*

No.	1958 U.T.		Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
662	July	16·60423	189 Phthia	19 59 39·81	—11 35 05·9	+0·02	—3·3
663	Aug.	7·48593	189 Phthia	19 40 02·38	—12 46 29·9	—0·12	—3·2
664	May	5·56946	192 Nausikaa	14 20 55·13	—23 32 49·7	+0·03	—1·6
665	May	19·51535	192 Nausikaa	14 07 17·15	—22 30 57·4	+0·01	—1·7
666	Aug.	26·67830	196 Philomela	0 15 46·97	— 9 29 41·9	+0·05	—3·6
667	Sep.	9·62544	196 Philomela	0 07 13·66	—10 39 09·3	+0·02	—3·5
668	Aug.	26·64708	201 Penelope	23 12 11·88	— 5 47 54·7	+0·09	—4·1
669	Oct.	1·53252	201 Penelope	22 49 25·70	—10 17 54·9	+0·09	—3·5
670	Mar.	31·66820	210 Isabella	14 25 09·18	—13 56 33·8	+0·03	—3·0
671	May	6·52596	210 Isabella	13 55 27·14	—12 15 27·4	—0·04	—3·2
672	Apr.	29·58226	212 Medea	14 55 35·63	—23 00 41·9	—0·06	—1·6
673	May	15·57104	212 Medea	14 42 52·05	—22 05 56·9	+0·08	—1·8
674	May	28·50960	212 Medea	14 33 45·07	—21 16 03·5	+0·01	—1·9
675	Aug.	18·56612	237 Coelestina	21 17 10·85	—29 04 50·5	+0·02	—0·7
676	Aug.	26·64708	240 Vanadis	23 08 27·71	— 8 15 43·8	+0·10	—3·8
677	Oct.	1·53252	240 Vanadis	22 40 39·86	—11 25 16·0	+0·11	—3·4
678	July	17·58053	241 Germania	20 07 24·55	—16 13 07·6	—0·06	—2·7
679	July	24·63179	241 Germania	20 01 26·92	—16 18 29·2	+0·04	—3·4
680	Aug.	11·55164	241 Germania	19 47 23·75	—16 35 04·2	+0·11	—2·6
681	July	24·66864	254 Augusta	21 27 40·15	—24 17 25·0	+0·11	—1·5
682	June	17·60238	268 Adorea	18 18 13·82	—21 33 03·2	—0·01	—1·9
683	July	9·51860	268 Adorea	17 59 57·14	—21 52 29·5	—0·05	—1·8
684	May	5·58778	270 Anahita	14 48 56·50	—18 27 14·2	+0·03	—2·3
685	May	20·51102	270 Anahita	14 33 34·72	—16 58 27·9	—0·05	—2·5
686	Aug.	19·67643	279 Thule	23 33 07·86	— 6 10 23·1	+0·08	—4·1
687	Sep.	18·58448	279 Thule	23 17 00·16	— 7 56 13·0	+0·08	—3·8
688	Sep.	11·62087	286 Iclea	0 23 05·90	—10 57 42·1	—0·01	—3·4
689	Sep.	22·63028	286 Iclea	0 16 15·67	—12 39 52·0	+0·13	—3·2
690	July	22·68756	332 Siri	21 07 03·48	—21 26 25·8	+0·19	—2·1
691	Aug.	26·64708	337 Devosa	23 10 44·47	— 9 06 05·1	+0·09	—3·7
692	Oct.	1·53252	337 Devosa	22 36 14·23	—10 20 30·9	+0·12	—3·5
693	Oct.	7·58229	348 May	0 56 22·37	—9 40 27·3	+0·02	—3·6
694	Apr.	28·55982	356 Liguria	14 13 03·24	—21 59 09·0	—0·04	—1·8
695	May	15·50452	356 Liguria	13 58 27·58	—20 59 02·6	—0·04	—1·9
696	Apr.	29·56054	372 Palma	13 56 31·89	—45 34 50·0	+0·01	+1·8
697	May	12·53177	372 Palma	13 43 52·47	—44 41 04·2	+0·08	+1·6
698	Mar.	20·64442	376 Geometria	13 50 05·76	—21 22 20·4	—0·06	—1·9
699	Apr.	28·52983	376 Geometria	13 17 06·60	—19 51 38·0	—0·01	—2·1
700	July	31·66290	385 Ilmatar	22 30 52·83	—16 41 08·2	+0·01	—2·6
701	Aug.	27·58382	385 Ilmatar	22 07 29·58	—17 29 14·1	+0·04	—2·5
702	June	18·64625	388 Charybdis	19 15 43·39	—31 50 57·9	+0·01	—0·3
703	July	2·58694	388 Charybdis	19 03 29·69	—32 13 31·6	—0·03	—0·2
704	July	21·52702	388 Charybdis	18 46 01·58	—32 12 19·8	—0·02	—0·2
705	Aug.	25·66844	402 Chloe	23 49 23·97	—12 41 20·4	+0·07	—3·2
706	Sep.	25·55072	402 Chloe	23 25 36·79	—16 55 26·7	+0·02	—2·6
707	July	16·67226	404 Arsinoe	21 53 03·29	—27 22 05·0	—0·01	—1·0
708	July	24·70888	404 Arsinoe	21 47 31·16	—28 42 51·8	+0·20	—1·0
709	Aug.	20·67090	412 Elisabetha	23 36 52·70	—20 42 51·0	+0·06	—2·0
710	Sep.	22·59342	412 Elisabetha	23 11 59·12	—24 36 10·3	+0·16	—1·5
711	May	19·68206	418 Alemannia	17 53 27·39	—21 52 28·5	+0·05	—1·8
712	June	18·56760	418 Alemannia	17 27 39·61	—20 20 55·1	0·00	—2·0
713	Feb.	26·61953	429 Lotis	11 35 41·22	— 9 08 38·1	—0·03	—3·6
714	Mar.	19·55103	429 Lotis	11 18 53·80	— 6 49 14·8	—0·03	—4·0
715	July	16·67226	432 Pythia	21 54 50·93	—27 43 56·4	—0·02	—0·9
716	July	24·70888	432 Pythia	21 50 18·50	—29 19 48·6	+0·20	—0·9
717	Aug.	11·62160	432 Pythia	21 34 53·63	—32 26 53·8	+0·11	—0·3
718	Sep.	1·54828	432 Pythia	21 16 39·49	—34 13 34·9	+0·10	0·0
719	May	29·59716	438 Zeuxo	16 50 16·06	—27 28 02·6	0·00	—1·0
720	June	17·57264	438 Zeuxo	16 30 36·94	—27 52 23·0	+0·14	—1·0
721	Sep.	22·67020	442 Eichsfeldia	1 21 45·29	— 0 15 24·0	+0·11	—4·9
722	Oct.	14·59016	442 Eichsfeldia	1 02 43·74	— 2 52 12·7	+0·09	—4·5
723	July	21·69789	472 Roma	22 05 15·32	—16 09 00·4	+0·09	—2·7
724	Sep.	3·56157	472 Roma	21 32 30·86	—23 41 12·8	+0·11	—1·6
725	July	28·66830	494 Virtus	22 23 14·37	—21 06 07·7	+0·01	—1·9
726	June	18·53634	503 Evelyn	16 00 51·30	—20 46 20·5	+0·09	—2·0

TABLE I—*continued*

No.	1958 U.T.		Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
727	May	29·62328	512 Taurinensis	17 07 10·24	—13 37 43·0	+0·03	—3·0
728	July	8·49978	512 Taurinensis	16 25 15·63	—15 47 04·6	+0·09	—2·7
729	Sep.	9·66524	536 Merapi	0 45 27·50	—22 33 26·5	+0·07	—1·7
730	Sep.	25·60906	536 Merapi	0 33 20·41	—23 23 13·3	+0·05	—1·6
731	Aug.	12·65510	537 Pauly	22 31 41·48	—17 23 35·3	+0·08	—2·5
732	Aug.	19·64164	546 Herodias	23 05 31·29	—24 22 03·0	+0·03	—1·4
733	July	28·63762	554 Peraga	21 32 03·54	—12 55 37·3	+0·03	—3·1
734	Sep.	3·53860	554 Peraga	20 57 31·93	—14 47 55·5	+0·11	—2·9
735	May	20·61521	562 Salome	16 25 46·88	—19 49 37·3	+0·03	—2·1
736	June	18·53634	562 Salome	16 00 31·82	—20 25 24·8	+0·09	—2·1
737	Aug.	19·67643	575 Renate	23 36 13·24	— 7 14 49·4	+0·07	—3·9
738	Sep.	3·64542	575 Renate	23 21 06·74	— 6 39 49·9	+0·13	—4·0
739	Feb.	24·67142	584 Semiramis	12 36 07·28	—19 52 44·2	—0·02	—2·1
740	Mar.	26·59787	584 Semiramis	12 11 02·82	—18 47 50·8	+0·06	—2·3
741	May	29·57234	595 Polyxena	16 14 37·53	—40 17 46·8	0·00	+1·0
742	Sep.	18·67476	596 Scheila	1 28 54·78	—10 34 30·2	+0·08	—3·5
743	July	14·56844	598 Octavia	18 53 51·76	—27 32 49·7	+0·04	—1·0
744	Aug.	7·46520	598 Octavia	18 33 32·36	—29 17 57·7	—0·04	—0·7
745	July	16·60423	622 Esther	19 52 26·08	—14 06 43·7	+0·04	—3·0
746	Aug.	12·51037	622 Esther	19 27 14·41	—17 02 46·4	+0·03	—2·5
747	July	8·57521	628 Christine	18 51 52·91	—20 00 03·4	+0·01	—2·1
748	July	17·54982	628 Christine	18 43 30·95	—20 57 10·4	+0·03	—1·9
749	Feb.	25·68592	631 Philippina	12 05 22·36	—23 33 23·9	+0·11	—1·6
750	Mar.	20·57726	631 Philippina	11 49 58·28	—21 08 07·5	—0·01	—1·9
751	July	31·62459	660 Crescentia	22 16 19·87	— 4 15 15·0	—0·08	—4·3
752	Aug.	19·61026	660 Crescentia	22 03 15·10	— 7 41 09·5	+0·06	—3·9
753	Apr.	9·69754	693 Zerbinetta	15 15 42·31	—34 37 09·3	+0·11	+0·1
754	May	19·54398	693 Zerbinetta	14 38 46·82	—35 12 17·0	+0·04	+0·2
755	May	19·58086	712 Boliviana	15 40 00·68	—17 19 02·6	+0·02	—2·5
756	May	20·56253	712 Boliviana	15 39 07·64	—17 12 44·8	—0·03	—2·5
757	June	17·47490	712 Boliviana	15 17 46·27	—14 33 25·4	—0·02	—2·9
758	Aug.	11·71417	772 Tanete	23 46 15·93	—46 31 18·2	+0·14	+1·8
759	Sep.	3·59602	772 Tanete	23 25 22·44	—48 51 50·8	—0·04	+2·3
760	Feb.	26·56401	779 Nina	10 19 31·17	— 8 03 47·2	—0·04	—3·5
761	Mar.	17·50910	779 Nina	10 03 40·69	— 6 47 14·8	—0·02	—4·0
762	Oct.	7·62186	781 Kartvelia	1 58 05·47	—13 27 29·3	+0·01	—3·1
763	Oct.	14·63088	781 Kartvelia	1 53 23·32	—14 15 25·4	+0·11	—3·0
764	Mar.	17·62114	792 Metcalfia	12 55 47·49	—20 40 04·8	—0·04	—2·0
765	Apr.	17·52632	792 Metcalfia	12 30 24·70	—17 36 45·5	—0·02	—2·4
766	July	16·60423	794 Irenaea	19 56 21·38	—13 38 36·2	+0·03	—3·0
767	July	24·59668	794 Irenaea	19 50 37·36	—14 12 53·8	+0·09	—3·0
768	June	18·69023	818 Kapteynia	19 50 08·68	—33 53 40·2	+0·09	0·0
769	July	8·60600	818 Kapteynia	19 34 38·28	—36 04 37·4	+0·02	+0·4
770	July	24·55964	818 Kapteynia	19 19 53·93	—37 17 59·6	+0·05	+0·5
771	July	17·67440	866 Fatme	21 15 47·27	—23 50 03·1	+0·09	—1·6
772	Aug.	11·58760	866 Fatme	20 56 59·72	—26 08 18·4	+0·08	—1·2
773	Sep.	1·52181	866 Fatme	20 42 36·88	—27 16 27·7	+0·08	—1·0
774	Oct.	7·54654	891 Gunhild	0 09 59·58	—20 31 16·6	+0·01	—2·0
775	May	6·59725	912 Maritima	15 03 22·50	—24 22 32·8	+0·04	—1·4
776	May	20·53523	912 Maritima	14 49 51·18	—24 28 24·6	—0·01	—1·4
777	May	28·54180	912 Maritima	14 42 54·32	—24 26 52·0	+0·10	—1·5
778	Apr.	9·66748	932 Hooveria	15 02 32·99	—22 23 35·2	+0·03	—1·7
779	May	6·55910	932 Hooveria	14 36 18·35	—22 05 14·7	—0·03	—1·8
780	May	15·53334	932 Hooveria	14 27 01·19	—21 43 18·1	—0·01	—1·8
781	May	19·64580	936 Kunigunde	17 14 44·64	—23 37 30·0	+0·02	—1·5
782	July	8·54306	936 Kunigunde	16 36 46·20	—23 17 45·0	+0·21	—1·8
783	Aug.	12·65510	1018 Arnolda	22 34 36·48	—18 33 03·7	+0·08	—2·3
784	Sep.	1·60908	1018 Arnolda	22 16 18·75	—18 10 27·9	+0·15	—2·5
785	May	19·58086	1028 Lydina	15 41 45·21	—17 58 04·3	+0·01	—2·4
786	June	17·52269	1028 Lydina	15 22 01·67	—17 40 56·0	+0·12	—2·5
787	Aug.	11·67276	1032 Pafuri	22 50 25·49	—22 02 03·2	+0·09	—1·8
788	Mar.	26·64344	1036 Ganymed	13 08 02·77	—19 49 50·8	+0·08	—2·1
789	Aug.	19·67643	1061 Paeonia	23 37 39·59	— 6 27 47·3	+0·07	—4·0
790	Sep.	18·58448	1061 Paeonia	23 17 49·79	— 8 54 47·1	+0·08	—3·7
791	July	16·67226	1087 Arabis	21 51 48·50	—28 06 02·4	—0·01	—0·9

TABLE I—*continued*

No.	1958 U.T.		Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
792	July	24·70888	1087 Arabis	21 46 38·59	—28 44 58·3	+0·20	—1·0
793	Sep.	18·63192	1124 Stroobantia	0 22 27·39	— 2 20 52·8	+0·09	—4·6
794	July	16·56716	1128 Astrid	19 00 38·46	—23 57 18·4	+0·04	—1·5
795	May	28·69400	1204 Renzia	18 21 32·80	—27 09 25·3	+0·11	—1·1
796	June	18·60182	1204 Renzia	18 08 32·70	—27 51 29·9	+0·02	—0·9
797	July	17·51753	1204 Renzia	17 44 03·20	—27 49 00·8	+0·06	—0·9
798	May	27·65752	1248 Jugurtha	17 15 18·14	—21 49 41·1	+0·12	—1·9
799	July	2·54060	1248 Jugurtha	16 42 41·03	—22 55 23·0	+0·14	—1·7
800	Sep.	11·65649	1304 Arosa	0 55 18·60	—22 13 36·8	+0·03	—1·8
801	July	22·68756	1332 Marconia	21 02 27·75	—20 34 40·7	+0·20	—2·2
802	Aug.	12·56802	1332 Marconia	20 45 21·92	—21 35 38·4	+0·04	—1·9
803	Aug.	19·67643	1336 Zeelandia	23 33 36·65	— 7 41 54·1	+0·07	—3·9
804	Sep.	3·64542	1336 Zeelandia	23 23 27·85	— 9 03 13·4	+0·13	—3·7
805	Sep.	18·58448	1336 Zeelandia	23 11 46·50	—10 21 58·9	+0·09	—3·5
806	Sep.	11·62087	1356 Nyanza	0 23 51·59	— 9 55 27·6	—0·01	—3·5
807	Sep.	22·63028	1356 Nyanza	0 15 39·75	—10 45 20·9	+0·13	—3·5
808	Aug.	19·61026	1376 Michelle	22 05 31·58	— 9 20 13·3	+0·06	—3·6
809	Sep.	11·50854	1376 Michelle	21 51 33·90	—12 15 08·2	—0·03	—3·2
810	Oct.	7·65833	1461 1937 YL	2 28 35·82	— 8 37 09·9	+0·06	—3·7
811	Nov.	14·55744	1461 1937 YL	2 00 15·71	—10 02 42·0	—0·13	—3·6
812	Aug.	12·69546	1556 Wingolfia	23 12 41·50	—26 50 15·1	+0·13	—1·2
813	July	21·66244	1618 1948 NF	21 39 09·66	—16 39 50·5	+0·03	—2·5
814	Aug.	12·61616	1618 1948 NF	21 22 30·30	—18 25 21·4	+0·11	—2·4
815	July	17·62892	1958 OA	20 02 47·07	—43 24 41·1	+0·14	+1·4

TABLE II

No.	Comparison Stars	Dependences			
640	Yale *16* 8, 33, *17* 34	0·24012	0·39124	0·36864	S
641	Yale *16* 8457, 8463, 8468	0·56822	0·07064	0·36115	R
642	Yale *16* 8408, 8426, *11* 8275	0·23207	0·44515	0·32278	W
643	Yale *12* II 8406, 8408, 8420	0·53093	0·16700	0·30206	R
644	Yale *13* I 8312, 8329, *12* II 8337	0·27205	0·30746	0·42049	S
645	Cape *17* 11188, 11202, 11214	0·33336	0·16488	0·50176	R
646	Cape *17* 11055, 11064, 11092	0·31161	0·37297	0·31541	R
647	Cape *17* 10845, 10847, 10870	0·24299	0·37622	0·38079	R
648	Yale *12* I 8265, 8267, 8284	0·33568	0·15163	0·51269	W
649	Yale *12* II 9286, 9287, 9303	0·39852	0·31407	0·28741	R
650	Yale *13* I 9171, 9200, 9210	0·41747	0·31505	0·26748	R
651	Yale *13* II 13917, 13946, 13958	0·35263	0·27045	0·37692	R
652	Yale *13* I 9581, *12* II 9583, 9602	0·16642	0·35444	0·47914	S
653	Yale *13* I 9477, 9479, 9488	0·23371	0·17234	0·59395	W
654	Cape *18* 7635, 7638, 7662	0·40832	0·30123	0·29045	S
655	Cape *17* 7855, 7884, *18* 7448	0·16481	0·64525	0·18994	R
656	Yale *13* I 7055, 7097, *14* 11961	0·13963	0·24845	0·61192	S
657	Yale *14* 11582, 11600, 11607	0·34512	0·40598	0·24890	W
658	Yale *17* 4437, 4449, 4457	0·22242	0·38603	0·39155	S
659	Yale *17* 4342, 4343, 4363	0·38374	0·24246	0·37379	S
660	Yale *12* I 5243, 5258, 5261	0·31223	0·32442	0·36335	R
661	Yale *12* I 5097, 5104, 5107	0·28681	0·42238	0·29080	R
662	Yale *11* 7040, 7059, 7071	0·55778	0·24472	0·19750	S
663	Yale *11* 6901, 6915, 6924	0·27456	0·18178	0·54367	W
664	Yale *14* 10395, 10405, 10420	0·31826	0·56394	0·11779	S
665	Yale *14* 10265, 10293, *13* I 5956	0·51879	0·21466	0·26655	R
666	Yale *11* 43, *16* 48, 59	0·44419	0·17220	0·38361	S
667	Yale *11* 10, 18, 21	0·31620	0·28296	0·40084	R
668	Yale *16* 8242, 8254, 8258	0·72040	—0·67502	0·95462	S
669	Yale *11* 8031, 8042, 8045	0·25523	0·40161	0·34316	R
670	Yale *11* 5072, 5085, *12* I 5383	0·43054	0·25701	0·31245	R
671	Yale *11* 4922, 4944, 4947	0·38076	0·16305	0·45619	S

TABLE II—*continued*

No.	Comparison Stars	Dependences			
672	Yale *14* 10726, 10727, 10736	0·38934	0·21857	0·39209	R
673	Yale *13* I 6129, 6144, 6145	0·49422	0·17497	0·33082	W
674	Yale *13* I 6066, 6089, 6092	0·25961	0·27098	0·46942	S
675	Yale *13* II 13997, 14011, 14030	0·26633	0·27868	0·45500	R
676	Yale *16* 8231, 8235, 8239	0·33855	0·38686	0·27458	S
677	Yale *11* 7992, 8000, 8016	0·26647	0·34048	0·39305	R
678	Yale *12* I 7563, 7576, 7578	0·37982	0·43369	0·18649	S
679	Yale *12* I 7525, 7540, 7543	0·16031	0·36362	0·47607	W
680	Yale *12* I 7444, 7462, 7473	0·44750	0·29159	0·26092	W
681	Yale *14* 14786, 14804, 14808	0·38928	0·16625	0·44447	W
682	Yale *13* I 7625, 7631, 7658	0·24494	0·31620	0·43886	R
683	Yale *13* I 7391, 7448, *14* 12371	0·24901	0·36841	0·38258	R
684	Yale *12* II 6172, 6174, 6181	0·28300	0·51438	0·20262	S
685	Yale *12* I 5402, 5412, 5413	0·37291	0·41507	0·21202	R
686	Yale *16* 8346, 8347, 8359	0·38594	0·21576	0·39830	R
687	Yale *16* 8270, 8292, 8297	0·50371	0·32093	0·17536	S
688	Yale *11* 68, 71, 76	0·34911	0·41028	0·24061	R
689	Yale *11* 45, 46, 58	0·34927	0·30095	0·34978	W
690	Yale *13* I 9061, 9083, *14* 14619	0·39866	0·36821	0·23313	W
691	Yale *16* 8238, 8239, 8250	0·22722	0·19479	0·57799	S
692	Yale *11* 7984, 7992, 8000	0·66380	0·28516	0·05104	R
693	Yale *11* 185, 202, *16* 205	0·44354	0·32141	0·23505	S
694	Yale *13* I 5960, 5975, *14* 10349	0·38749	0·45865	0·15386	R
695	Yale *13* I 5890, 5910, 5912	0·28380	0·54490	0·17130	W
696	Cord. D 9334, 9342, 9407	0·57579	0·10439	0·31982	R
697	Cord. D 9175, 9181, 9245	0·20978	0·55304	0·23718	W
698	Yale *13* I 5850, 5852, 5868	0·28788	0·24374	0·46837	S
699	Yale *12* II 5691, 5694, 5708	0·66125	0·17236	0·16638	R
700	Yale *12* I 8400, 8404, 8414	0·24961	0·39069	0·35970	R
701	Yale *12* I 8284, *12* II 9417, 9443	0·40534	0·27126	0·32340	S
702	Cape *17* 10504, 10519, 10547	0·25971	0·26130	0·47899	R
703	Cape *17* 10362, 10404, 10408	0·31400	0·40552	0·28049	W
704	Cape *17* 10187, 10197, 10231	0·25716	0·50890	0·23394	W
705	Yale *11* 8281, 8282, 8305	0·27848	0·50319	0·21833	S
706	Yale *12* I 8652, 8667, 8672	0·18362	0·29516	0·52121	W
707	Yale *13* II 14283, 14313, 14324	0·28057	0·24779	0·47163	S
708	Yale *13* II 14253, 14265, 14275	0·18256	0·29045	0·52699	W
709	Yale *13* I 9870, 9881, 9884	0·48039	0·06408	0·45553	R
710	Yale *14* 15586, 15603, 15623	0·40402	0·17588	0·42010	W
711	Yale *13* I 7331, 7353, 7369	0·24953	0·26305	0·48743	R
712	Yale *13* I 7157, 7176, 7178	0·38567	0·29740	0·31692	R
713	Yale *16* 4330, 4334, 4345	0·44903	0·28959	0·26138	S
714	Yale *16* 4257, 4270, 4278	0·20571	0·54619	0·24810	S
715	Yale *13* II 14313, 14324, 14339	0·47201	0·25032	0·27766	S
716	Yale *13* II 14265, 14285, 14298	0·25083	0·19699	0·55217	W
717	Cape *17* 11777, 11778, 11802	0·32502	0·45869	0·21629	W
718	Cape *17* 11624, 11631, 11665	0·35833	0·32476	0·31691	W
719	Yale *13* II 10577, 10589, 10609	0·06985	0·28358	0·64657	S
720	Yale *13* II 10340, 10368, 10377	0·44779	0·37775	0·17445	R
721	Yale *21* 251, 265, 267	0·21681	0·54829	0·23489	W
722	Yale *17* 237, 238, 252	0·58596	0·16652	0·24752	W
723	Yale *12* I 8267, 8284, 8292	0·25864	0·30436	0·43700	W
724	Yale *14* 14832, 14836, 14848	0·56429	0·33361	0·10210	W
725	Yale *13* I 9494, 9524, *14* 15225	0·31911	0·33252	0·34837	R
726	Yale *13* I 6619, 6631, 6634	0·39438	0·50312	0·10250	R
727	Yale *11* 5853, 5863, 5874	0·14677	0·38092	0·47232	S
728	Yale *12* I 5937, 5947, 5951	0·26541	0·36739	0·36720	R
729	Yale *14* 356, 364, 392	0·38196	0·19683	0·42121	R
730	Yale *14* 227, 258, 276	0·29552	0·26488	0·43960	W
731	Yale *12* I 8404, 8414, *12* II 9554	0·42441	0·23559	0·34000	W
732	Yale *14* 15543, 15566, 15568	0·60211	0·23603	0·16186	R
733	Yale *11* 7643, 7648, 7653	0·15235	0·41222	0·43544	R
734	Yale *12* I 7899, 7901, 7918	0·24426	0·35837	0·39737	W
735	Yale *12* II 6768, 6770, 6786	0·52817	0·01478	0·45705	R
736	Yale *13* I 6619, 6631, 6634	0·57635	0·13615	0·28750	R
737	Yale *16* 8350, 8368, 8370	0·39663	0·20483	0·39854	R

TABLE II—*continued*

No.	Comparison Stars	Dependences			
738	Yale *16* 8296, 8305, 8316	0·41331	0·34314	0·24355	W
739	Yale *12* II 5456, 5465, 5467	0·13073	0·48659	0·38268	S
740	Yale *12* II 5293, 5296, 5321	0·25549	0·26234	0·48217	W
741	Cord. D 11334, 11344, 11380	0·52244	0·04766	0·42989	S
742	Yale *11* 321, 329, 334	0·38039	0·13488	0·48473	S
743	Yale *13* II 12339, 12356, 12394	0·21922	0·32715	0·45364	S
744	Yale *13* II 12044, 12088, 12094	0·23860	0·35988	0·40152	W
745	Yale *12* I 7477, 7490, 7492	0·23147	0·44952	0·31902	S
746	Yale *12* I 7299, 7300, 7323	0·32149	0·29386	0·38464	W
747	Yale *13* I 7969, 7981, 7996	0·44575	0·31793	0·23632	R
748	Yale *13* I 7876, 7882, 7899	0·37803	0·23722	0·38474	S
749	Yale *14* 9183, 9199, 9210	0·24305	0·34626	0·41069	S
750	Yale *13* I 5156, 5175, 5185	0·34250	0·21609	0·44141	S
751	Yale *17* 7759, 7760, 7774	0·23225	0·35414	0·41361	R
752	Yale *16* 7908, 7920, 7932	0·38834	0·31801	0·29366	R
753	Cape *17* 7905, 7933, 7944	0·36022	0·25132	0·38846	S
754	Cape *18* 7112, 7144, *17* 7592	0·37464	0·20495	0·42041	R
755	Yale *12* I 5741, 5752, 5753	0·32963	0·49776	0·17261	R
756	Yale *12* I 5741, 5749, 5753	0·55302	0·32002	0·12695	R
757	Yale *12* I 5624, 5628, 5644	0·34373	0·30307	0·35320	W
758	Cape Ft. 20469, 20472, 20492	0·41033	0·39845	0·19122	W
759	Cape Ft. 20331, 20334, 20362	0·32423	0·38093	0·29484	W
760	Yale *16* 3967, 3974, 3979	0·29553	0·42374	0·28073	S
761	Yale *16* 3890, 3907, *17* 3920	0·26107	0·22278	0·51615	S
762	Yale *11* 452, *12* I 514, 522	0·43415	0·36178	0·20407	S
763	Yale *12* I 480, 492, 503	0·10101	0·34053	0·55845	W
764	Yale *12* II 5574, 5594, *13* I 5586	0·36625	0·13386	0·49989	S
765	Yale *12* I 4809, 4814, 4826	0·44867	0·23721	0·31412	W
766	Yale *12* I 7490, 7518, *11* 7038	0·30133	0·35461	0·34406	S
767	Yale *12* I 7460, 7471, 7487	0·13249	0·43324	0·43427	W
768	Cape *17* 10822, 10834, 10845	0·35819	0·44248	0·19933	R
769	Cape *18* 10168, 10178, 10180	0·35150	0·38357	0·26494	R
770	Cape *18* 10027, 10064, 10068	0·41647	0·34321	0·24032	W
771	Yale *14* 14689, 14691, 14715	0·24478	0·44488	0·31034	S
772	Yale *14* 14517, 14531, 14539	0·24480	0·23029	0·52491	W
773	Yale *13* II 13649, 13661, 13679	0·34095	0·33091	0·32814	W
774	Yale *13* I 15, 32, 53	0·21622	0·43197	0·35181	S
775	Yale *14* 10775, 10795, 10802	0·22461	0·36766	0·40773	S
776	Yale *14* 10656, 10673, 10687	0·29872	0·40436	0·29692	R
777	Yale *14* 10585, 10597, 10628	0·37706	0·21289	0·41005	S
778	Yale *14* 10771, 10787, *13* I 6249	0·24396	0·27263	0·48341	S
779	Yale *13* I 6089, 6093, 6108	0·36237	0·22336	0·41427	S
780	Yale *13* I 6045, 6053, 6062	0·46281	0·31681	0·22038	W
781	Yale *14* 11930, 11952, 11958	0·52172	0·27263	0·20565	R
782	Yale *14* 11545, 11549, 11558	0·38523	0·26596	0·34880	R
783	Yale *12* II 9554, 9565, 9578	0·32769	0·41005	0·26226	W
784	Yale *12* II 9468, 9481, 9485	0·46155	0·40715	0·13130	W
785	Yale *12* II 6499, 6521, *12* I 5752	0·15363	0·29539	0·55098	R
786	Yale *12* I 5652, 5658, 5668	0·53350	0·26833	0·19817	R
787	Yale *14* 15409, 15425, *13* I 9652	0·42177	0·31054	0·26769	W
788	Yale *12* II 5633, 5655, 5661	0·37841	0·33153	0·29006	W
789	Yale *16* 8359, 8370, 8373	0·30640	0·55055	0·14305	R
790	Yale *16* 8270, 8283, 8302	0·30849	0·27516	0·41635	S
791	Yale *13* II 14279, 14283, 14313	0·17819	0·23289	0·58892	S
792	Yale *13* II 14253, 14265, 14275	0·42857	0·34895	0·22248	W
793	Yale *17* 72, 88, 98	0·21257	0·67423	0·11320	S
794	Yale *14* 13230, 13231, 13256	0·29939	0·31564	0·38498	S
795	Yale *13* II 11912, 11935, *14* 12750	0·09455	0·43627	0·46918	S
796	Yale *13* II 11719, 11721, 11764	0·29189	0·37166	0·33645	R
797	Yale *13* II 11279, 11283, 11344	0·38005	0·43927	0·18068	S
798	Yale *13* I 7055, 7097, *14* 11961	0·53909	0·36333	0·09757	S
799	Yale *14* 11586, 11600, 11602	0·41338	0·27701	0·30961	W
800	Yale *14* 449, 478, *13* I 246	0·40671	0·24434	0·34895	R
801	Yale *13* I 9034, 9044, 9055	0·28231	0·49747	0·22023	W
802	Yale *14* 14415, 14453, *13* I 8925	0·44652	0·28027	0·27321	W
803	Yale *16* 8349, 8350, 8368	0·37791	0·45410	0·16799	R

TABLE II—*continued*

No.	Comparison Stars	Dependences			
804	Yale *16* 8302, 8319, *11* 8189	0·39364	0·34603	0·26033	W
805	Yale *11* 8126, 8133, 8151	0·16334	0·48936	0·34730	S
806	Yale *11* 63, 71, 85	0·25875	0·26259	0·47866	R
807	Yale *11* 35, 48, 57	0·28050	0·54073	0·17877	W
808	Yale *16* 7923, 7931, 7944	0·25253	0·46774	0·27973	R
809	Yale *11* 7747, 7764, 7769	0·17614	0·56761	0·25625	R
810	Yale *16* 549, 559, 565	0·31166	0·35878	0·32956	S
811	Yale *11* 447, 463, 471	0·31396	0·40905	0·27699	R
812	Yale *13* II 14831, 14861, *14* 15616	0·34896	0·34135	0·30969	W
813	Yale *12* I 8144, 8156, 8167	0·31487	0·48487	0·20026	W
814	Yale *12* II 9162, 9179, 9186	0·40707	0·30124	0·29168	W
815	Cord. D 14623, 14646, 14676	0·40649	0·53212	0·06140	S

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Ronchi Test Charts for Parabolic Mirrors*

A. A. SHERWOOD

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ABSTRACT—This paper deals with the preparation of a series of test charts giving the shape of the Ronchi shadow band patterns for testing parabolic mirrors for a wide range of aperture ratios. The method of application of the results for specific cases is discussed.

Introduction

The Ronchi (1925) test is well known and requires only simple apparatus to achieve a high degree of precision. Using a very low frequency grating, of the order of 100 lines per inch, analysis by geometrical optics is adequate. In a previous paper (Sherwood (1958)) the general case for a concave mirror of any given figure has been solved in this manner. Since the parabolic mirror is needed more often than other forms, it would be of practical value if the results of the analysis were presented in the form of a comprehensive chart, so as to avoid the labour of individual computations for each specific case. In order to allow for all the variables, a three-dimensional graph would be required; since this is impracticable, three charts have been computed, which may be regarded as sections of this space graph. It is thought that these will cover most requirements. In order to make this paper complete in itself, the analysis of the parabolic case will be derived from first principles instead of making use of the general solution given in my previous paper.

Analysis

Fig. 1 shows diagrammatically the layout for the test, and Fig. 2 a section on plane OBS at angle θ to the horizontal. The grating line is considered to be very thin, consequently the geometric shadow band will also be thin. The idealized case considered will therefore represent the centre lines of the actual grating line and shadow band. The slit is shown on the optical axis; in practice a small lateral displacement is necessary in order to view the shadow bands unless a beam splitter is used. The latter is only necessary when the focal length is so small that lateral displacement causes noticeable lack of symmetry in the shadow pattern. Any point B on the shadow band and its corresponding point A on the grating line must be such that a ray from the slit S will pass through A after reflection in the mirror at B. BC is the normal to the surface at B, and β is the angle of incidence of the ray, also equal to the angle of reflection. Other symbols used are defined in Figs. 1 and 2.

From the geometry of the figures

(1) $\tan(\varphi+\beta)=r/(R-s)$,

(2) $\tan(\varphi-\beta)=(r-H)/(R-s-d)$,

(3) $s=r^2/2R$ (equation of parabola),

and (4) $\tan\varphi=ds/dr=r/R$.

Eliminating β,φ from equations (1), (2) and (4) gives

$$\frac{rs}{R^2-Rs+r^2}=\frac{rs+rd-RH}{Rs+Rd+Hr-r^2-R^2}$$

Substituting $s=r^2/2R$ and making H the subject of the equation

(5) $$H=r\left(\frac{2R^3d+2R^2r^2+r^4}{2R^4+R^2r^2+r^4}\right)$$

Equation (5) is exact in terms of the data. A little calculation shows that terms dr^2/R^3 and r^4/R^4 are too small to show on the charts. Therefore we may write

(6) $H=r(d/R+r^2/R^2)$.

Now from Fig. 1, $H=H_0\sec\theta$.

Therefore

$$H_0\sec\theta=r(d/R+r^2/R^2).$$

This equation transforms easily to Cartesian coordinates, giving, after substitution of $R=2F$

(7) $y^2=4F^2H_0x^{-1}-2Fd-x^2$.

Equation (7) is the form used for computation. One other effect has been neglected; that is the shadow bands in the analysis exist on the surface of a paraboloid of revolution, while the charts are drawn on a flat surface. This effect has been shown (Sherwood (1958)) to be insignificant for the aperture ratios covered by the charts.

* The publication of this paper was assisted by a grant from the Donovan Astronomical Trust, Sydney.

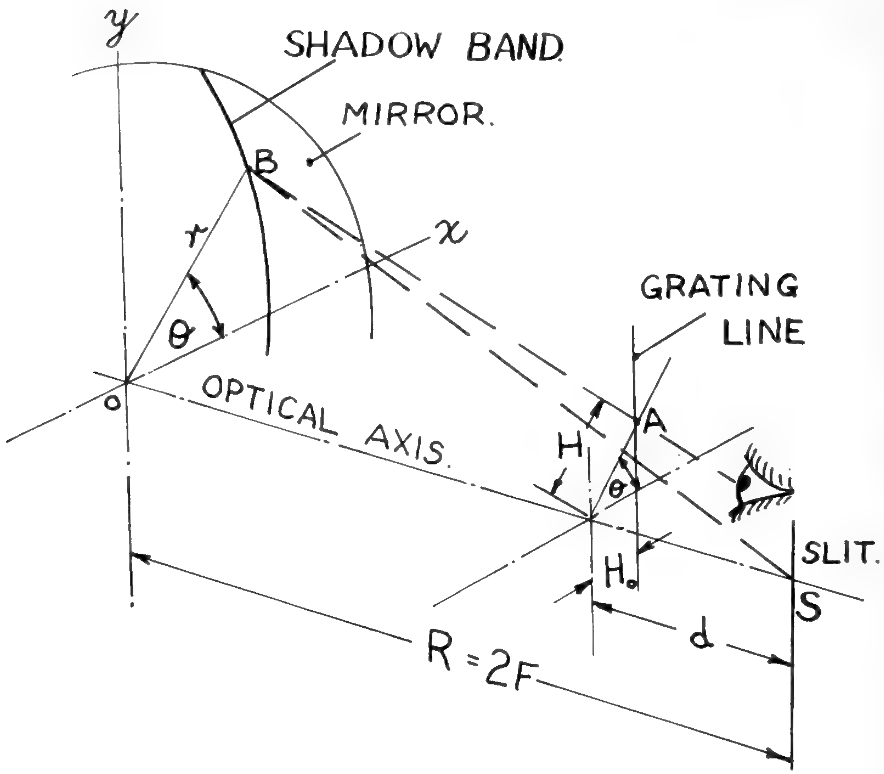

FIG. 1

Computation

For convenience in computation, the following arbitrary values were chosen

Focal length, $F=100$ in.
$H_0=0\cdot01$ in., $0\cdot02$ in , $0\cdot03$ in., . . . etc.

corresponding to a grating of 100 lines per inch.

Formula (7) then becomes

$$y^2=400Nx^{-1}-200d-x^2$$

where N takes integral values for successive shadow bands. Actually some fractional values of N were also taken for reasons which will be obvious at a later stage.

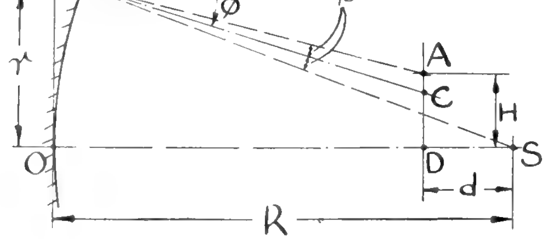

FIG. 2

Variation in d, corresponding to a shift of the grating along the optical axis, requires a third dimension. The only practical solution is therefore to produce a series of charts, each based on a selected value of d. Three values were chosen, namely

$$d=1\cdot0 \text{ in.}, \ d=0\cdot5 \text{ in.}, \ d=0\cdot2 \text{ in.}$$

The formulae then become

$y^2=400Nx^{-1}-200-x^2$ for chart No. 1,
$y^2=400Nx^{-1}-100-x^2$ for chart No. 2,
$y^2=400Nx^{-1}-40-x^2$ for chart No. 3.

Each chart has been plotted for one quadrant of the mirror only, since the normal Ronchi patterns are symmetrical about the vertical and horizontal axes. The series of circular arcs centred on the origin and numbered from 4 to 20 represent the outer edges of mirrors of various aperture ratios. Values of N are given along the x-axis and repeated along the outer curved boundary of the charts.

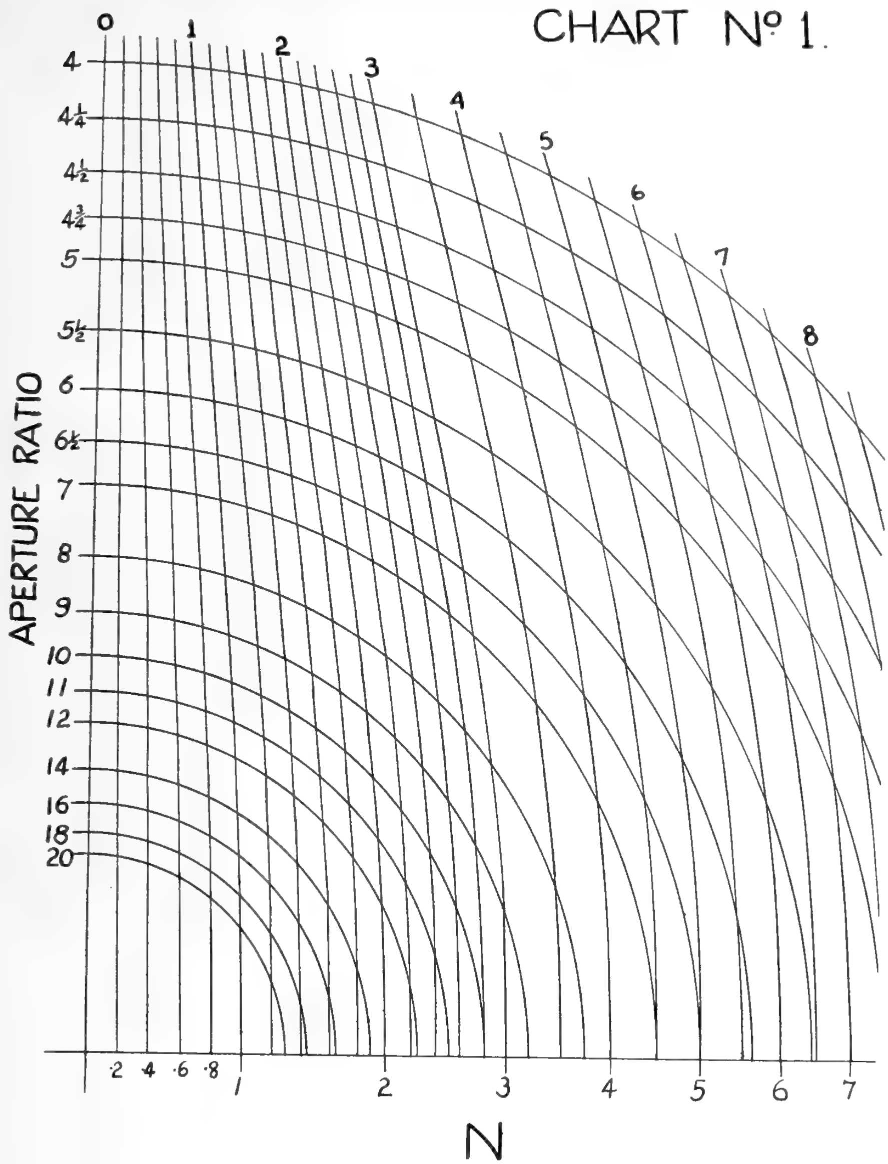

CHART 1

Use of the Charts

In order to apply the charts to a given mirror, the focal length, F, and the number of lines per inch, n, of the grating to be used must be known. A number, p, may be defined by

$$p=10{,}000/(Fn).$$

For a symmetrical pattern, there are two alternatives :—

(a) Select the lines on the chart numbered 0 (i.e. the y-axis) $N=p$, $N=2p$, $N=3p$, . . . etc. to give a pattern with a central dark band ;

(b) Select the lines on the chart numbered $N=p/2$, $N=3p/2$, $N=5p/2$, . . . etc. to give a pattern with a central light band.

The above procedure is applicable to any one of the charts ; the one finally chosen should be that giving the most convenient band positions. This can best be demonstrated by an example.

Example

It is required to test a mirror of 50 in. focal length and aperture ratio $f/8$ with a grating of 100 lines per inch.

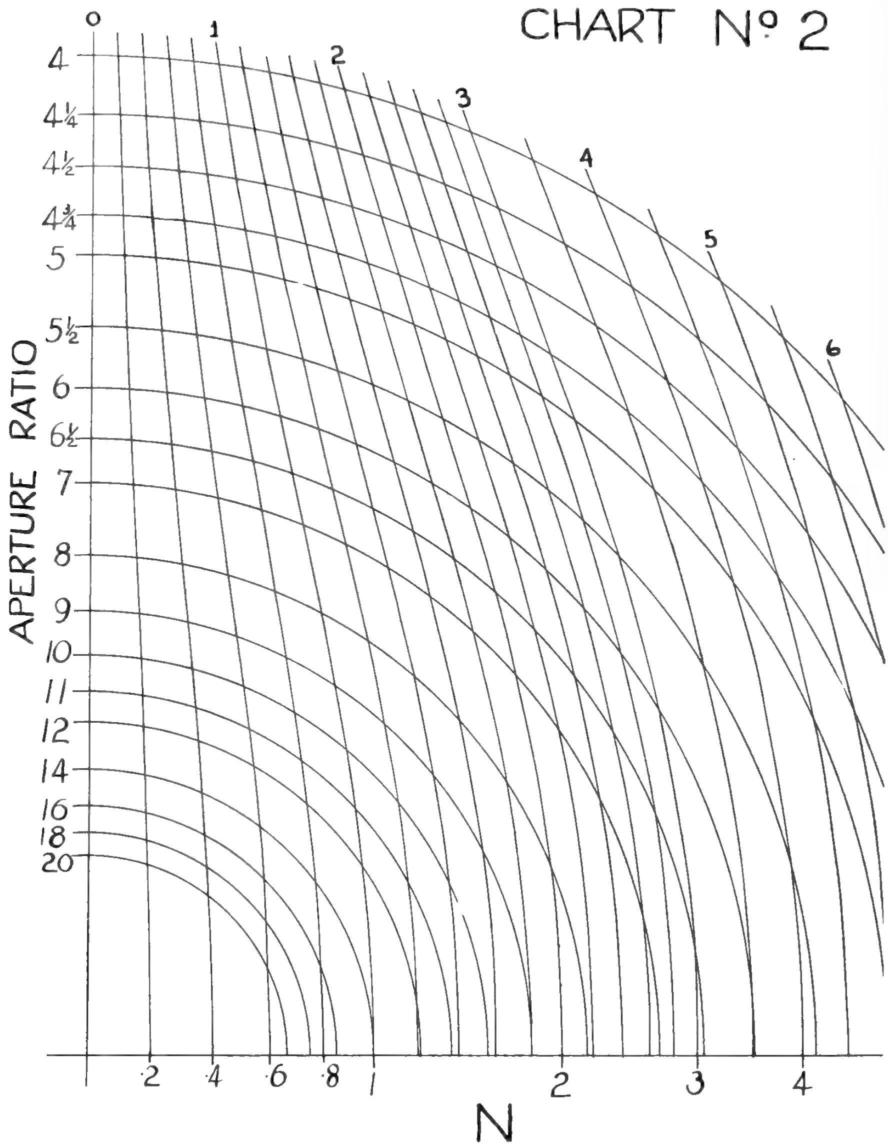

CHART 2

Therefore $F=50$ in., $n=100$, and $p=2$.

Applying this to chart No. 3, we find band No. 2 outside the $f/8$ aperture ratio circle, i.e. off the mirror. If the case for the central light band is considered, line No. 1 is just within the $f/8$ circle, thus giving no check on the central region of the mirror. Chart No. 1 will give a satisfactory pattern in this case, four bands (i.e. Nos. 1 and 3 on each side) appearing within the $f/8$ circle with a central light band, and three bands (i.e. central and No. 2 on each side) with a central dark band. If the grating is placed in the correct position on the optical axis, and if the mirror is of accurate parabolic figure, these band patterns will agree with the centre lines of the actual shadow bands obtained in the test. It should be noted that it is not necessary to measure the position of the grating. It is only necessary, while observing the band pattern, to move the grating until the appropriate band spacing appears. This is very fortunate, since it obviates the necessity of placing the slit precisely at the centre of curvature, as small errors in the location of the

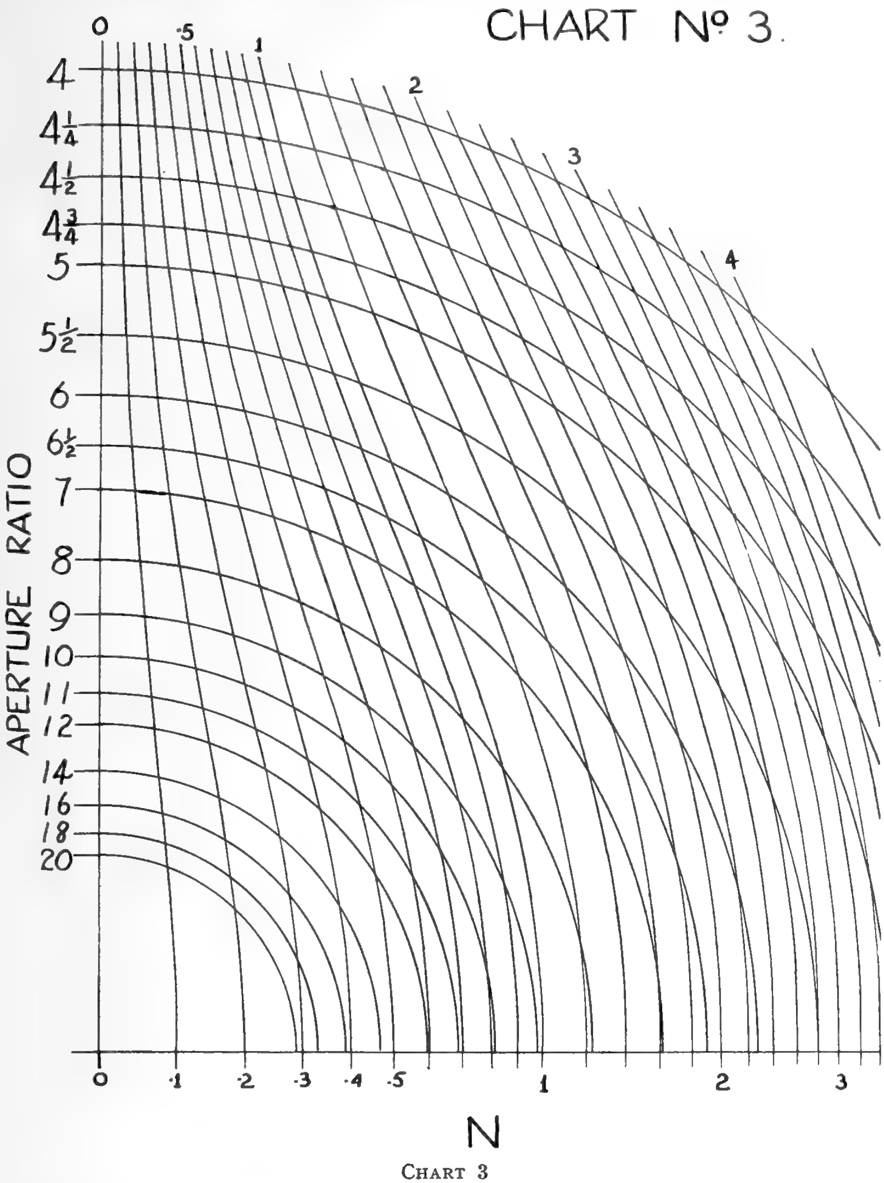

CHART 3

slit can in practice be allowed for by adjustment in the position of the grating. While, in this paper, it is not proposed to discuss at length the order of accuracy, an indication of the sensitivity in this example may be obtained by noting the curvature of the bands; straight bands would indicate a spherical surface, and the difference between the sphere and the parabola of best fit in this case is well under a quarter of a wavelength. In the example given, N works out to an integer; in most cases this will not be so. The intervals chosen for plotting the curves are sufficiently close for linear interpolation when non-integral values of N are involved.

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Occultations observed at Sydney Observatory during 1958

K. P. Sims

(*Received March 19, 1959*)

The following observations of occultations were made at Sydney Observatory with the 11½-inch telescope. A tapping key was used to record the times on a chronograph. The reduction elements were computed by the method given in the Occultation Supplement to the *Nautical Almanac* for 1938 and the reduction completed by the method given there. The necessary data were taken from the *Nautical Almanac* for 1958, the Moon's right ascension and declination (hourly table) and parallax (semi-diurnal table) being interpolated therefrom. No correction was applied to the observed times for personal effect but a correction of —0·00152 hour was applied before entering the ephemeris of the Moon. This corresponds to a correction of —3″·0 to the Moon's mean longitude.

Table I gives the observational material. The serial numbers follow on from those of the previous report (Sims, 1958). The observers were H. W. Wood (W), W. H. Robertson (R)

Table I

Serial No.	N.Z.C. No.	Mag.	Date	U.T.	Observer
371	895	5·9	Feb. 28	11 29 56·8	R
372	1116	7·4	Mar. 29	8 51 53·6	W
373	1257	7·5	Mar. 30	10 03 52·4	R
374	654	6·0	Apr. 22	8 26 41·5	R
375	1577	7·1	Apr. 29	11 08 41·6	W
376	1911	7·1	May 29	9 37 58·1	W
377	2092	7·2	July 24	9 51 08·4	R
378	2531	7·3	July 27	10 42 58·1	W
379	2210	6·8	Aug. 21	12 32 19·6	R
380	2555	7·5	Oct. 17	11 10 43·4	S
381	2883	5·5	Oct. 19	12 38 13·3	W
382	30	7·0	Nov. 21	10 37 42·5	R
383	98	6·2	Dec. 19	11 00 05·7	S

Table II

Serial No.	Lunation	p	q	p^2	pq	q^2	$\Delta\sigma$	$p\Delta\sigma$	$q\Delta\sigma$	Coefficient of $\Delta\alpha$	Coefficient of $\Delta\delta$
371	435	+ 76	—65	58	—49	42	—0·7	—0·5	+0·5	+10·4	—0·68
372	436	+ 57	—82	32	—47	68	—1·5	—0·9	+1·2	+ 6·2	—0·90
373	436	+100	0	100	0	0	+0·2	+0·2	0·0	+14·1	—0·22
374	437	+ 86	—52	73	—44	27	0·0	0·0	0·0	+12·7	—0·44
375	437	+ 99	+12	99	+12	1	—1·6	—1·6	—0·2	+14·7	—0·20
376	438	+ 99	—16	97	—16	3	—0·5	—0·5	+0·1	+13·2	—0·44
377	440	+ 94	—34	88	—32	12	—1·2	—1·1	+0·4	+12·2	—0·54
378	440	+ 81	—59	65	—48	35	—0·9	—0·7	+0·5	+11·5	—0·59
379	441	+ 12	+99	1	+12	98	—2·1	—0·3	—2·1	+ 4·1	+0·96
380	443	+ 98	+20	96	+20	4	—2·2	—2·2	—0·4	+13·9	+0·22
381	443	+ 91	—42	82	—38	18	—1·7	—1·5	+0·7	+13·9	—0·26
382	444	+ 43	+90	18	+39	82	—2·6	—1·1	—2·3	+ 1·7	+0·99
383	445	+ 34	+94	12	+22	88	—1·1	—0·4	—1·0	+ 0·5	+1·00

and K. P. Sims (S). In all cases the phase observed was disappearance at the dark limb. Table II gives the results of the reductions, which were carried out in duplicate. The N.Z.C. numbers given are those of the *Catalog of 3539 Zodiacal Stars for the Equinox* **1950·0** (Robertson, 1940), as recorded in the *Nautical Almanac*.

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Sydney Observatory
Sydney

Journal and Proceedings, Royal Society of New South Wales, Vol. 93, pp. 27–38, 1959

Petrology in Relation to Road Materials
Part I: The Rock Types used to produce "Aggregate"

E. J. Minty

(*Received March* 3, 1959)

Abstract—During the past six years the Dept. of Main Roads, N.S.W., has received for testing over 2,000 rock samples for possible use as aggregates with bitumen or cement. From the records of the physical tests conducted on these samples details were extracted and tabulated with the object of correlating the geological features of the rocks with the properties which are of interest to the engineer.

The more basic requisites of shape, resistance to abrasion and soundness of aggregate are briefly discussed, whilst the cause of poor adhesion between aggregate and bitumen, where such failure occurs, is shown to be due to the presence of hydrated minerals, generally as part of the rock but sometimes only as a surface coating. A good correlation coefficient based on calculations for 29 aggregates supports this conclusion.

The recent problem of *polishing* of aggregate, a phenomenon which causes slippery pavements to develop, is discussed with a view to laying the foundation for more detailed study when more data on frictional coefficients are available.

Reference is also made to the work of Jagus and Bawa (1957) on alkali reaction in concrete.

The prime object of this paper is to illustrate the value of petrological study in assessing the potential of aggregate resources, and to bridge the gap between engineering and geological concepts related to concrete.

Introduction

Whilst a substantial amount of Australian road pavements are still built or composed of natural mixtures of gravel, sand and clay, nevertheless all "sealed" roads are topped with rock in the form of "aggregate", or incorporate it in a mixture with bitumen. In addition crushed rocks have a very important role in providing concrete aggregate, and to some extent as road base material. Lastly, but not least, a variety of fissile and/or well jointed rocks, irrespective of hardness, are finding increasing use in place of sandy loams and natural "road gravels" (gravel-sand-clay mixtures).

In view of the increasing use that is being made of rock for road building some comments on the petrological characteristics of materials in use may be timely.

In this paper it is proposed to deal principally with matters of petrographic interest and only with a cross-section of those rocks which find use as "aggregate" with either bitumen or cement. It will be necessary to outline first the methods of test to illustrate the useful properties; but sampling, preparation and grading procedures will be omitted.

Methods of testing Aggregate used by Road building Authorities in Australia

Tests for resistance to abrasion—The principal tests of this kind are the Los Angeles test and the British crushing test.

The Los Angeles test is carried out by subjecting a known quantity of material to ball milling and then recording the amount of fines (powder) produced by abrasion. More than 35% is generally regarded as unsatisfactory.

The British crushing test result is given as a percentage breakdown after crushing a soaked specimen of aggregate.

Further details can be found in the relevant British and American Standards for Testing Materials.

Tests for shape—Marked elongation or flakiness are generally considered to be undesirable and aggregates are measured with slot gauges or between pegs to obtain a flakiness index. Flakiness indices over 30 are regarded as undesirable.

Tests for adhesion to bitumen—In Victoria and New South Wales a test is employed in which pieces of the aggregate are placed on a metal tray which contains bitumen. The aggregate is given every opportunity to adhere, and the plates are then placed in a thermostatically controlled water-bath. Following this the pieces of aggregate are plucked from the plate, and a count made to determine how many come away without a coating of bitumen.

This test is a good index of "stripping". The latter is a distressing phenomenon observed sometimes on newly constructed roads, particularly after rain, and characterized by a rapid loss of aggregate from the surface. In severe cases the bitumen is exposed and is likely to be torn from the road by adhesion to motor vehicle tyres.

Tests for polishing—When aggregate becomes highly polished motor vehicles are likely to skid. At present there is no generally accepted test, but in England and America field tests to determine the coefficient of friction of road surfaces have been made. Also, certain laboratory investigations have been made here and overseas, and are being continued.

In New South Wales the problem is fortunately at present restricted to a few intensely trafficked roads.

Tests for soundness and resistance to weathering—Most authorities use a test for soundness employing sodium sulphate. In addition the N.S.W. Department of Main Roads employs micropetrological studies to give an indication of the probable behaviour of the rock ; tests on wet aggregate are also made.

Tests for alkali reaction in concrete—Both the British standard mortar test and the compressive strength of the concrete are a guide to alkali reaction, but no truly specific tests are in general use.

Petrology in relation to individual Tests

The following sections give a discussion of test results in the light of petrological knowledge.

Petrology and resistance to abrasion—The results for aggregates set out in Table I indicate that a group of quartzites gave a Los Angeles test value similar to that for limestones. This fact indicates that the test does not differentiate between hard and soft rocks. However, the test does serve as an index of *toughness*, in the geological sense.

TABLE I

Relationship between Rock Type and Results of Abrasion Tests

Sample Number	Rock Type	Los Angeles Test % Loss	Sample Number	Rock Type	Los Angeles Test % Loss
A 265	Granite, crushed	42	A 687	Quartz	44
A 289	Granite	36	A 986	,,	24
A 320	,,	16			
A 204	Granodiorite	30	A 620	Limestone	20
A 673	Crushed Bi. Granite	36	A 640	,,	26
A 674	,, ,, ,,	45	A 873	,,	24
A1141	Granite	22	A 532	,,	18
A 496	Or. Porphyry	22	A 554	Nodular calcareous rock	31
A 55	Dolerite	23	A 268	,, ,, ,,	33
A 600	Q. Or. Porphyry	14			
A 915	Microdiorite	11	A 709	Indurated siltstone	40
A 932	Dolerite	21	A 828	Silicified mudstone	18
A 962	Quartz porphyry	15	A 915	Indurated shale	14
A 186	Dolerite	25	A 252	,, ,,	17
			A 238	,, ,,	16
A 511	Basalt	17	A 995	Slate	17
A 217	,,	10	A1058	Silicified mudstone	13
A 597	Rhyolite	15			
A 684	Basalt	15	A 321	Quartzite	19
A 711	Basaltic dolerite	19	A 443	,,	21
A 714	Semi-vesicular basalt	13	A 994	,,	18
A 827	Basalt	11	A 713	Silicified sandstone	22
A 915	,,	10	A 763	Quartzite	23
A 957	,,	12	A 791	,,	25
A 994	,,	11	A 596	,,	12
A 995	,,	17	A1058	,,	16
A 995	,,	13			
A1013	,,	14	A 569	Slag	18
A1017	,,	16			
A1018	,,	20	A 296	River gravel	26
A1058	,,	13	A 280	,, ,,	35
A1175	,,	21	A 299	,, ,,	30
			A 329	,, ,, crushed	24
A1301	Volcanic breccia	13	A 353	,, ,,	22
A 297	Tuff	18	A 349	,, ,,	14

TABLE I—*continued*

Sample Number	Rock Type	Los Angeles Test % Loss	Sample Number	Rock Type	Los Angeles Test % Loss
A 378	,, ,, ,,	18	A 715	Rounded river gravel	23
A 401	,, ,, ,,	27	A 747	River gravel	36
A 241	,, ,, ,,	31	A 778	,, ,,	22
A 510	,, ,,	18	A 807	,, ,,	14
A 498	,, ,, ,,	18	A 893	,, ,,	18
A 945	,, ,,	40	A 576	,, ,, crushed	22
A 962	,, ,, ,,	12	A 66	,, ,, screened	18
A1017	,, ,, ,,	17	A 622	,, ,,	17
A1018	,, ,,	29	A 414	,, ,,	26
A1046	,, ,,	44	A 482	,, ,, crushed	20
A1059	,, ,,	28	A 363	,, ,, ,,	25
A 685	,, ,,	15	A 269	,, ,,	40
A 712	Rounded river gravel	28	A 34	,, ,,	32

The table also shows that the fine-grained rocks are the most consistent under test, whilst the coarser grained granites, for example, are variable and generally less resistant.

Having established that toughness is the property being sought, the petrologist may make some relatively safe generalizations with regard to the performance of each rock-type. However, jointing, degree of weathering and deuteric alteration sometimes superimpose characteristics which are alien to a certain rock type in its fresh condition. Such is the case with quartz veins or quartz pebbles which have been buried in clay. The clay invades the minute fractures in the quartz, further weakening the structure, possibly by alternate shrinkage and swelling.

Petrology and shape—The geologist is well acquainted with the various types of fracture common to different rock species. In general it is possible to predict which rocks will be more susceptible to flakiness by observing their fracture. Any tendency towards conchoidal fracture is a sign of incipient flakiness.

Jointing must also be taken into consideration; rocks having close-spaced joints generally yield aggregate of good cubic shape, whereas

TABLE II

Relationship between Flakiness Index and Rock Type

Sample Number	Shire or Locality	Rock Type	Flakiness Index	L.A.
A1831(ABG)	Boree	Granite	12·2	18
,, (BNG)	,,	,,	12·5	37
,, (CGG)	,,	,,	15·6	37
,, (DRG)	,,	,,	10·4	28
A1831(HCD)	,,	Dolerite	13·2	16
A2048	Woy Woy	Quartzite and sandstone	15·9	28
A1831 1GK	Boree	Quartz keratophyre	16·2	16
A1999		Volcanic breccia	13·9	13·3
A1301		,, ,,	18	13
A2135		,, ,,	19·4	13
A1932	Molong	Limestone	18·9	19
A1831ERL	Boree	,,	22·8	26
,, FCL	,,	,,	14·3	24
A2037	,,	Basalt	28·9	16
A1841	Wakool	,,	21·8	19
A1831	Boree	,,	24·5	15
A1175	Carrathool	,,	24	21
A2020(3A)	Adelong	Quartzite	25·6	19
,, (3B)	,,	,,	23·6	23
,, (3C)	,,	,,	31·0	23
,, (4A)	,,	Schist, porphyry and quartz	24·8	18

massive rocks are prone to flakiness unless they are crushed by stages. Rocks possessing schistose or fluidal fabric are more likely to crush to a bad shape than those having a more granitic type of fabric.

Another factor that must not be overlooked is the effect of the type of crusher used. Gyratory crushers appear to produce the least satisfactory aggregate.

Table II lists the flakiness index for different rock types. It will be noted that granite is the best.

Petrology and adhesion to bitumen—(i) Very few rocks are immune from the troublesome effect known as "stripping". Table III summarizes the results of an investigation by the author into the causes of this phenomenon.

(ii) The theory mentioned in *Main Roads* (Anonymous, 1952) deals with "stripping failure" as a surface tension effect in terms of the aggregate-bitumen, aggregate-water and bitumen-water interfaces. From the results set out in Table III the author has formed the view that the most important factor is the strength of the bond between the aggregate and the bitumen. The plucking action imposed by motor tyres passing over the road surface is the disturbing force in the case of surfaced pavements but is less effective where bitumen-aggregate mixtures are used.

Whilst it is generally agreed that water weakens the bond between the aggregate and bitumen, the important question is why it should do so more readily in some cases than in others. The answer now offered to this question is that the water is absorbed in the first place by clay or clay-like minerals on or near the surface of the rock. When such strongly polar minerals are present over much of the surface, the bitumen being substantially non-polar and only weakly bonded to the less polar minerals composing the rock is easily dislodged from the aggregate when the polar minerals absorb water and exhibit stronger polar properties.

(iii) Statistically there is a good correlation between the amount of adverse constituents in the aggregate and the amount of stripping, see Table III.

TABLE III

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate

Specimen Number	A463	A484	A485	A496	A506
Shire or Locality	Bathurst	Waradgery	Cooma	Marthaguy Shire	Jemalong Shire
Rock Type ..	Basalt	Olivine basalt	Olivine basalt	Microgranite	Sheared Microdiorite
Type and Amount Adverse Constituents	Moderate amount iron hydrates	Moderate amount Serpentine, some Iddingsite	Small amount Iddingsite and Zeolites	Large amount Kaolin, some Chlorite	Large amount Kaolin and Chlorite
Stripping Rating[1]					
Bitumen A ..	2	4	1	4	2
Bitumen B ..	2	4	1	3	2
Adverse Constituent Rating[2]	3	3	2	4	4
Shape	Flaky	Flaky	—	Angular	Angular, some flakes
Cleanliness (Fresh faces or old and/or dusty)	Fresh	Fresh	—	Fresh	Fresh
Remarks ..	—	—	—	—	—

[1] Stripping ratings—1 : 0–25% ; 2 : 26–50% ; 3 : 51–75% ; 4 : 76–100%.

However, it must be noted that an important step in the investigation was to recognize that the amount of these adverse constituents is rarely very large on a gravimetric basis, but should be described as a " large amount " when most of the particles composing the rock are coated with clay or clay-like minerals. The ratings used are set forth in Table III.

In some cases stripping occurred in the plate tests where it was not predicted by microscopic examination. Every case of such departure is attributed to the clay being on the surface of the aggregate as an extraneous coating and not as part of the rock. That is to say, the aggregate was " dirty ".

(iv) From Table III it becomes apparent that a large number of alteration products may be listed as adverse constituents. The structure of these minerals is in general similar to that of the clay minerals familiar to soil scientists.

Among adverse constituents may be listed " kaolin ", limonite, iron and aluminium sesquioxides, chlorite and possibly serpentine. (The term *kaolin* is used in Table III in a general sense only, owing to the difficulty of precise identification.)

(v) Aggregates susceptible to stripping are illustrated in Plate I, Figs. 1, 2 and 3. A relatively safe type—a basalt only slightly altered—is shown in Plate I, Fig. 4.

Polishing and petrology—Present indications from field data in New South Wales are that river gravel consisting substantially of porphyry and quartzite is less susceptible to polishing than basalt or limestone.

At the outset it was not entirely clear whether the high polish and slippery conditions were due to wear of the aggregate or to a film of extraneous material. Whilst oil slick deposited from exhausts and leaking engine components, and plasticized rubber from skidding tyres instantaneously overheating may be a contributing factor, there is certainly no doubt that the individual stones taken from troublesome pavements do show a small amount of wear and a high polish on the high spots. Evidence of this wear is graphically illustrated by the photographs of sections made through the upper and

TABLE III—*continued*

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate—continued

A509	A510	A532	A554	A569 GC2	A661
Narrandera Showground Quarry	Goodradigbee	Jemalong	Wentworth District	Cobar Mine tailings	Gundurimba
Quartzite	River gravel (Quartz porphyry)	Limestone	Marl	Slag	Basalt
Small to moderate amount Kaolin	Small amount Kaolin	Very small amount indefinite clay mineral	Moderate Limonite	Negligible	Moderate amount Serpentine and Clay
2 1	4 4	1 1	4 4	1 1	2 2
2	2	1	3	1	3
Flaky	Rounded	Angular	Concretionary to Irregular	Angular (vesicular in part)	Flaky
Fresh	Dirty	Fresh	Very dusty	Tarnished but dust-free	Fresh
—	The high stripping is probably due to dirty surface	—	—	—	—

[2] Adverse constituent ratings—1 : Negligible ; 2 : small amount ; 3 : moderate amount ; 4 : large amount.

lower surfaces of basalt taken from one such road, shown in Plate I, Figs. 5 and 6. It will be noted that the individual feldspar crystals firmly held in the groundmass have worn down.

Let us reflect briefly on the possible cause of this effect :—Fundamentally hardness is probably the most important single factor. In this regard it should be noted that the Los Angeles test is not a good index of hardness, as is shown by the similar test figures for limestones and quartzites. (See Table I.)

As most rocks are composed of more than one mineral, the fabric and texture are important, and together with the type of groundmass largely determine whether the rock is tough or friable.

Naturally, hard minerals wear less than softer ones, and maintain sharp edges longer. These sharp edges probably increase the resistance to skidding.

Friable rocks which are continually wearing down by losing whole crystals would not polish, but their usefulness depends on the degree of friability, for example some granites are too friable.

In conclusion then, the fine grained rocks containing minerals of only moderate hardness firmly embedded in a tough groundmass should tend to polish well, whilst the rocks of coarser texture containing hard minerals are expected to resist polishing.

Consequently, a rock may be assessed in regard to polishing susceptibility on the basis of three factors :—

(i) Hardness of mineral constituents.
(ii) Toughness (fabric, texture and groundmass relationship for microscopic determination).
(iii) Texture.

In Table IV are shown some typical predictions of the probable behaviour of rocks of the common types.

Some preliminary experimental tests to obtain comparative values of friction have been made. It is recognized that improvements in technique may give more reproducible results, but the figures are of interest.

TABLE III—*continued*

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate—continued

Sample Number	A668	A670	A104	A224	A244
Shire or Locality	Wangoola	Western Division Broken Hill	Lyndhurst Shire	Wakool (from stockpile at Balranald and Barham)	Murray
Rock Type ..	Limestone	Garnetiferous granite	Tachylytic basalt	Biotite granite	Vesicular basalt
Type and Amount Adverse Constituents	Very small amount Limonite	Moderate amount chlorite	Moderate amount hydrated Iron Oxides	Moderate amount Kaolin and Sausserite	Moderate amount Serpentine/ Limonite
Stripping Rating[1]					
Bitumen A ..	1	4	3	4	4
Bitumen B ..	1	4	2	4	3
Adverse Constituent Rating[2]	1	3	3	3	3
Shape	Flaky	Angular	Flaky	Angular to flaky	Vesicular and flaky
Cleanliness (Fresh faces or old and/or dusty)	Fresh	Fresh	Fresh	Fresh	Fresh
Remarks	—	—	—	—	—

[1] Stripping ratings—1 : 0–25% ; 2 : 26–50% ; 3 : 51–75% ; 4 : 76–100%.

Table V gives the resistance to skidding in terms of a coefficient. It seems probable that some other factor than simple friction is involved. In any event, these coefficients vary with type of rubber and speed. Coefficients of a different magnitude were obtained for the same specimens using rubber of two different hardnesses. Photomicrographs of thin sections of some of the samples listed in Table V are shown in Plate I, Fig. 4, and Plate II, Figs. 1–4.

Table VI gives coefficients for tests made on specimens of asphaltic concrete (a mixture of graded aggregate and bitumen) containing two of the aggregates quoted in Table V.

In this case, however, the tests were carried out with a motor tyre of hardness approx. 70 shore degrees rubbing the surface of the asphaltic concrete, and having a peripheral speed of 30 m.p.h., just as a tyre would have skidding at this speed.

The inclusion of more quartz sand in the basaltic mix would probably improve the wet coefficient.

Summing up, there are three questions to be answered :—

(a) At what stage in its service will any particular aggregate become unsafe ?
(b) Can the problem be solved merely by selecting aggregates of a more suitable type ?
(c) Can the troublesome aggregate be used in asphaltic concrete ?

(a) On the first question, the only local evidence at present is that fresh and polished aggregates give quite different coefficients, as set out in Table V, and that in both cases the polishing was most pronounced on winding sections of road. On both of the roads concerned the aggregate had only been in service for a few years, but traffic was heavy.

It appears, therefore, that the rate of polishing is a function of the parent material, traffic density, curvature of the roadway, speed of traffic, and climate.

(b) It is most unlikely that selection of more suitable aggregates will provide a completely

Table III—*continued*

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate—continued

A297	A298	A320	A321	A322	A350
Forbes	Jemalong	Burrangong (Young Municipal Quarry)	Burrangong	Bland Quarry at State Forest, Binga Mountain	Murray Shire Moana Quarry
Tuff	Microdiorite	Granite	Quartzite	Quartzite	Schistose slate
Moderate amount indefinite clay	Large amount Kaolin	Moderate amount Kaolin, some Chlorite	Small amount Kaolin	Small to moderate amount Kaolin and some Haematite	Negligible
4 —	3 —	4 4	— 1	4 —	3 2
3	4	3	2	2½	1
Irregular	Angular, some some flakes	Angular	—	Flaky	Vesicular, flaky and somewhat fissile
—	Fresh	—	—	Fresh	Fresh
—	Compare sample A506	No hand specimen	—	—	The fissile nature of the material possibly affects the stripping

[2] Adverse constituent ratings—1 : Negligible ; 2 : small amount ; 3 : moderate amount ; 4 : large amount.

satisfactory answer from the economic viewpoint. This is clear from Table I, in which 40% of the aggregates listed are likely to polish if the hypotheses on which Table IV depends is accepted.

(c) The third question cannot as yet be answered with assurance. Considerable effort is now being devoted by the Department of Main Roads towards an elucidation of the problem.

Petrology in relation to soundness and susceptibility to weathering—The general soundness of argillaceous sedimentary rocks, greywackes and some other types is usually readily determined, but in the igneous rocks inconspicuous features may be of great importance. On microscopic examination apparently sound basalts are sometimes found to contain plagioclase which is highly kaolinized, olivine which is red or green due to alteration, or, in the groundmass, there may be patches of chloritic material. In bad cases the aggregate may actually soften on wetting and crumble under light pressure.

In one recent case a rock submitted to the Department to be tested as an aggregate for use in concrete was found to be a basic igneous rock with serpentine along shear planes (Plate II,

TABLE III—*continued*

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate—continued

Specimen Number	A390	A394	A430	A443	A673	A674
Shire or Locality	Wade Shire	Liverpool	Colo Shire, Mt. Tomah Quarry	Bland Shire Deposit 6 miles S.E. West Wyalong	Wakool	Wakool, Mt. Hope deposit
Rock Type ..	Contaminated Basalt	Breccia (volcanic)	Olivine Basalt	Weathered Quartzite	Biotite Granite	Granite
Type and Amount Adverse Constituents	Moderate amount Chlorite	Large amount Chlorite and Kaolin	Negligible amount Serpentine	Moderate amount Limonite, Haematite	Moderate amount Limonite, Kaolin	Large amount Kaolin
Stripping Rating[1]						
Bitumen A	4	4	1	4	4	4
,, B	4	3	1	3	4	4
Adverse Constituent Rating[2]	3	4	1	3	3	4
Shape ..	Angular	Angular, some flakes	Angular to flaky	Angular	—	Very flaky
Cleanliness (Fresh faces or old and/or dusty)	Fresh	Fresh	Fresh	Fresh faces, but very dusty	—	Fresh
Remarks ..	—	—	—	—	—	—

[1] Stripping rating—1 : 0–25% ; 2 : 26–50% ; 3 : 51–75% ; 4 : 76–100%.

Figs. 5 and 6). Test cylinders were made, and these showed that the aggregate was weaker than would have been expected on the basis of the Los Angeles test.

These two types of weakness are the principal characteristics which microscopic examination is ideally suited to find.

As the same minerals which are adverse in regard to adhesion to bitumen are the ones which if present in quantity will lead to unsound aggregate, it can be seen that micropetrology and hand specimen petrology are very useful tools. Whilst this is clear enough to the geologist, unfortunately engineers have been slow to recognize the value of such methods.

Alkali reaction in concrete and its relation to the petrology of the aggregate—Very little attention has been given to this problem in Australia because it has been considered that the use of low-alkali cement was a sufficient safeguard. However, Jagus and Bawa (1957) have recently suggested that the use of low-alkali cement with reactive aggregates is not a complete answer.

The question now arises whether any failures in Australia may be due to overconfidence in low-alkali cement. Appendix 1 of the Indian article gives a table of the "alkali reactive minerals in aggregates". From the latter table it appears that the less siliceous rocks are the safest aggregates with respect to alkali reaction.

TABLE III—*continued*

Schedule of Stripping (Plate) Test Results and Observations on the Aggregate—continued

A680	A685	A690	A694	A707 (Several Samples)	A707	R58 (B1038 B1034)
Martin's Gully	Muswellbrook (Patrick Plains)	Coolah Shire	Dept. Works, Canberra	Dunmore	Emu Plains	Prospect
Weathered Porphyry	River gravel (Basalt and Quartzite)	Impure Marble	Quartz Porphyry	Basalt with inclusions	Crushed river gravel (much Quartzite)	Analcite, Dolerite
Large amounts Kaolin and Chlorite	Very small amount Serpentine in Basalt, Limonite in Quartzite	Small amount Limonite	Moderate amount Limonite and Kaolin	Moderate amount Serpentine	Small amount Limonite and Kaolin	Moderate amounts Kaolin and Chlorite
4 4	4 4	1 1	4 4	2 2	4 3	3 2
4	1	2	3	3	2	3
Rounded to irregular (due to crushing)	Smooth rounded	Angular to flaky	Angular to flaky	Flaky	Angular to flaky	No specimens
—	Dirty	Fresh	Fresh	Fresh	Somewhat dirty	—
—	The stripping is probably due to the dirty surface of the aggregate	—	—	—	Penrith is similar. Stripping probably due to dirty surface	—

[2] Adverse constituent ratings—1 : Negligible ; 2 : small amount ; 3 : moderate amount ; 4 : large amount.

TABLE IV

Sample No.	Type of Rock	Predicted Susceptibility to Polishing
A661	Basalt	Moderate to high
A532	Limestone	,, ,,
A690	Marble	Moderate
A445	Microdiorite	,,
A320	Granite	Low
A350	Hornfels containing a large amount of hard minerals	Low to moderate
A707	Quartzite	Low

Curiously, the basalts are included due, according to Jagus and Bawa, to the more acidic glass in basalts.

The latter reference and the use of the term " Diabase " are somewhat vague (cf. Harker (1908)). It is to be expected that both olivine basalts and olivine microgabbros, or similarly basic rocks, would not be alkali-reactive. In any event all basalts do not contain glass (Hatch, Wells and Wells (1949)). Owing to the frequent use of basalts in New South Wales, it appears that this aspect warrants some special attention. A later publication by the U.S. Highway Research Board (1958) gives a very similar table to that in the Indian Roads Congress Bulletin.

Acknowledgements

Whilst all the micropetrological work and the correlation with other test results is the work of the author, he deeply appreciates the permission given by the Commissioner for Main Roads, N.S.W., to utilize the Department's records and to publish this paper.

TABLE VI

Rock Type (Principal constituent in asphaltic concrete)	Shire Area	Degree of Wear	Coefficient of Sliding Friction	
			Dry	Wet
Olivine basalt	Gosford	Specimen artificially polished	0·87	0·46
Nepean River gravel	Penrith	,,	0·86	0·52

Thanks are also due to my associates in the Materials Branch for their assistance by way of discussion, to the Parkes and Chatswood Laboratory Staff, and the Divisional Engineers and Engineering Staff of the Central and Central-Western Divisions.

The opinions expressed are those of the writer and not necessarily the views of the Department of Main Roads.

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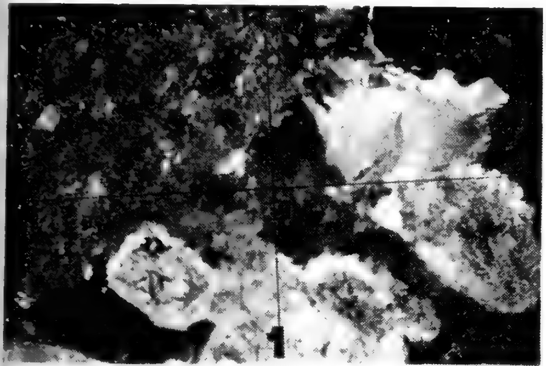
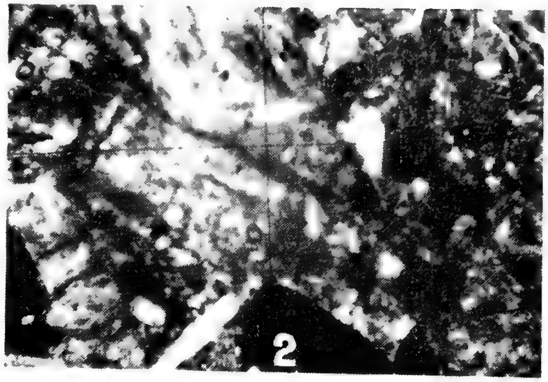
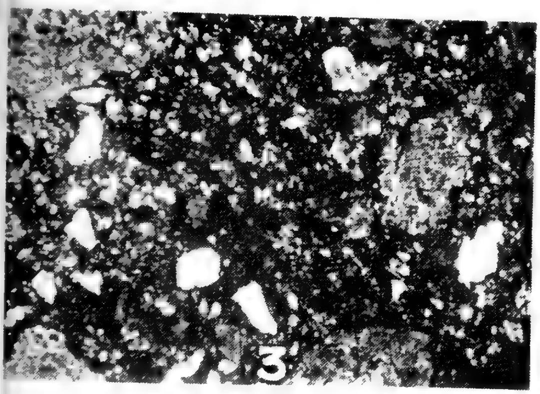
TABLE V

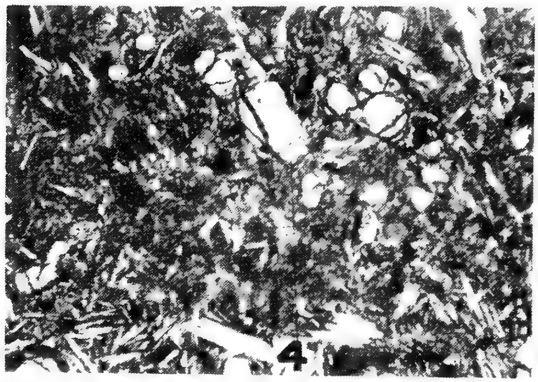
Rock Type	Shire or Area	Degree of Wear	Coefficients of Limiting Friction			
			Dry[1]	Wet[1]	Dry[2]	Wet[2]
Tachylytic Basalt (angular specimens)	Abercrombie	None	0·59	0·62	0·99	0·92
Tachylytic Basalt (flaky specimens)	,,	,,	0·63	0·60		
Tachylytic Basalt	,,	Approx. two years in pavement	0·56	0·55	0·69	0·71
Olivine Basalt	Gosford	,,	0·48	0·57	0·72	0·72
Rounded River Gravel[3] ..	Penrith	River action	0·64	0·62	0·91	0·92
Angular River Gravel[3] ..	Penrith	None	0·68	0·70	1·09	0·95

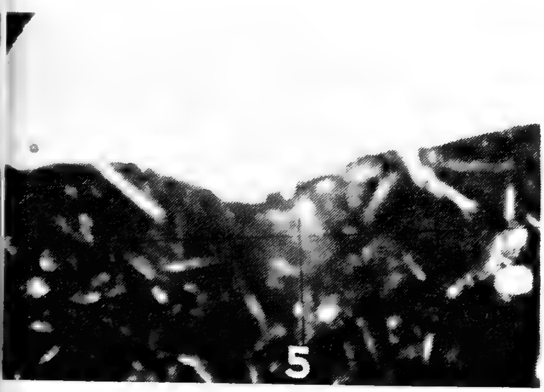
[1] Using rubber of 50 shore degrees, with the aggregate on the rubber.
[2] Using rubber of 90 shore degrees.
[3] Containing porphyry and quartzite.

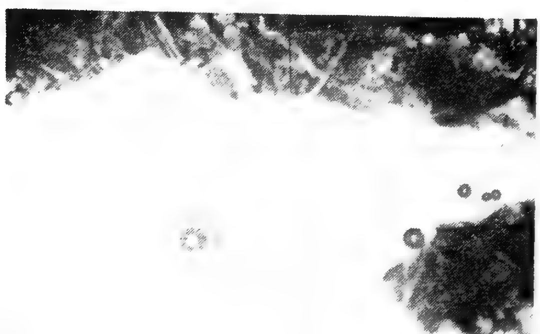












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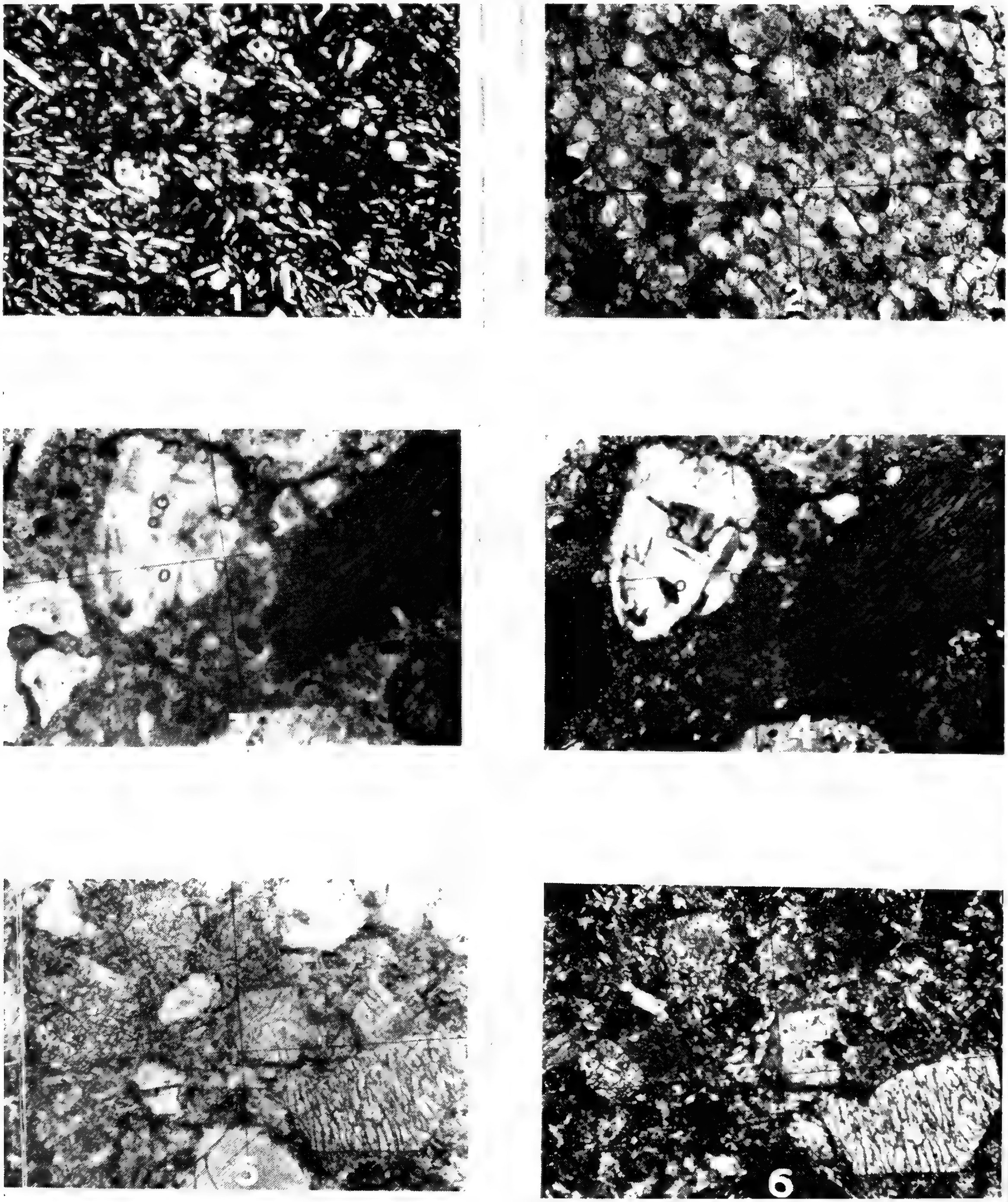

Explanation of Plates I and II

Plate I—Thin Sections of Road Materials

Fig. 1—Biotite granite from Wakool Shire. Minerals shown are quartz, biotite and saussuritized feldspar. Crossed Nicols.

Fig. 2—Analcite dolerite. Minerals shown include altered plagioclase and deuteric minerals. Crossed Nicols.

Fig. 3—Volcanic breccia. Apart from a few quartz grains this section consists of particles of argillaceous sedimentary rocks, chlorite and indefinite clay minerals. Ordinary light.

Fig. 4—A basalt in which there has been relatively little alteration ; it outcrops at Peat's Ridge, north of the Hawkesbury River. Principal constituents are plagioclase, olivine, magnetite and/or ilmenite ; the groundmass contains in addition some titaniferous augite. Crossed Nicols.

Fig. 5—Section of highly polished upper surface of a basalt fragment from a slippery section of pavement.

Fig. 6—Section through the lower surface of the pebble of Fig. 5 above, showing original irregular nature of surface.

Plate II—Thin Sections of Road Materials

Fig. 1—Tachylitic basalt, Abercrombie Shire. Crossed Nicols.

Fig. 2—Quartzite from river gravel at Penrith. Crossed Nicols.

Fig. 3—Porphyry from river gravel at Penrith. Ordinary light.

Fig. 4—The same. Crossed Nicols.

Fig. 5—Basic igneous rock with serpentine in clear areas. ×20. Ordinary light.

Fig. 6—The same. Crossed Nicols.

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Palaeozoic Stratigraphy of the Area to the West of Borenore, N.S.W.

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Abstract—The area contains a folded and faulted sequence of Ordovician, Silurian and Devonian rocks, overlain by flat-lying Tertiary lava-flows. The Ordovician rocks are dominantly andesitic volcanic products with a limestone developed near the middle of the sequence. The overlying Panuara Formation (Silurian) consists of shales, sandstones and limestones. In the north-west of the area two new members have been defined—the Rosyth Limestone Member, and, higher in the sequence, the Borenore Limestone Member. The last-mentioned member inter-tongues to the west with siltstones, then passes into shales. The boundary of the Wallace Shale (Silurian-? Devonian) with the underlying Panuara Formation is difficult to recognize at some localities.

The Bull's Camp Rhyolite overlies the Wallace Shale, but its relationship to the next youngest unit, the Garra Beds, is obscure but possibly unconformable. The Upper Devonian Black Rock Sandstone rests unconformably on the Garra Beds in the north-west, and on the Bull's Camp Rhyolite in the south-east.

Introduction

The Palaeozoic rocks to the west of Borenore, west of Orange, New South Wales, are generally only exposed in creek sections, where the overlying cover of Tertiary basalt has been removed. The area links those extensively mapped in recent years south of Spring and Quarry Creeks (Packham and Stevens, 1955), to those to the north studied by Joplin and Culey (1938), and included in the compilation of Joplin and others (1952).

Continuing north from the mapping of Packham and Stevens, the appearance of the Garra Beds, a new lithological unit beneath the Upper Devonian, introduces the problem of its relation to the rock units previously defined to the south ; problems also arise in the Borenore area in the differentiation between the Panuara Formation and the Wallace Shale. The formation terms of Joplin and others have not been used, because, in this area, they do not appear to be applicable to discrete lithological units.

Borenore has been known geologically mainly for the extensive outcrops of limestone which were quarried for building stone until about 1930. De Koninck (1898), Dun (1907) and Etheridge (1909) have described fossils from this limestone, most of the outcrops of which have been mapped by Carne and Jones (1919). Fletcher (1950) described some trilobites from below the Borenore Limestone, and suggested a correlation with the work of Sussmilch (1907), who mapped the southern part of the area. The present paper describes the area adjoining that mapped by Packham and Stevens, and includes the results of remapping parts of the areas examined by Sussmilch and by Joplin and Culey.

Ordovician

The Ordovician rocks of Spring and Quarry Creeks can be traced to the north as far as Mouse Hole Creek. The succession is not clear in the Spring Creek area, but at Oaky Creek an anticlinal structure exposes andesitic volcanic rocks overlain first by the Barton Limestone and then by further andesitic volcanic rocks. The andesitic rocks are highly weathered and not well exposed. The Barton Limestone is a typically poorly bedded and dark grey aphanitic limestone, is commonly calcite-veined, and contains black siliceous nodules. The lack of significant bedding obscures the structure of the area. The limestone is poorly fossiliferous, having yielded only a gastropod and a small tabulate coral. Packham and Stevens have, however, suggested an Ordovician age for the limestone, although the only palaeontological evidence is the similarity of two tabulate corals to forms in the limestone at Bowan Park. The Barton Limestone is approximately 200 feet thick at Oaky Creek, but to the north, at Mouse Hole Creek, it is apparently less than 100 feet thick. A fresh augite andesite, occurring to the west of the limestone in Oaky Creek, is probably a later intrusion, and not part of the Ordovician succession.

At Mouse Hole Creek it appears that a steeply inclined, in part overturned, succession is

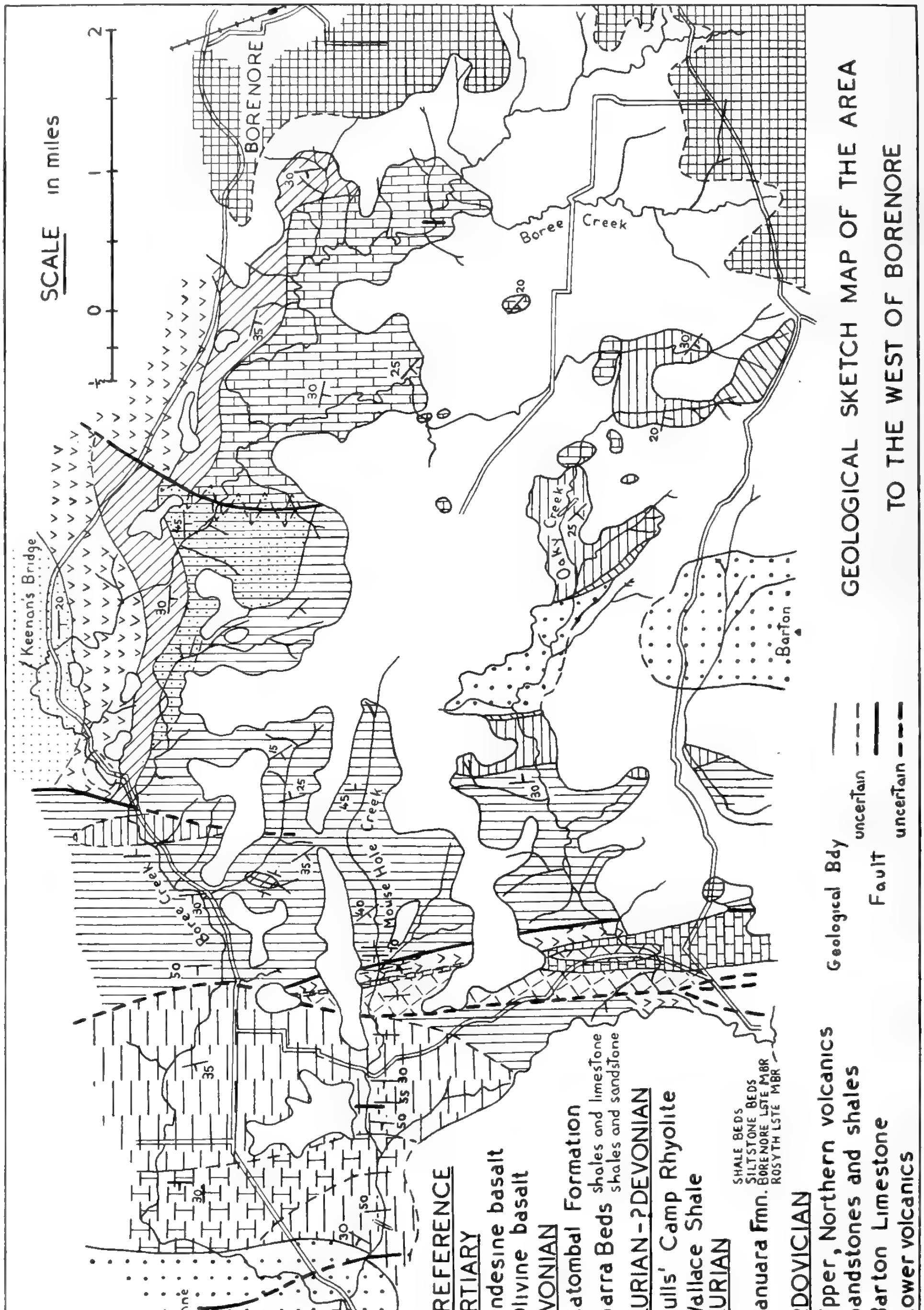

FIG. 1. Geological Sketch Map of the area to the West of Borenore

present. The volcanic rocks in this section are considerably fresher and better exposed. The western volcanics, considered to be the lower volcanics, are about 500 feet thick, and three rock types (possibly flows) can be recognized. The lowest member is a massive, medium-grained, altered andesite (?), consisting of pink, iron-stained, albite phenocrysts set in a groundmass of albite and chlorite. The rock is veined by quartz and calcite and contains, as do the other members of these volcanics in this section, significant quantities of pyrite. Above this is a much altered rock, possibly volcanic, with patches of chloritic material apparently relict after ferro-magnesian phenocrysts, in a saccharoidal groundmass of albite, chlorite and epidote. The top member is a dacite.

To the east of the Barton Limestone, 200 feet of (?) upper volcanics are present. These consist of a dark green, coarse, porphyritic andesite overlain by an altered dacite, containing phenocrysts of epidote apparently replacing an amphibole. Above this dacite there are a few feet of black fissile shales, from which one specimen of *Climacograptus* (identified by G. H. Packham), has been obtained. These shales are overlain, with apparent conformity, by Silurian limestone.

In the northern part of the area, near Keenan's Bridge, Ordovician rocks outcrop in a south-plunging anticlinal structure. The lowest beds exposed are of sandstone with interbedded shale lenses, at least 500 feet thick. Mapping by K. Wood (unpub. Hons. Thesis, Sydney University, 1955) indicates that these beds are of limited lateral extent, occurring within a succession of andesitic volcanics. The lowest sandstones are pink in colour, due to the presence of iron-stained feldspar grains, and both pelitic and volcanic detrital fragments are present, set in a clay matrix. Thin lenses of fissile brown and black shales are common. Towards the top of the succession the sandstones are more typically grey in colour and contain large shale pebbles. One horizon contains abundant limestone pebbles which have yielded tabulate corals and crinoid stems. A black shale lens near the top of the succession contains abundant *Climacograptus bicornis*, *Orthograptus truncatus* var. *intermedius* and *Dicellograptus*, together with a small straight nautiloid.

Overlying these beds are about 800 feet of andesitic lavas, characteristically with pink iron-stained andesine phenocrysts. Several flows are probably represented, one of which, near the top, shows columnar jointing.

In the Bowan Park area Stevens (1957) noted the upward succession of Cargo Andesite, Bowan Park Limestone (correlated with the Barton Limestone) and Malachi's Hill Formation. Tentatively, then, the upper and lower volcanics may be identified as the Malachi's Hill Formation and the Cargo Andesite respectively, provided the correlation of the Bowan Park with the Barton Limestone is accepted. However, the base of the upper two formations in the Borenore area may be slightly younger than is indicated by Stevens, since Packham and Stevens record Upper Ordovician graptolites apparently from beneath the Barton Limestone. The graptolite fauna from within the andesite succession to the north indicates an Eastonian age, so that this andesitic succession probably occupies at least the same period of time as the two upper formations to the south. It is of note that to the north these andesites succeed a limestone (Pritchard, unpub. Hons. Thesis, Sydney University, 1955) which would then appear to occupy a position lower than the Barton Limestone.

Silurian

Stevens and Packham (1953) defined the Panuara Formation as one of thinly-bedded sandstones and shales, with some limestones, resting unconformably upon Ordovician rocks and being overlain by the Wallace Shale, a distinctive shale lithology. Difficulties exist in extending the use of the term Panuara Formation in that, because of its variable, non-diagnostic lithology, it may be necessary to rely heavily on fossil evidence of age to identify what is primarily a lithological unit, and the danger may arise of extending the use of the term in a time and not in a lithological sense. This problem is emphasized by the fact that in parts of the Borenore area the Panuara and the Wallace lithologies are similar. A related problem concerns the boundary between these two formations.

In the type locality, and at Spring and Quarry Creeks, the Panuara Formation and the Wallace Shale are of distinctive lithologies, but, to the north, the Panuara lithology is in places similar to that of the Wallace Shale, and there is an apparently gradual transition between the two. To the south, the base of the Wallace Shale appears to be a natural boundary, a distinct change in lithology, which is conveniently marked by tuffaceous beds. There is no evidence to suggest a relationship between the change in lithology and the volcanic activity.

In Oaky Creek, where the boundary between the two formations appears gradational, the base of the Wallace Shale has been drawn at this tuffaceous horizon. This method is suitable only over limited areas, for extended use would imply that the Panuara-Wallace boundary is isochronous; however, in this case it retains the desired identity of these most useful formation names. The presence of a natural break at the tuffaceous beds is shown in the eastern Oaky Creek, where the change in lithology is from a massive limestone to shales. Distinctive Wallace Shale lithology occurs in Boree Creek, and possibly has its base at the same horizon, but neither the tuff nor any fossil evidence is present to indicate this.

Panuara Formation—In the Borenore area, the upper part of the Panuara Formation is notable for the marked changes in lithofacies, from a massive crinoidal limestone in the east to shales in the west. Between the two a siltstone facies can be recognized to the south of Keenan's Bridge. A calcareous facies is present where the base of the formation is exposed, the Rosyth Limestone Member, named from the property, one and a half miles to the west of Borenore, near which it is best exposed. This facies is equivalent to the Bridge Creek and the Quarry Creek Limestone Members.

The Rosyth Limestone Member consists for the most part of a richly fossiliferous marly limestone, interbedded with labile sandstones and shales. To the south of Rosyth the member is more than 900 feet thick. The basal beds of feldspathic sandstone are overlain by a calcarenite which grades upwards into a marly limestone about 300 feet thick, this limestone being interrupted near the base by 100 feet of feldspathic sandstone. The euhedral kaolinized feldspars in this rock suggest that it may be tuffaceous in origin. The marly limestone contains an extremely rich fauna which is commonly etched out on weathering. Much of the fauna remains unidentified, but it contains *Arachnophyllum* (?) *epistomoides* Eth., *Cystiphyllum*, *Phaulactis* (?), *Mycophyllum*, *Rhizophyllum* (?), *Halysites orthopteroides* Eth., *H*. cf. *pycnoblastoides* Eth., *Heliolites daintreei* Nich. and Eth., *Coenites* spp., *Favosites*, stromatoporoids and crinoid stems, together with brachiopods and other coral genera. Fifty feet of green and brown shales overlie this limestone, and at the top of the succession these is about 300 feet of interbedded calcarenites and feldspathic sandstones. To the east, only about 500 feet of the succession is exposed. Limestone is absent here, the sequence consisting of interbedded shales, labile and calcareous sandstones and mudstones. The more argillaceous nature of these sediments is probably responsible for the absence of the coral fauna, the only fossils being occasional brachiopod valves. Fine-grained basic igneous rock-fragments are notable in some of the labile sandstones. The succession thins to the west of Rosyth to about 550 feet, the lower part being typically of feldspathic sandstone, the upper part of marly limestone. To the west of the fault in this area the member is considerably thicker, probably because lateral equivalents of the Borenore limestone are necessarily included. The section consists almost entirely of limestones and calcareous shales. In the upper part of this succession the presence of detrital quartz in beds of calcareous sandstones is of note. Near the top a thin bed of green acid tuffs is present, but does not extend for more than a mile along the strike. Farther west the member becomes thinner. Commonly the limestone grades into a calcareous mudstone, but in the western part of Boree Creek the member is represented by a coarse crinoidal limestone. This crinoidal limestone is also exposed as a small inlier one mile to the south-west, where it is in part brecciated, and has yielded *Halysites sussmilchi* Eth., *Hercophyllum*, *Mycophyllum* (?), *Favosites*, gastropods, bryozoans, large pentamerids and abundant crinoid stems. The limestone exposed in western Mouse Hole Creek is considered to be the same limestone member, and contains *Halysites* sp., *Coenites* sp., *Favosites*, *Heliolites*, pentamerids and a (?) pycnactid rugose coral.

The total extent of the Borenore Limestone Member is unknown because of the later basalt cover, but where exposed it often forms strong outcrops, rising about 60 feet above the river level at Borenore Caves. Stratification is usually absent, so no accurate estimate of the thickness of the limestone can be obtained. It apparently dips gently to the south-west and probably is of the order of 1,500 feet thick. Texturally the limestone varies from aphanitic to coarsely crystalline, this latter phase more commonly being rich in crinoid stems. Typically a brecciated limestone is present near the base. De Koninck (1898) and Etheridge (1909) have described trilobites from near the base of the limestone, and Sussmilch (1907) has listed the fauna from the crinoidal limestone at the top of the member in Oaky Creek, Dun (1907) having described some new species in this fauna. Throughout the succession large gastropods,

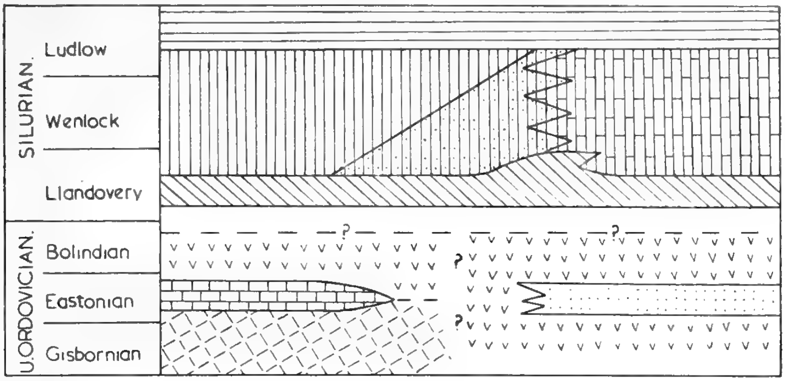

FIG. 2. Diagrammatic section showing the suggested relations of the Ordovician and Silurian rock units in the area to the west of Borenore. Reference as for Fig. 1

pentamerids and colonial tryplasmids are common.

The beds of the siltstone member to the west of the limestone are incompletely known as they form poor, broken outcrops The lower beds are buff-coloured, fine sandstones, siltstones, and shales, with minor compact red claystones. Muscovite is a significant constituent of these beds. Higher in the sequence red shales and siltstones are more common, and muscovite is abundant. Green shales appear near the top of the beds. This member is interpreted as inter-tonguing laterally with the Borenore Limestone, but these relations are not exposed. To the west, the member thins rapidly and is absent at Boree Creek, where the Rosyth Limestone Member is overlain by shales.

It is with the shale member of the Panuara Formation that difficulty arises in distinguishing the formation from the Wallace Shale. Typically the Panuara shale member in the southern part of the area consists of red and green splintery shales, while to the north massive beds of fine sandstone and siltstone, in beds of the order of a foot in thickness, are more common.

In Oaky Creek the lowest beds exposed are of blue-green siltstones and shales, with occasional calcarenite beds a few inches thick. These beds are overlain by highly jointed red and green shales and siltstones, with occasional distinctive thin bands of light coloured siltstones. This is a feature more typical of the overlying Wallace Shale, and the change in lithology to this upper formation is gradational, its base being drawn at the horizon of the tuffaceous beds and slumped mudstones. Folding, which is notably tight in the western part of this creek section, makes it difficult to estimate the thickness of the shale member, but it probably does not exceed 1,000 feet.

In the northern part of the area, the shales are more typically green and brown in colour, and fine sandstone and siltstone beds are common. These beds directly overlie the Rosyth Limestone, and indeterminate monograptids, and trilobites, have been found in shales just above the limestone. The structure is not clear in this region, and unobserved faulting may be present, but it is possible that the succession is somewhat thinner than to the south. Thin calcarenite beds occur interbedded with the siltstones. Towards the top the siltstones show graded bedding ; a thin pebble band is present, and just below the top of the succession there is a slump structure involving several beds. Near the top in the north-western part of the area quartz sandstones occur interbedded with plant-bearing shales, and from these shales a specimen of *Monograptus* has been obtained (F. G. Larminie, personal communication).

The relations of the different lithological units within the Panuara Formation can be tentatively suggested (Fig. 2), but as yet there is insufficient fossil evidence to establish this, and the absolute time relations are largely suggested from the faunas recorded by Packham and Stevens.

Silurian-? Devonian

Wallace Shale—The problem of recognizing a boundary between the Panuara Formation and the Wallace Shale has been mentioned above. In the areas to the south, the Wallace Shale is less well bedded than the Panuara Formation, but this is not so in the Borenore area. Although a Wallace Shale lithology is present comparable to that of the areas to the south, there is considerable variation from this lithology. The typical lithology in the Borenore area is of red and green jointed shales with occasional thin, persistent, light-coloured siltstone bands, which clearly indicate the bedding. In the south-east part of the area these grade up into well-bedded interbedded buff-coloured fine sandstones and shales in beds a few inches thick. No fossils have yet been found in the shales.

The basal beds overlying the Borenore Limestone exposed in the south-eastern part of Oaky Creek are well-bedded light-coloured mudstones, possibly in part tuffaceous in origin. One distinct green, coarse, acid tuff bed is present. The mudstones are well bedded, and in places show small flow markings on the bedding planes. These beds are about 100 feet thick, but are not exposed to the west of the Borenore Limestone. The overlying jointed green shales and siltstones are approximately 900 feet thick ; in the south, towards the top, bedding becomes distinct and thin sandstone beds abundant. In an unnamed southern tributary of Oaky Creek a slump structure in the shales several feet in amplitude contains small boulders of various rock types, including one limestone boulder more than one foot in diameter. This horizon appears to be somewhat lower than the boulder bed recorded by Packham and Stevens. Between this tributary and Oaky Creek to the east a small mass of limestone outcrops which, although an isolated outcrop, is apparently within the Wallace Shale. In the western part of Oaky Creek a similar succession of green shales overlies mudstone beds, showing small scale slumping and tuffs.

In Boree Creek, a few feet of typical red and green Wallace Shale is preserved overlying the Panuara Formation. These shales can be distinguished from the well-bedded siltstones and shales of the Panuara Formation at this locality, however, in the absence of fossils or the tuffaceous beds, they cannot be correlated with the Wallace Shale to the south.

Bulls' Camp Rhyolite—Only a small part of this formation has been preserved in the southern part of the area. In Oaky Creek a few feet of poorly-exposed red tuff containing patches of dark chloritic material are present, overlain by a few feet of Wallace Shale ; this tuff also appears to be filling scours in the shale. To the south of the eastern creek exposure a fresh devitrified virtoclastic tuff is exposed, and farther south a " coarse " pink acid tuff outcrops, the coarse appearance of this rock being due to a patchy development of albite replacing the groundmass of the tuff. Although this rock is a tuff, a similar lithology appears in a creek to the west showing an intrusive relation with the Wallace Shale, and is considered to be part of the same vulcanism. To the south-east of this area, pink and grey rhyolites and dacites occur in the succession.

That the succession is conformable from the base of the Panuara Formation to the Bulls' Camp Rhyolite agrees with the findings to the south. The Panuara Formation rests on the Ordovician rocks without any apparent angular discordance in the Borenore area, but a small erosional break possibly exists. In Mouse Hole Creek the succession is not clearly exposed and represents an interpretation, but in the northern part of the area the basal beds of the Panuara Formation appear to rest without discordance on the Ordovician lavas. The time interval between the topmost fossiliferous Ordovician strata and the Silurian beds may in part be represented by a period of exposure, and the presence of volcanic detritus in the basal beds of the Panuara Formation, considered to be derived from the underlying volcanics, suggests that this is so.

Devonian

Garra Beds—Joplin and Culey (1938) applied the term " Garra Beds " to a succession of mainly shales and limestones of supposed Middle Devonian age. Hill and Jones (1940) showed that the general indication was of a Lower Devonian age for these beds, but Hill (1912) later showed that, in what is in all probability a northern continuation of the same beds, both a Lower Devonian (Garra) and a probable Middle Devonian fauna are present. The lack of stratigraphic evidence of the relations of the horizons from which the fauna have been obtained and the necessary interregional correlation makes it difficult to suggest a range for the beds.

The Garra Beds in the Borenore area consist for the most part of green and brown shales. Towards the top the shales are more calcareous and limestone beds appear. To the north of this area, the whole of the Garra succession appears to be of limestone (Wood, unpub. Hons. Thesis, Sydney University, 1955).

In Mouse Hole Creek, a tightly folded succession of interbedded very coarse sandstones and shales, probably less than 200 feet thick, is considered to represent the base of the Garra Beds. The very coarse sandstones are more common near the base, but towards the top, alternating beds of sandstone and shale about one foot thick occur. The sandstones are compact rocks with pebbles (of average size of 2 mm.) of limestone, indeterminate argillaceous material, and feldspar. Crinoid stems, bryozoa and corals are present in the rock, but can usually only be seen as moulds when the calcareous fossil has weathered out. The shales contain abundant fragments of plant stems.

A thick succession of green shales, in places highly jointed, overlies these basal beds, but the junction is not exposed. The shales which have yielded occasional plant remains, and a straight nautiloid fragment, appear to be of the order of 1,000 feet thick, and are overlain by about 700 feet of interbedded shales and limestones. For the most part the limestones are not richly fossiliferous, containing crinoid stems and tabulate corals; but one bed near the middle of the sequence contains a rich coral and brachiopod fauna dominated by the large solitary coral *Pseudamplexus princeps* (Eth.).

In Boree Creek, exposures near the base of the Garra Beds are poor, and the base is apparently absent due to faulting. The lowest beds are of soft red argillaceous siltstones and labile sandstones which are overlain by the highly jointed green shales. The transition to the more calcareous shales is indicated by a thin lens of limestones which has yielded *Tryplasma columnare* Eth., *Plasmopora gippslandica* (Chapman), *Favosites* and crinoid stems. In the overlying grey shales there are notably no other limestone horizons.

At no place is there any satisfactory indication of the relation between the Garra Beds and the Bulls' Camp Rhyolite. The junction of the Garra Beds with the underlying beds is believed either to be faulted, or is not exposed. Packham and Stevens have indicated that the Bulls' Camp Rhyolite is most probably Lower Devonian in age. The fossil evidence suggests a general age for the Garra Beds above this horizon, and there is no indication that the rhyolites occupied an horizon within the Garra succession. It is reasonable to consider that the Bulls' Camp Rhyolite preceded the commencement of the Garra sedimentation. Joplin and others have indicated an unconformity between the Silurian and the Devonian from regional considerations.

Upper Devonian—The sediments mapped as Black Rock Sandstone by Stevens and Packham can be lithologically identified as the same as the lower beds of those mapped as Lambie Beds by Joplin and Culey, and have been termed Catombal Formation by Joplin and others. The lowest beds consist typically of a coarse conglomeratic sandstone at the base overlain by shales, red friable sandstones and conglomerates. Sussmilch recognized these beds as of Upper Devonian age.

Joplin and others have pointed out the presence of a structural unconformity between the Garra Beds and the Upper Devonian sediments. This is borne out in the present work, although the concordance in dip between the Garra Beds and the Upper Devonian in the Mouse Hole Creek section is somewhat misleading. However, it is considered that here the base of the Upper Devonian rests on an horizon within the Garra Beds some distance stratigraphically below the top.

Tertiary

The area is for the most part covered by an olivine basalt, the remnants of what must have been an extensive flow over a moderately flat land surface, sloping gently to the west. The flow is considered to have preceded the andesine basalt flows which can be recognized on the higher ground in the eastern part of the area. At least two such flows which are obviously part of the Canobolas vulcanism can be identified, a lower porphyritic andesine-basalt and an upper flow with augite phenocrysts.

Three small basaltic intrusions, probably related to the Tertiary vulcanism, have been observed, viz. a plug (?) in Boree Creek to the west of Keenan's Bridge, and two small dykes, one in western Mouse Hole Creek, the other in eastern Oaky Creek.

River gravels cemented by iron oxides, similar to those noted by Colditz (1943) and by Stevens (1950), are present in the area. The age of cementation is not known, but the gravels must, at least in some instances, have belonged to a drainage pattern which existed before the outpouring of the Tertiary lavas. The restriction of the gravels to areas overlying limestone supports the suggestion made by Stevens that the iron cementing material has been derived from the limestone.

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This work was carried out at the University of Sydney, and the author would like to thank Professor C. E. Marshall for the facilities to undertake the work. The author was introduced to the area as a student by Dr. G. H. Packham, and is greatly indebted to him for considerable advice and discussion of the problems of the area. The author is also grateful to Professor W. F. Whittard for his helpful criticism of the manuscript.

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Variation in Physical Constitution of Quarried Sandstones from Gosford and Sydney, N.S.W.

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Abstract—Variation in petrographic, water absorption, density and porosity attributes of quarried sandstones from Gosford and Sydney is traced to genetic factors, among which variation in the ratio of quartz sand to argillaceous material in the original sediment and the consequent variation in the roles of quartz welding and clay compaction are dominant.

Quartz welding results from concurrent stylolitization and silica cementation of quartz while clay compaction includes that induced by lode stress and that accompanying illite authigenesis. These processes and also carbonate deposition contributed to porosity reduction but void formation resulted from solution of carbonate in one of the samples examined.

Some relations between the petrographic and other attributes are indicated and the diagenetic evolution of the sandstones is outlined.

Introduction

The building sandstones from Gosford and Sydney merit consideration as favourable materials for studies of certain fundamental sandstone attributes. This is a consequence not only of their somewhat specialized characters but also of the availability from active quarries of large, unweathered, relatively homogeneous samples. While such studies apply primarily to the types examined, they may, in addition, contribute to the elucidation of wider problems concerning the sandstones of the area.

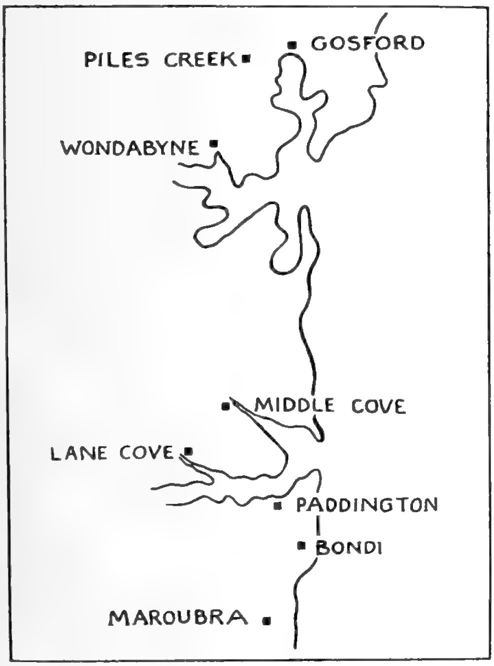

Fig. 1
Sydney-Gosford District, N.S.W.

Lithological diversity in building sandstones from Gosford and Sydney quarries was noted by Chalmers and Golding (1950) during a survey of building-stone resources of New South Wales. More recently the writer has attempted to correlate the petrographic attributes with certain physical properties for samples from some of these quarries (Golding, 1956*b*).

In this paper the composition, texture, initial rate of water absorption, bulk and grain density and porosity of sandstone samples from Piles Creek, Gosford, Paddington and Maroubra quarries (Fig. 1) are compared, the relations between the petrographic and other attributes are examined, the genetic factors which determined ultimate physical constitution are suggested and some implications of the study in aspects of applied sedimentary petrology are noted. Brief references also are made to sandstones from the two other major building-stone quarries in the area, at Bondi and Wondabyne, and to sandstones from Lane Cove and Middle Cove (Fig. 1), which were random locations sampled to obtain current-bedded Hawkesbury sandstone for comparison with the other samples.

The writer desires to express his indebtedness to Mr. R. O. Chalmers of the Australian Museum, Sydney, for introducing him to the subject and for the loan of slides of Wondabyne sandstone; to Professor D. W. Phillips, New South Wales University, for helpful discussion; to Dr. W. R. Browne for reading the manuscript and making valuable suggestions; to Mr. F. C. Loughnan, New South Wales University, for advice on clay mineral determinations, and to Mr. G. Z. Foldvary, New South Wales University, for assistance with micropreparations.

Sampling and Lithology

The study was limited to fourteen field samples from which seventy sub-samples for physical tests, sixty thin sections, and material for lithological, heavy mineral and clay-fraction determinations were obtained. Binocular examination of sawn surfaces of sandstone before, during and following acid treatment to detect carbonates and iron, and following the application of benzidine hydrochloride solution, which stains the clay blue, provided supplementary data for larger areas of sandstone than were available for study in thin sections. These data are incorporated in the appropriate petrographic sections of this paper, while the mineralogical studies are restricted to those bearing on the main theme of physical constitution.

Notwithstanding variation within single quarries, samples from the quarries at Piles Creek, Gosford and Sydney (Paddington and Maroubra grouped) correspond respectively to three moderately well defined compositional and textural types or " modes ", a comparison of which provides the basis for the present study.

From Piles Creek quarry (**530–560** ft. above sea level, ? Middle Hawkesbury Sandstone) four samples numbered **P1–P4** from the surface downwards, taken over the upper eighteen feet of the quarry face, were generally similar, white, medium grained, relatively friable quartzose sandstones. The uppermost sample (P1) was faintly iron-stained. A reddish, slightly ferruginous, rhythmically - banded variety, occurring sporadically in the quarry, was also sampled (P5).

The Gosford quarry (**100–150** ft. above sea level, ? Upper Narrabeen Group or base of Hawkesbury Sandstone) provided four samples from central (G1), central-upper (G3) and near surface (G4, G5) levels, a fifth sample (G2), similar to G1, being taken from a somewhat weathered quarried block. These sandstones were grey, compact and highly argillaceous, and varied upwards from fine to very fine grained. Sporadic masses of a brown, moderately ferruginous, rhythmically-banded, sandstone with micaceous and graphitic bedding-planes separated by massive bands several inches thick also occur (G6). Sub-samples of G6 were prepared from the massive bands.

Samples from the Sydney quarries (Upper Hawkesbury Sandstone, probably within **100** feet of the base of the Wianamatta Group) were argillaceous sandstones with rather prominent graphitic markings, those from Paddington (S1, S2) being pale yellow and fine grained, while the Maroubra sample (S3) was grey and of medium grain size.

Constituents

All samples contain essential quartz and clay minerals with accessory leucoxene, anatase, graphite, white mica, rutile (Golding, **1956*a***), zircon, tourmaline and occasional particles of quartzite and chert. The three modes differ, however, in their quartz and clay content and in the presence and character of further constituents (Table I).

Thus carbonate is absent from the Gosford banded specimen (G6) and from all Piles Creek specimens, but is present in all others. In the Gosford samples the carbonate is dominantly calcitic ; single grains, usually containing both calcite and siderite, are relatively large and at times envelop associated quartz grains. By contrast, in the Sydney samples a more homogeneous siderite (with limonite) occurs, often as small rhombs bridging quartz grains or isolated within the argillaceous matrix.

A distinctive feature in all Gosford specimens is the presence of about one per cent. of feldspars (microcline, albite and probably orthoclase). The grains, which include both limpid and cloudy types, are angular, smaller than associated quartz grains, and located within clay pellets, the feldspar clay contact usually being sharp, though marginal alteration of feldspar to clay is occasionally suggested. Smaller silt-sized fragments occur within the matrix. David and Pitman (**1902**) reported feldspar in sandstones from Sydney quarries, but none was recognized by the writer in either the Sydney or Piles Creek specimens examined.

Both the Piles Creek and Sydney samples, and typical current-bedded Hawkesbury sandstones from Middle Cove and Lane Cove, slides of which were examined for comparison, contain conspicuous traces of a variably leached biotitic mica, often thickly peppered with opaque, possibly leucoxenic " dust " (Plate I, Figs. 1 and 2).

Limonite and haematite occur only in traces associated with carbonate, except in the two rhythmically banded ferruginous specimens (P5 and G6), which contain up to about **0·5** per cent. (G6) of these constituents. Magnetite and ilmenite are lacking in all specimens.

The Gosford and Sydney samples also contain traces of opaque carbonaceous and transparent brown organic matter.

The argillaceous matrix in all specimens presents several aspects in thin section (Osborne,

TABLE I

Bulk Volume Composition of Sandstones from Piles Creek (P), Sydney (S) and Gosford (G) Quarries

Sample No.	Sand				Matrix			Cement			
	Quartz	Feldspar	Accessories	Total	Clay	Porosity	Total	Quartz	Calcitic Carbonate	Siderite	Total
P1	74	—	2	76	3	18	21	3	—	—	3
P2	75	—	2	77	2	18	20	3	—	—	3
P3	73	—	2	75	5	17	22	3	—	—	3
P4	77	—	2	79	1	17	18	3	—	—	3
P5	73	—	2	75	7	15	22	3	—	—	3
S1	63	—	2	65	15	14	29	1	—	5	6
S2	61	—	2	63	14	16	30	1	—	6	7
S3	65	—	2	67	18	11	29	1	—	3	4
G1	55	1	2	58	24	14	38	tr	4	—	4
G2	55	1	2	58	19	17	36	tr	6	—	6
G3	53	1	2	56	25	12	37	tr	7	—	7
G4	41	1	2	44	38	8	46	tr	10	—	10
G5	42	1	2	45	37	9	46	tr	9	—	9
G6	58	1	2	61	18	21	39	tr	—	—	—

1948; Golding, 1956*b*). Thus it appears as (1) areas of colourless well-crystallized illite, at times exhibiting a parallel orientation of flakes which apparently results from stress accompanying recrystallization, but which may be a function also of depositional factors (syngenetic, or inherited, as with shale fragments) or of load stress (Williamson, 1951). These areas do not stain with methyl-violet preparations. (2) Areas of colourless, low birefringent micromosaics and meshworks of fine shreds with a characteristic random orientation resulting in a grid-pattern as viewed between crossed nicols (since only in the 45° position are shreds clearly visible). These areas stain intensely with methyl-violet and some include voids from 1–10 μ wide between shreds. (3) Areas of similar aspect to the last, containing clay intermixed with silt-size particles of all other constituents, which stain in patches; and (4) various uncommon types which include intensely staining, loosely packed and parallel oriented rod-like aggregates, green vermiculoid types and also opaque clay. Examination of the fine clay from several of the sandstones (Loughnan and Golding, 1956), indicated dominantly illitic types in all, with kaolinite reaching a maximum of about 40 per cent. of the minus 2-micron fraction in the rhythmically banded Gosford specimen G6.

Of these constituents most of the quartz and all the feldspars, rutile, tourmaline, zircon and rock particles are detrital, while secondary silica, carbonates, anatase, haematite and limonite are authigenic. The argillaceous material may include detrital clay, and a proportion represents original sand-grade shale particles leached either before or after deposition, the indistinct detrital outline of which is occasionally discernible. Much of the well crystallized illite present presumably results from reconstitution within the rock of degraded illite (Grim, 1952) or from diagenetic reactions of kaolinite with silica and with potash in the connate water or from comminuted feldspars and micas. The leucoxene is mainly detrital, but much of it has recrystallized to clusters of recognizable anatase crystals and some may have developed from former ilmenite or biotite diagenetically. The carbonaceous material and the graphite presumably are detrital, but occasional well formed hexagonal plates of the latter suggest its reconstitution from the former within the rock.

Most of the constituents show the effects of load stress. Thus feldspars and the larger grains of rutile and zircon frequently are cracked and offset along shears or cleavages, while tourmaline is found shattered into aggregates of shards. Brittle leucoxene is often crushed, whereas plastic types (Golding, **1955**, and Plate I, Fig. 3), graphite, clay pellets and shale fragments, have been squeezed into lenticles or " schlieren " and detrital micas have been warped. Quartz, however, shows little if any evidence of cataclasis, while strain shadows, which occur infrequently, and planes of minute inclusions (along tension or shear directions. Tuttle, **1949**) which are of moderate frequency, probably are inherited characters of the grains, Quartz, however, frequently has dissolved at stressed contacts and has been precipitated at points of stress relief as authigenic silica.

Slides of Bondi (Clyde Street) and Wondabyne sandstones showed these to be sideritic, argillaceous, non-feldspathic types, similar in composition to those from Paddington and Maroubra.

Texture

Texture and Bulk Composition—A quantitative approach to a textural as well as bulk compositional comparison of samples is provided by thin section evaluation of sand, matrix and cement according to the following somewhat arbitrary terminology : " cement " is restricted to secondary silica and carbonates ; of the other constituents " sand " refers to particles greater than **50** microns in section short diameter, while " matrix " refers to the remaining portion of the sandstone (Table I and Fig. 5).

Further petrographic resolution of the matrix into its two main physical elements, clay and voids, was attempted by means of stained-resin-impregnated thin sections (Milner, **1952**). Such thin sections, however, show a broadly similar staining pattern for the three modes, about 75 per cent. of the matrix becoming coloured. While most discrete areas of matrix stain as a whole or in patches, areas of well crystallized illite and the cores of some former shale fragments resist staining. The degree of staining of a zone of matrix is apparently a function of clay mineral, particle size, degree of compaction and other factors. Nevertheless, it is evident that the porosity in these sandstones is largely microporosity (pores less than five microns in diameter ; Niggli, **1954**) within the argillaceous matrix. Macroporous clay meshworks as well as some larger " clean " macropores occur in Piles Creek specimens (Plate II, Fig. 4), and numerous macroporous voids partly lined with iron oxides, and occasionally having a rhomboidal outline, occupy the sites of former carbonate grains in the Gosford banded specimen **G6**.

Quantitative resolution of the matrix into clay and voids was accomplished (Table I, and Fig. 5) by subtracting from the micrometrically determined values for matrix the experimentally determined porosities.

Morphology, Size and Packing of Quartz Grains—Comparison of grain section outlines in vertically and horizontally cut thin sections suggests that most quartz grains in all samples have a somewhat oblately spheroidal shape, horizontal flattening having been induced to some extent by solution from upper and lower surfaces of grains and lateral deposition of quartz. The resulting elongation of grains (maximum elongation 2 : 1) in vertically cut thin sections is most perceptible in Piles Creek sandstone (Plate I, Fig. 5).

The original surface features of most grains in all samples have been considerably modified within the rock. This is evident from a comparison of the rounded, usually incomplete, outlines of detrital cores, which are preserved within authigenically enlarged grains, with the outlines of the present grains which display a variety of angular, sinuous, dentate and ragged forms.

Most of these forms apparently result from :

1. Solution at stressed contacts of abutting detrital quartz grains. (Discussed in the next section.)
2. Deposition of authigenic on detrital quartz at locations of stress relief. (Discussed in a later section.)
3. Corrosion of detrital and authigenic quartz attending the passage of solutions during diagenesis or weathering (in samples **P1**, **G2** and **G6**).
4. Solution of detrital and authigenic quartz at stressed quartz-clay contacts attended by clay compaction presumably without clay-mineral transformation or pronounced recrystallization. (Perhaps the corrosion at *C*, Fig. 3.)
5. Solution of detrital and authigenic quartz at contacts with authigenic illite developed from kaolinite, a process perhaps favoured at originally stress-free locations since the volume increase involved requires accommodation, but as a result of which local clay compaction increases and some replacement of quartz occurs (Loughnan and Golding, **1956**, illustrations).
6. Replacement of detrital and authigenic quartz by carbonate.

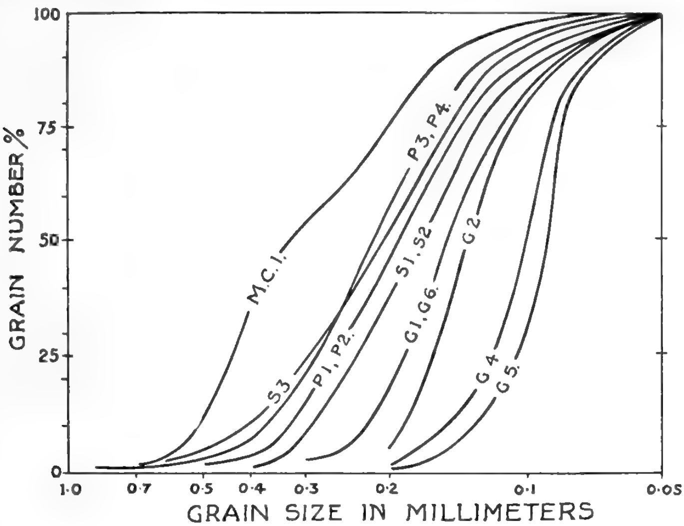

FIG. 2

Size distribution of quartz grains in current-bedded Hawkesbury (MC1), Piles Creek (P), Sydney (S) and Gosford (G) sandstones, in terms of the short diameter of grains measured in horizontally cut thin sections

A slight reduction is envisaged in total original quartz content resulting from fixation of silica in illite and complete removal of silica (item 3 above), but no substantial modification to the over-all size and sorting of the original quartz grains is thought to have occurred.

Cumulative frequency curves (Fig. 2) based on short-diameter measurements of grain sections for representative samples show a well defined separation between Piles Creek and Gosford sandstones (see also Plate I, Figs. 5 and 6), the Sydney sandstones tending toward an intermediate grain size, while the curve for a current bedded specimen (MC1), included for comparison, shows this sandstone to be distinctively coarser. For a single value comparison of grain size the third-quartile measure for the fourteen samples is plotted in Fig. 5.

Of the three modes, that of the Piles Creek sandstone shows the tightest packing of quartz grains with intergranular matrix areas, in vertically cut thin sections, equal to or less than areas of associated single quartz grains, while apparently "floating" grains (i.e. grain sections completely surrounded by matrix) are few (Plate I, Fig. 5). By contrast, Gosford sandstones show the loosest packing of quartz grains, with intergranular matrix areas usually greater than areas of associated quartz grains, and numerous apparently "floating" grains (Plate I, Fig. 6). The Sydney samples display an intermediate degree of packing.

Directional Textures and Pressure Solution—Directional textures visible in vertically cut thin sections result from (*a*) the mechanical alignment, approximately parallel to the bedding direction (horizontal), of sporadic mica and graphite flakes, and of lenticles of clay, graphite, leucoxene and (in samples G4 and G5) of carbonate; and (*b*) from the pressure solution of quartz to give elongated and sutured grain sections and microstylolitic seams. These textures embody both depositional and deformation fabrics (Fairbairn, 1949), while the elongation of quartz grains, to which reference was made in the preceding sub-section, is a dimensional, not lattice, orientation (Fairbairn, 1949, 1950).

Quartz grain sections with gently sinuous contacts suggesting rudimentary mutual pressure solution are numerous in all samples, but well defined suturing is frequent in Piles Creek, of moderate frequency in Sydney, and rare in the Gosford samples. Sutures which continue along the boundaries of several adjacent pairs of grains (microstylolites) accompanied by films of insoluble residues (microstylolitic seams) occur in Piles Creek and Sydney sandstones and similar directional features were noted in the upper Gosford specimens G4 and G5.

In the Piles Creek specimens small groups of well sutured grain sections associated with short microstylolitic seams of clear microporous illite (Plate I, Fig. 7) are characteristic, such groups being separated from similar groups by zones of grain sections with gently sinuous contacts. Less commonly sharp interpenetration suturing occurs, and rarely microstylolites also traverse biotite-biotite and biotite-quartz contacts (see Fig. 3 and Plate II, Fig. 1). Some almost straight contacts in Piles Creek sandstone (Plate I, Fig. 8) apparently result from uniform mutual solution as contrasted with interpenetration mutual solution. The coincidence of the trace directions of inherited planes of inclusions in these two grain sections, as contrasted with the angular difference of similar trace directions in pairs of grain sections displaying sharp interpenetration (Fig. 3), suggests that the relative orientation of these structural planes in abutting stressed quartz grains is one factor influencing the form of the resultant contact, an observation corresponding in part to that of Lowry (1956).

Numerous other factors influencing the degree of general development of quartz pressure solution in sandstones or the form of particular resultant contacts have been suggested in other overseas studies. Factors listed by Gilbert (1949) included depth of burial, grain morphology and packing and various kinds of positioning and orientation as well as physico-chemical environmental factors. Heald (1955, 1956) has referred also to the possible role of clay coatings on grains as a catalytic promoter of solution. If stylolitization in sandstones requires pressures

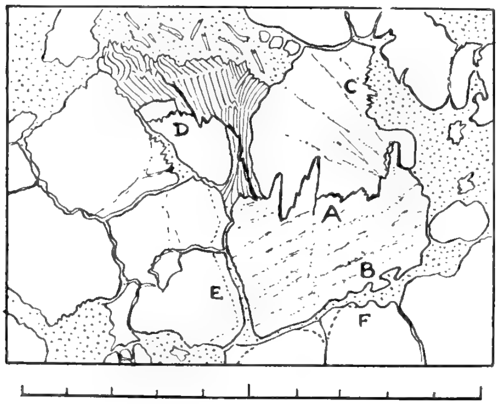

Fig. 3

Short microstylolite in Piles Creek sandstone traversing quartz-quartz (A), biotite-biotite, and quartz-biotite boundaries, and bifurcating at D to follow quartz-quartz and biotite-biotite boundaries. Solution of quartz at A may have supplied the silica for precipitation at the " dovetail " quartz-clay contact at B. C: corroded quartz at ? stressed junction with fine clay. E: partial " dust ring ". F: semi-circular embayments. (Photomicrograph is shown in Plate II, Fig. 1.)

exceeding some critical threshold value, as proposed for stylolite formation in limestones (Dunnington, 1954) the possibility arises of estimating a lower limit for depth of burial or thickness of former cover for some beds.

In the Sydney specimens low-amplitude microstylolites with brown transparent organic and other insoluble matter along seams traversing numerous pairs of grains, which at times show sharp suturing (Plate II, Fig. 2), are of moderate frequency, two or three seams, spaced 1–2 mm apart, being observed in some slides. The Gosford specimens from the central levels of the quarry lacked well defined seams but the near-surface samples showed low amplitude structures (Plate 2, Fig. 3) characterized mainly by opaque carbonaceous matter, but also containing clay, leucoxene and the brown transparent material. These seams may be solution residues or primary bedding plane accumulations, or may perhaps result from both primary deposition and later pressure solution.

Pressure solution effects were not observed in slides of the current bedded specimens examined for comparison.

Authigenic Silica—The maximum development of authigenic silica in the building sandstones examined (about three per cent. in Piles Creek sandstones) does not equal that seen in the current bedded specimens MC1 and LC1. In the former authigenic silica is more perceptible in horizontally- than in vertically-cut thin sections, a distinction probably inapplicable to the latter for which, however, thin sections normal and parallel to the current bedding or randomly cut thin sections were examined.

Apart from occasional pellucid areas up to 0·2 mm wide, composed of " frozen " straight-sided quartz mosaics which occur in the Piles Creek and Sydney samples, the authigenic silica observed is of the general type known as " secondary enlargement ". It is recognized in the Piles Creek and current-bedded sandstones by apparently subhedral outlines (Plate I, Fig. 4), facet traces bounding " clean " macropores (Plate II, Figs. 4, 5, 6), moulded straight edges with re-entrant angles (Plate II, Fig. 4) and approximately straight contacts of outgrowths (Plate II, Fig. 6), while specimen MC1 also exhibits types of articulating interlock and associated sinuous contacts (Plate II, Fig. 5).

Other criteria for secondary enlargement in the thin sections examined include pellucid rims, usually optically continuous with partial or complete rounded detrital cores containing scattered or planar dust-like, or acicular or larger inclusions (Piles Creek samples and MC1), or demarcated from similar or clear cores by a partial or complete " dust ring " of minute inclusions (all specimens). Roundness also is indicative of associated authigenic silica in these samples (Plate II, Fig. 2).

Small clay-filled peripheral embayments or " gaps in the secondary rim ", due to inhibition of silica deposition at the site of clay " clots " (Heald, 1956), are indicative of associated authigenic rims, and correspond to some types of surface " druses " visible in whole isolated grains. In section these embayments are semi-circular or irregular (Plate I, Fig. 4), " toothed " or " cored " (that is, showing longitudinal or cross sections of finger-like outgrowths (Plate II, Fig. 5)), or, when bounded by straight sided outgrowths, wedge-shaped (Plate I, Fig. 4). Repetition of semi-circular and cored embayments results in a variety of scalloped or crenellated marginal features (Plate II, Fig. 5), and repetition of wedge-shaped forms results in " dovetail " quartz-clay contacts (Plate II, Fig. 1). Where clay " clots " have been engulfed by continued deposition of authigenic silica around them they appear as large, apparently " sealed-in " clay inclusions along the " dust ring ", or along the otherwise clear junction of detrital and authigenic quartz. These features are conspicuous in stained thin sections and suggest that the relatively highly compacted clay in the " clots " retains considerable micro-porosity, and that authigenic silica is unlikely as a disseminated precipitate within other portions of the clay matrix.

Smooth straight-sided quartz outgrowths surrounding large " clean " macropores suggest that the latter are real features of the rock (that is, they have not been induced by removal of compacted clay during thin-section preparation), not only because silica deposition is favoured by original free space but also because contacts of quartz with compacted clay usually show irregularities of the types described in this and previous sub-sections of this paper.

Whereas the current bedded specimens exhibit a relatively continuous, though incomplete and macroporous, development of authigenic silica, with abundant complete detrital outlines, in the Piles Creek sandstone similar well cemented zones are confined to sporadic grain section clusters which are separated from similar clusters by larger zones showing a weak development of silica cementation in thin partial rims. In the Sydney specimens well cemented zones are still fewer and large macropores are absent, while in the Gosford specimens evidence of authigenic silica is relatively slight.

Minor contributions to authigenic quartz may include silica released during the decomposition of feldspar or biotite or during obscure clay-mineral transformations, or may include silica dissolved from non-stressed quartz. But the major source of the authigenic quartz in the building sandstones evidently was the intimately associated detrital quartz from which the silica was dissolved at stressed grain contacts. An approximate balance of silica lost and gained seems to be achieved within a space of millimetres or less (for example, see Fig. 3). This combination of pressure-solution with cementation of grains is conveniently termed quartz " welding " or " pressure welding ", although the latter term has been applied also to pressure-solution textures lacking well defined authigenic silica (Gilbert, 1954). The duplex process of solution and deposition of quartz attending differential stress also was termed " load recrystallization ", " low stress flow " and " pseudoviscous flow " by Fairbairn (1949), who presents it as essentially Rieke's principle applied to polycrystalline aggregates. The mechanism envisaged is that of solution transfer of ions around crystals from points of higher to lower stress, but the possibility of lattice transfer of ions through crystals also has been raised (H. Seng, referred to by Fairbairn, 1949).

The major source of the authigenic silica in the current-bedded sandstones probably was extraformational, the silica originating either from pressure solution in other " presolved " beds (Heald, *ibid*), or as a result of solution of quartz accompanying the passage of connate or ground-water in other beds, but solution from portions of the same bed is not excluded. The latter (ground-water) process operating either intra- or extraformationally, and either locally or over wider areas during weathering, presumably accounts also for the surface deposition of silica known as " case hardening " (Osborne, 1948). This feature was not specifically investigated in the present study, although the secondary enlargement in the current-bedded sandstones may be one of its manifestations.

Irrespective of the " source type ", incomplete silica cementation occurs at the site of large pre-existing voids. In the welded sandstone, if the abutting of quartz outgrowths contributed to stress equilibrium, authigenic silica first resulted from but later partly controlled pressure solution. Although continued application of load stress to quartzose sandstone would tend

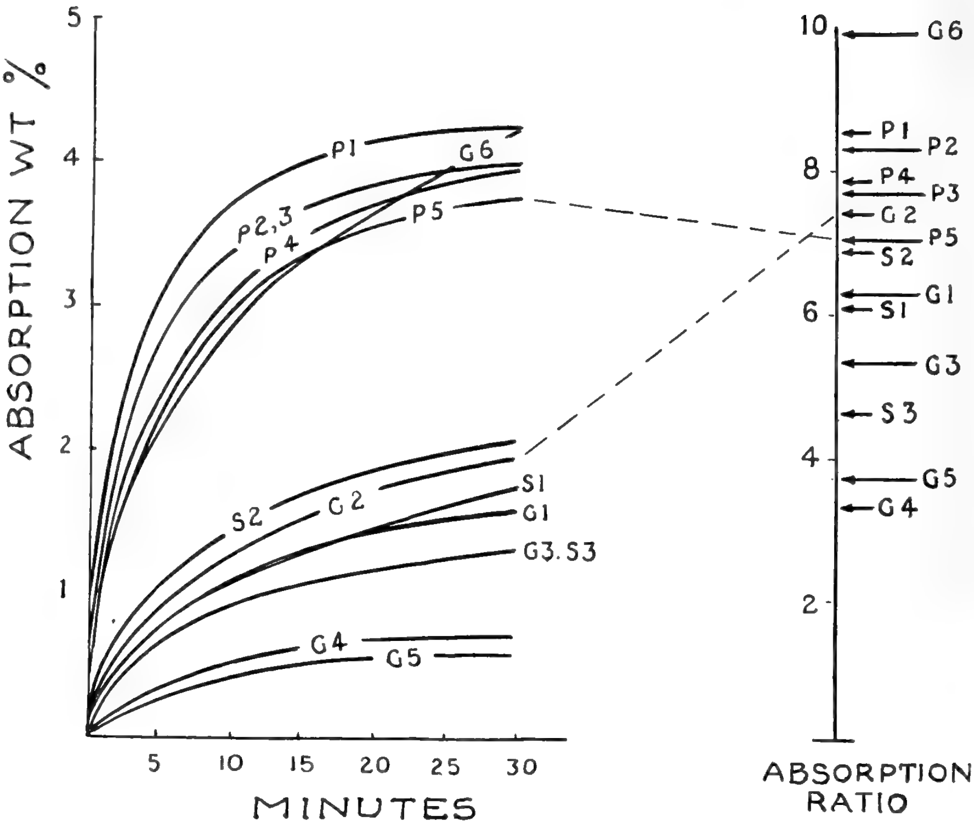

FIG. 4

Initial Rate of Water Absorption (left) and Absorption Ratio (right) of sandstones from Piles Creek (P), Sydney (S) and Gosford (G).
The vertical scale (per cent weight of water absorbed) in the right-hand diagram is one-half that in the left-hand diagram

to produce quartzite (Fairbairn, 1950), the achievement in nature of such " epi-zonal load metamorphism " is questionable (Turner and Verhoogen, 1951).

Physical Properties

Following a series of experiments to standardize procedure (Golding, 1956*b*), physical tests were made using 4 cm sub-sample cubes after drying them at 105° C for twenty-four hours, or, for the two highly argillaceous types G4 and G5, forty-eight hours. Usually three sub-samples per field sample have been tested to obtain a mean value for the required parameter.

Initial rate-of-absorption curves (Fig. 4, left-hand diagram) were obtained by weighing surface dried " blotted " (Edwards, 1950) cubes after each of six successive five-minute immersions in water at N.T.P., mean values for per cent. weight absorption (of dry cube weight) being plotted against time.

A distinctive two-fold grouping of these curves separates all Piles Creek samples together with the Gosford banded specimen G6 in the upper group from the remaining samples in the lower. The former group, under the test conditions, absorbed water at a rate from twice to eight times that of the latter, while within the upper group the flattening of the Piles Creek curves after about ten minutes was barely perceptible for sample G6. These results reflect variation in a complex of factors of which pore-size distribution and " labyrinth " (Niggli, 1954) or " tortuosity " (Scheidegger, 1957) factors are more significant than total interconnected porosity, while swelling of clay accompanying imbibition of water also may be involved to a minor degree. Such swelling would be substantially of a non-lattice-expanding type (Williamson, 1955) in illitic-kaolinitic clays.

In order to compare the density and porosity of samples, dried cubes were evacuated at 2·5 cm Hg pressure, covered with water, the exhaustion being maintained until bubbles ceased to rise from the specimens, and immersion continued to constant weight of the surface dried specimens. From the absorption ratios (per cent. weight increment of dry weight) thus obtained (Fig. 4, right-hand diagram) and bulk volumes, bulk and grain specific gravities and porosities have been computed (Parasnis, 1952; A.S.T.M., 1952).

In general the sequence of the initial rate of absorption curves is maintained for the absorption ratios, and hence for the computed porosities, but some departures occur (Fig. 4, broken lines), the pronounced two-fold grouping of the former being replaced by a more uniform spread of values for the latter.

The mean values and ranges obtained for bulk dry specific gravity, grain specific gravity (which approximates the weighted average specific gravity of the constituents), and porosity (which approximates the ratio of the interconnected pore volume to the bulk volume) are given in Table II.

The maximum range in mean values for bulk specific gravity and porosity is shown by the specialized Gosford types with bulk and grain specific gravities and porosities respectively of about 2·5, 2·74 and 9 (G5) as compared with 2·1, 2·69 and 21 (G6). The values for central level Gosford and Sydney samples are rather similar: about 2·3, 2·71 and 15, but these contrast with values for Piles Creek sandstone of about 2·2, 2·66 and 17.

The Piles Creek samples show decreasing porosity with depth. This probably is a weathering effect, as suggested by the relatively broader range of values for sub-samples of the uppermost sample (P1) from this quarry, in which over-burden is absent. The weathered sample G2 shows a somewhat similar range of values among sub-samples. The unweathered Gosford samples, however, decrease in porosity upwards and sub-sample values for the uppermost samples (G4 and G5) show a high degree of homogeneity. This is due partly to "sub-modal" stratigraphic variation within the quarry with grain size decreasing upwards, but is also due to the protection afforded by some fifty feet of cover in the quarry.

Relation of Petrographic to Physical Property Trends

In Fig. 5 some petrographic and physical property trends are compared for samples arranged in order of decreasing sand content from left to right, a sequence also resulting in a modal grouping in the order: Piles Creek, Sydney and Gosford.

Dominant trends include the sympathetic variation of sand content, grain size and, excluding sample G6, initial rate of water absorption, and the inverse sympathetic variation of clay and carbonate contents with bulk and grain density.

The reciprocal relation between the initial rate of absorption and grain density reflects variation in mineral composition of the samples. Thus the rate of absorption decreases but the

TABLE II

Density and Porosity of Sandstone Samples

Sample No.	No. of Sub-samples Tested	Bulk Dry S.G.		Grain S.G.		Porosity	
		Mean	Range	Mean	Range	Mean	Range
P 1	2	2·18	2·143–2·220	2·66	2·660–2·668	18·1	16·7–19·5
P 2	2	2·19	2·190–2·190	2·67	2·665–2·670	17·7	17·6–17·9
P 3	3	2·22	2·203–2·240	2·66	2·659–2·660	16·7	15·9–17·2
P 4	3	2·22	2·220–2·220	2·67	2·665–2·670	16·9	16·7–17·0
P 5	3	2·25	2·245–2·260	2·66	2·660–2·668	15·3	15·2–15·3
S 1	3	2·33	2·331–2·337	2·71	2·710–2·710	13·9	13·7–14·0
S 2	3	2·29	2·290–2·294	2·71	2·709–2·714	15·5	15·4–15·5
S 3	3	2·39	2·389–2·400	2·70	2·696–2·700	11·1	10·9–11·3
G 1	2	2·32	2·315–2·321	2·70	2·696–2·697	14·2	14·1–14·4
G 2	4	2·27	2·261–2·315	2·72	2·710–2·721	16·5	14·7–16·9
G 3	3	2·39	2·393–2·396	2·73	2·725–2·729	12·3	12·1–12·4
G 4	2	2·51	2·515–2·515	2·73	2·730–2·735	7·9	7·8– 7·9
G 5	3	2·49	2·489–2·498	2·74	2·731–2·738	8·9	8·8– 8·9
G 6	4	2·13	2·098–2·150	2·69	2·680–2·690	20·6	19·7–21·5

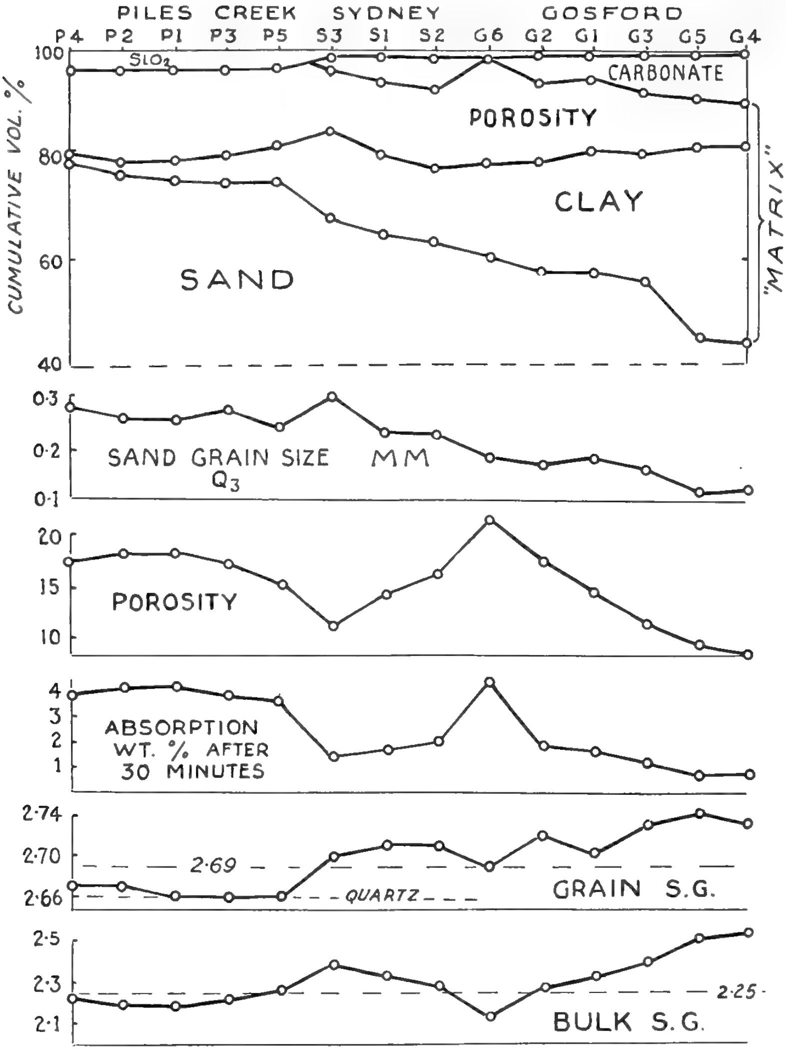

Fig. 5

Variation in petrographic attributes and physical properties for samples arranged in order of decreasing sand content from left to right

grain density increases with content of clay (the specific gravity of illites varies from 2·64 to 2·69 or higher ; Grim, 1953), and carbonates (calcite : 2·71 to siderite : 3·89).

Davis (1954) computed the approximate porosities of sandstones from their bulk densities, assuming an average grain density for all sandstones of 2·66, i.e. the value for quartz. Davis's formula applied to the present samples gave results for porosity from 1·5 to 2·5 below those obtained by the method outlined above, except for the Piles Creek specimens, for which the difference was negligible.

Values of 2·25 for bulk specific gravity and of 2·69 for grain specific gravity (broken lines in Fig. 5) and a corresponding blank field from 2·2 to 3·7 per cent. absorption after 30 minutes, separate carbonate from non-carbonate bearing sandstones.

A guide to the clay compaction in the samples is provided by the following clay-matrix ratios :

Piles Creek, 6 to 32 ; Gosford (G6), 46 ; Paddington, 47–52 ; Maroubra, 62 ; Gosford (other than G6), 63 to 83 per cent. " average " clay compaction.

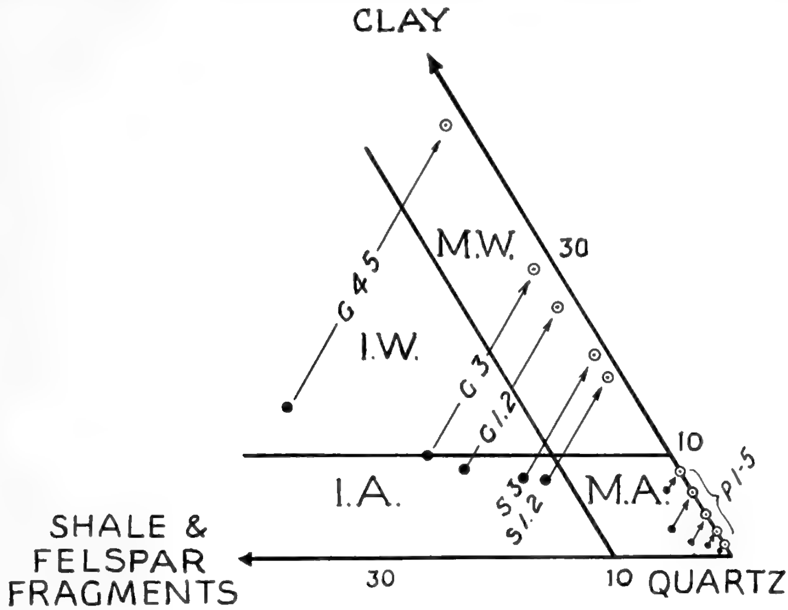

FIG. 6

Possible diagenetic evolution of sandstones from Piles Creek (P), Sydney (S) and Gosford (G) quarries. I.W., M.W. : immature, mature wacke ; I.A., M.A. : immature, mature arenite ; ⊙ : present sandstone ; ● : progenitor

Major Petrologic Determinants of Physical Constitution

Petrologic determinants of present physical constitution include depositional (syngenetic) and post-depositional (diagenetic) factors. Since the former also are those invoked in genetic classifications of sandstones, a brief consideration of classification is here appropriate.

Applying Gilbert's basic genetic classification to the present types, all three modes belong to the broad class of mature wackes (impure sandstones), or, substituting clay content (matrix minus porosity) for matrix, the Piles Creek specimens plot (Fig. 6) as mature arenites (pure sandstones). Sedimentational considerations, however, seem to support the view that much of the present clay originated as sand grade material of which shale predominated over feldspar fragments.

The Maroubra sandstone occupies a narrow channel in coarser beds, while the Gosford deposit lenses out rapidly to the east. At the base of the latter deposit and also in the Bondi quarry shale inclusions up to several inches long occur. These features suggest the erosion and redeposition after relatively slight transport of sandstones and shales, with the production of a final sediment rich in newly contributed shale particles of all size grades, but lacking new contributions of feldspar, the particle size of which would be diminished as a result of two cycles of erosion.

Possible progenitors of the present sandstones therefore also have been indicated in Fig. 6 by reallocating two-thirds of the present clay as unstable (lithic rather than feldspathic) constituents, while arrows in the diagram indicate the directions of diagenetic advancement of " maturity " which are envisaged.

As well as reflecting local depositional conditions, the variation in the original sediments may correspond to a broader sequence of sandstone types. The sequence of sandstones referred to is :

Wianamatta : lithic and feldspathic,
Hawkesbury : quartzose, and
Narrabeen : lithic and quartzose,

recorded for the area by Hanlon, Osborne and Raggatt (1954), Lovering (1954), and Crook (1956).

More significant than the original clay-shale ratio as a determinant of present physical constitution in the three modes, however, was the ratio of total plastic material (clay plus shale plus silt) to hard (quartz) sand, the typical end-member (Piles Creek and Gosford) types having advanced along lines of contrasted constitutional adjustment to load stress which are usefully related to this one dominant factor, although concomitant variables such as grain-size necessarily are involved.

Thus the Piles Creek sandstone is thought to have originated as a quartz-rich sand with some "clean" intergrain voids containing water but most others including loosely aggregated clay. Load stresses acting mainly on the quartz grains resulted in moderate welding which only partly destroyed the "clean" macroporosity, while the clay, protected by the bridging of surrounding quartz grains, remained relatively uncompacted and macroporous. Since the loci of maximum suturing also are those of maximum silica cementation, small groups, about 0·5 mm wide, of relatively well-bonded grains, are separated from similar groups by domains, about 1 mm wide, of weak bonding. The resulting rock is a rather friable, low-density, quartz-framework sandstone with considerable syngenetic macroporosity.

By contrast, the Gosford sandstones appear to derive from sands which contained numerous shale and quartz grains and which lacked clean macropores since the intergrain spaces were filled with clay, silt-grade feldspar and carbonate. Much of the load stress acted upon shale grains, resulting in their mechanical merging with the clay and silt to which some of the stress also was transmitted, while illite authigenesis, augmenting clay compaction from within, completed the destruction of the residual syngenetic macroporosity. These sandstones thus are denser, quartz-clay aggregate types, lacking, or barely achieving, a continuous framework of hard grains but characterized by a continuum of compacted and reconstituted clay, strengthened by carbonate cement, which provides a strong bond for the quartz grains themselves reinforced by minor welding.

Transecting these two main evolutionary trends is a modification induced by specialized syngenetic and diagenetic or weathering conditions. Thus periodic local detrital accumulations of mica and graphite resulted in bedding planes (sample G6) which apparently facilitated the passage of later solutions which penetrated the massive bands, effecting the initial removal of carbonate and the subsequent minor precipitation of iron oxides on the walls of the cavities so provided. This diagenetically induced or restored macroporosity accounts for the physical properties which simulate those of the Piles Creek sandstone.

The Sydney sandstones are considered to derive from sands of intermediate types, the subsequent roles of quartz welding and of clay compaction having been about equal.

The present physical constitution is thus the resultant of syngenetic and diagenetic factors, the former to some extent controlling the latter. In terms of incipient metamorphism (Pettijohn, 1957) variation between the three modes reflects differences in type rather than rank, the decemented Gosford sandstone representing a retrograde development.

During the weathering of such sandstones those effects dependent on the passage of solutions (e.g. removal of clay, "case hardening", crystallization of salts) presumably would be more significant for macroporous than for microporous types in which, however, stresses, promoted by swelling of clay, might induce deformation or fracture in some conditions. Low amplitude microstylolites, "lubricated" along seams with talc-like microporous illite and graphitic or carbonaceous matter, probably would contribute to small scale spalling.

While petrographic and experimental data are mutually supplementary for elucidating the history and physical constitution of these sandstones, on the basis of the relations recorded above, either set of data in conjunction with lithological observations, for generally similar samples from the area, would enable some degree of prediction of the other.

Further studies bearing on the foregoing might include those on the texture of current-bedded sandstones from unweathered locations, on the nature and incidence of channel fillings within the Hawkesbury Sandstone, on the extension into Wianamatta beds of microstylolites, on the stability of siderite during weathering and on further physical properties. Pending such investigations the present study provides initial data for reference in problems of utilization of the sandstones examined and the types characterized may serve for comparison with others, particularly those from massive, uniform lenses, encountered within the area.

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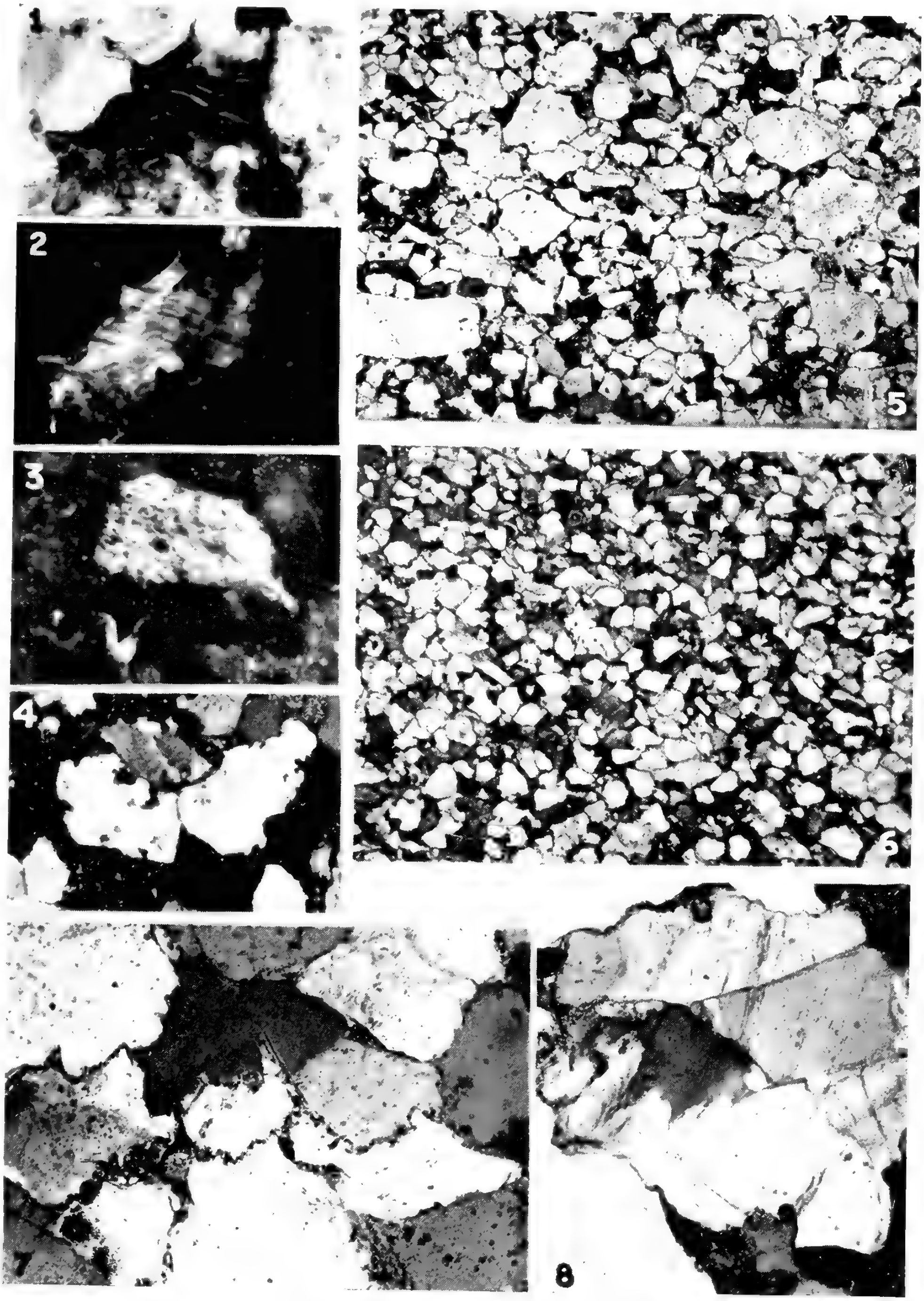
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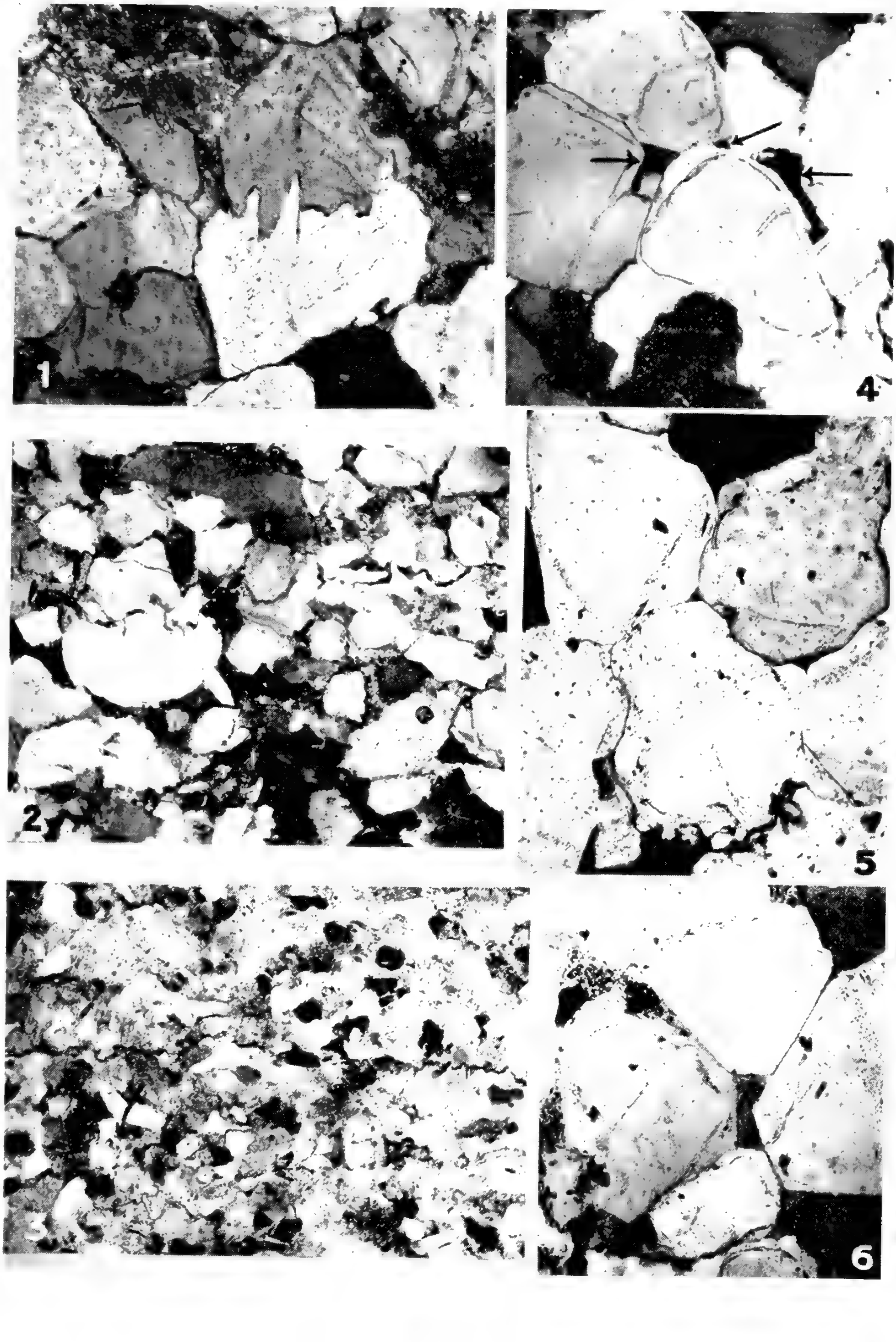
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Explanation of Plates I and II

Plate I

Fig. 1—Contorted biotite peppered with opaque leucoxenic (?) "dust" in Paddington sandstone, ×66, ordinary light.

Fig. 2—As Fig. 1, inclined incident light.

Fig. 3—Slightly crushed pitted leucoxenic grain and (below) "plastic" leucoxene "schlieren", in Gosford sandstone (G6), ×90, inclined incident light.

Fig. 4—Quartz grain (centre) showing faceted outgrowths separated by irregular, semi-circular and wedge-shaped clay-filled embayments; Piles Creek sandstone (P2), horizontally cut thin section, ×66.

Fig. 5—Piles Creek sandstone (P3), vertically cut thin section, ordinary light, ×13. Field dimensions: 5 mm×4 mm. Slice impregnated prior to sectioning with phenolic resin stained with methyl violet. Most areas of argillaceous matrix (dark) have stained wholly or partially. Uneven grainsize, quartz-framework character and some elongation are apparent.

Fig. 6—Gosford sandstone (G2), vertically cut thin section, ordinary light, ×13. Field dimensions and section preparation as last. Most areas of argillaceous matrix appear dark. Areas of matrix (including a little carbonate cement) are equal to or greater than areas of associated quartz grains in contrast to Fig. 5 (above).

FIG. 7—Piles Creek sandstone (P2), vertically cut thin section, ×90, showing zone of well sutured contacts, with illite films along contacts.

FIG. 8—Piles Creek sandstone (P3), vertically cut thin section, ×90, showing interpenetration sutures (lower centre), a straight contact (above) resulting from uniform mutual solution and (lower right) partial secondary rims.

PLATE II

FIG. 1—Piles Creek sandstone (P4), diagonally cut thin section, showing short microstylolite with sharp interpenetration suturing and " dovetail " quartz-clay contact, ×66. (See Text-Fig. 3.)

FIG. 2—Paddington sandstone (S1), vertically cut thin section, ×34, showing microstylolite traversing the boundaries of numerous pairs of grains.

FIG. 3—Gosford sandstone (G4), vertically cut thin section, ×34, showing low amplitude carbonaceous microstylolitic (?) seam.

FIG. 4—Piles Creek sandstone (P4), horizontally cut thin section, ×60, showing zone of well developed but incomplete silica cementation. Arrows indicate large " clean " macropores (short diameters : 10–50 mu) bounded by facet traces. Moulded straight edges with re-entrant angles and " dust rings " are evident.

FIG. 5—Current bedded Hawkesbury sandstone (MC1), randomly cut thin section, ×80, showing types of cementation interlock resulting from variation in distance between detrital outlines, and differential rate of silica deposition on grains, in the plane of the thin section. Triangular areas (centre) are macropores. Repetition of semi-circular and " cored " breaks in the secondary rim result in a crenellated marginal feature (lower centre).

FIG. 6—Same thin section as last. Straight edges bounding the large central macropore are crystal facet traces ; other grain outlines include straight-edged traces of moulded planes and approximately straight or sinuous junctions of authigenic outgrowths in the plane of the thin section.

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On Some of the Singularities of the Hankel Transform

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ABSTRACT—If $F(z)=\int_0^\infty xJ_\nu(zx)f(x)dx$, where $f(x)\sim Ax^ce^{-bx}$, $b=B+i\beta$, $B\geqslant 0$, $c=C+i\gamma$ as $x\to\infty$, it is shown that

(i) when $B>0$, $F(z)$ is analytic in the strip $|\operatorname{Im} z|<\operatorname{Re} b$ and possesses a singularity at $z=\pm ib$,

(ii) if $B=0$ and z real, there is a discontinuity at $z=\beta$, when $-1\frac{1}{2}\leqslant C<-\frac{1}{2}$.

The nature of the singularities and discontinuities are determined.

1

The Hankel transform $f(x)$ of a function $F(z)$, such that $z^{\frac{1}{2}}F(z)$ belongs to $L^1(0,\infty)$ may be written in the form

$$f(x)=\int_0^\infty zJ_\nu(xz)F(z)dz$$

where

$$J_\nu(t)=\sum_{r=0}^{\infty}\frac{(-1)^r(\frac{1}{2}t)^{\nu+2r}}{r!\Gamma(\nu+r+1)}.$$

The inversion formula is

$$F(z)=\int_0^\infty xJ_\nu(zx)f(x)dx \qquad (1.1)$$

in which

(i) $x^{\frac{1}{2}}f(x)$ belongs to $L^1(0,X)$ for all $X>0$, and .... (1.2a)

(ii) the integral exists as a Cauchy limit at the upper end. .... (1.2b)

We will examine some of the singularities of $F(z)$ determined from formula (1.1) for a large class of functions for which

$$f(x)\sim Ax^ce^{-bx},\ b=B+i\beta,\ B\geqslant 0,\ c=C+i\gamma \qquad (1.3)$$

as $x\to\infty$. It will be assumed throughout that the constant A will be different from zero.

When $B>0$, it will be seen that $F(z)$ is analytic in a strip on the z-plane, but when $B=0$, this strip will reduce to the real axis. When $B=0$ we will consider that $F(z)$ is defined only for real positive values of z. In this case, by a singularity we will understand a discontinuity.

If $f(x)=0$ for all $x>X$, it is obvious that $z^{-\nu}F(z)$ is analytic for all z (Griffith, 1955). In our case, it will be found that the singularities occur at $z=\pm ib$ and that the type of singularity will be determined by c and ν.

The author has found the results of this paper rather useful in confirming his suspicions of misentries in tables of transforms.

The general method adopted to determine our results is to replace the Bessel function by its asymptotic formula for large x, and then show that the behaviour of $F(z)$ near one of the singularities can be found from the behaviour of an integral of the type

$$\int_1^\infty e^{-ux}x^{c+\frac{1}{2}}dx,\quad \int_1^\infty x^{c+\frac{1}{2}}\cos uxdx,\ \text{or}\ \int_1^\infty x^{c+\frac{1}{2}}\sin uxdx$$

as $u\to 0+$.

2

Writing

$$w=\tfrac{1}{2}\nu\pi+\tfrac{1}{4}\pi \quad (2.1)$$

we know that

$$J_\nu(zx)=(\tfrac{1}{2}\pi zx)^{-\frac{1}{2}}\cos(zx-w)[1+0(|zx|^{-1})] \quad (2.2)$$

as $x\rightarrow\infty$ $(z\neq 0)$ (Watson, Ch. 7).

If we assume that $B>0$, it is immediately obvious that the integral in (1.1) converges for all $|\operatorname{Im} z|<B$ and that $z^{-\nu}F(z)$ is analytic in this strip. The same conclusions would follow if we replaced equation (1.3) by $f(x)=0(x^c e^{-Bx})$ for some $B>0$ as $x\rightarrow\infty$.

We restrict z to lie in the neighbourhood N of ib defined by

$$N:\ -\tfrac{1}{2}\pi-\varphi<\arg(z-ib)<-\tfrac{1}{2}\pi+\varphi,\ 0<\varphi<\tfrac{1}{2}\pi,\ 0<|z-ib|<B.$$

Then we may write

$$\begin{aligned}F(z)&=\int_0^X xJ_\nu(zx)f(x)dx+\int_X^\infty xJ_\nu(zx)f(x)dx\\&=Z_1(z)\qquad\qquad\qquad\quad +Z_2(z)\end{aligned} \quad (2.3)$$

where X has been chosen so large that

$$f(x)=Ax^c e^{-bx}[1+p(x)] \quad (2.4)$$

where $|p(x)|<\varepsilon<1$ for all $x>X$, and

$$J_\nu(zx)=(2\pi zx)^{-\frac{1}{2}}e^{iw}e^{-izx}[1+q(zx)] \quad (2.5)$$

where $|q(zx)|<\varepsilon<1$ for all $x>X$ and all z in N.
Now $z^{-\nu}Z_1(z)$ is analytic for all z (including ib), and

$$Z_2(z)=(2\pi z)^{-\frac{1}{2}}e^{iw}A[Z_3(z)+Z_4(z)] \quad (2.6)$$

where

$$Z_3(z)=\int_X^\infty e^{-(b+iz)x}x^{c+\frac{1}{2}}dx$$

and

$$Z_4(z)=\int_X^\infty e^{-(b+iz)x}x^{c+\frac{1}{2}}[p(x)+q(zx)+p(x)q(zx)]dx.$$

Now as z approaches ib along the line $\operatorname{Re} z=-\beta$, $b+iz$ is real and positive. This fact allows us to use Doetsch, p. 256, Theorem 1, to see that as z approaches ib along any line in N

$$Z_3(z)\sim\Gamma(c+1\tfrac{1}{2})(b+iz)^{-c-1\frac{1}{2}} \quad (2.7)$$

provided that $C>-1\tfrac{1}{2}$.

Writing $z=u+iv$,

$$|Z_4(z)|<3\varepsilon\int_X^\infty e^{-(B-v)x}x^{C+\frac{1}{2}}dx<3\varepsilon\Gamma(C+1\tfrac{1}{2})(B-v)^{-C-1\frac{1}{2}} \quad (2.8)$$

In this last inequality, we observe that since z lies in N, $B-v>|b-iz|\cos\varphi$ and that ε may be chosen arbitrarily small. So we use equations (2.3), (2.6), (2.7) and (2.8) to show that

$$F(z)\sim(2\pi ib)^{-\frac{1}{2}}e^{iw}A\Gamma(c+1\tfrac{1}{2})(b+iz)^{-c-1\frac{1}{2}}$$

as $z\rightarrow ib$ from below. More simply, we may write

$$z^{-\nu}F(z)\sim(2\pi)^{-\frac{1}{2}}A\Gamma(c+1\tfrac{1}{2})b^{-\nu-\frac{1}{2}}(b+iz)^{-c-1\frac{1}{2}} \quad (2.9)$$

There is no necessity to make an explicit discussion of the singularity at $z=-ib$, since $z^{-\nu}F(z)$ is even in z.

In order to obtain a result for the case $c=-1\frac{1}{2}$, we require a formula.

From $\int_0^\infty e^{-ux}x^{p-1}dx=u^{-p}\Gamma(p)$, $p>0$ we obtain

$$\int_1^\infty e^{-ux}x^{p-1}dx+\int_0^1 x^{p-1}(e^{-ux}-1)dx=u^{-p}\Gamma(p)-p^{-1},\ p>-1\ ;$$

the right side must be replaced by $\Gamma'(1)-\log u$ when $p=-1$.
Thus

$$\int_1^\infty e^{-ux}x^{-1}dx\sim-\log u+\Gamma'(1)+0(u) \quad \ldots\ldots\ldots\ldots\ldots\ldots (2.10)$$

as $u\to 0+$ (Re $u>0$).

Applying this result to $Z_3(z)$ and $Z_4(z)$, we obtain

$$Z_3(z)\sim-\log(b+iz)+\Gamma'(1)-\log X+0(u)$$

and

$$Z_4(z)\sim 3\varepsilon[-\log(B-v)+\Gamma'(1)-\log X+0(u)]$$

as $z\to ib$ (in N). Since the first terms of the right sides dominate the other terms, we write

$$F(z)\sim-(2\pi ib)^{-\frac{1}{2}}e^{iw}A\log(b+iz)$$

and

$$z^{-\nu}F(z)\sim-(2\pi)^{-\frac{1}{2}}Ab^{-\nu-\frac{1}{2}}\log(b+iz).$$

A summary of the work of this section is

Theorem 2 :—If (1.1), (1.2) and (1.3) hold, then

(*a*) $z^{-\nu}F(z)$ is analytic in the strip $|\operatorname{Im} z|<\operatorname{Re} b$, and

(*b*) $z^{-\nu}F(z)\sim(2\pi)^{-\frac{1}{2}}A\Gamma(c+1\frac{1}{2})b^{-\nu-\frac{1}{2}}(b\pm iz)^{-c-1\frac{1}{2}}$, if Re $c>-1\frac{1}{2}$

$\sim-(2\pi)^{-\frac{1}{2}}Ab^{-\nu-\frac{1}{2}}\log(b\pm iz)$, if $c=-1\frac{1}{2}$,

as $z\to\pm ib$ along any straight line inside the strip.

3

We now examine the case when $C<-1\frac{1}{2}$ (and incidentally $C=-1\frac{1}{2}$, $\gamma\neq 0$).

Our reason for expressing the results in the form of Theorem 3 below is that we require an " infinity " at the singularity.

In §2, we observed that if $f(x)\sim Ax^ce^{-bx}$ as $x\to\infty$, $z^{-\nu}F(z)$ is analytic in the strip $|\operatorname{Im} z|<B$ for any c. The recurrence formula (Watson, p. 46) shows that

$$(-1)^m\left[\frac{d}{zdz}\right]^m z^{-\nu}F(z)=z^{-\nu-m}\int_0^\infty xJ_{\nu+m}(zx)x^mf(x)dx. \quad \ldots\ldots\ldots\ldots (3.1)$$

Thus $(d/zdz)^mz^{-\nu}F(z)$ is analytic in the same strip at $F(z)$.

Suppose that $c\neq-p-\frac{1}{2}$ for $p=1, 2, 3, \ldots$, in fact assume that

$$-p-1\tfrac{1}{2}<C\leqslant-p-\tfrac{1}{2}$$

for some positive integer p, the equality holding only when $\gamma\neq 0$. Thus $-1\frac{1}{2}<C+p\leqslant-\frac{1}{2}$.

From equation (1.3), we see that

$$x^p f(x) \sim A x^{c+p} e^{-bx} \text{ with } C+p > -1\tfrac{1}{2} \quad \text{(3.2)}$$

as $x \to \infty$. Then by Theorem 2

$$\left[\frac{d}{zdz}\right]^p z^{-\nu} F(z) \sim (2\pi)^{\frac{1}{2}} (-1)^p A \Gamma(c+p+1\tfrac{1}{2}) b^{-\nu-p-\frac{1}{2}} (b \pm iz)^{-c-p-1\frac{1}{2}} \quad \text{(3.3)}$$

with $\operatorname{Re} c > -p-1\frac{1}{2}$ as $z \to \pm ib$ from inside the strip $|\operatorname{Im} z| < \operatorname{Re} b$.

Similarly, we may show that when $c = -p-1\frac{1}{2}$ with p a positive integer

$$\left[\frac{d}{zdz}\right]^{p-1} z^{-\nu} F(z) \sim (2\pi)^{-\frac{1}{2}} (-1)^p A b^{-\nu-p+\frac{1}{2}} \log (b \pm iz) \quad \text{(3.4)}$$

as $z \to \pm ib$ from inside the strip $|\operatorname{Im} z| = \operatorname{Re} b$.

The summary of these results is

Theorem 3 :—If the assumptions of Theorem 2 hold, we have

(*c*) if $-p-1\frac{1}{2} < \operatorname{Re} c < -p-\frac{1}{2}$ or $c = -p-\frac{1}{2}$ with $\operatorname{Im} c \neq 0$, equation (3.3) holds, and

(*d*) if $c = -p-\frac{1}{2}$, equation (3.4) holds, p being a positive integer.

We close this section with the remark that neither Theorem 2 nor 3 implies that there is only one singularity on the line $\operatorname{Im} z = \operatorname{Re} b$.

4

We now assume that $\operatorname{Re} b = B = 0$. The integral in equation (1.1) diverges for all non-real z. In order that $F(z)$ should be defined on the real axis we must add an additional restriction that $\operatorname{Re} c = C < -\frac{1}{2}$.

When $C < -2\frac{1}{2}$, it is obvious that the integral for $F(z)$ converges absolutely and that $F(z)$ is differentiable for all real $z > 0$.

Now assuming that $-2\frac{1}{2} \leqslant C < -1\frac{1}{2}$, we may prove that $F(z)$ is continuous for $z > 0$.

Using the notation of equation (2.3), where $Z_1(z)$ is continuous (differentiable), we may write

$$Z_2(z) = z^{-\frac{1}{2}} \int_X^\infty (zx)^{\frac{1}{2}} J_\nu(zx) x^{-\delta} [x^{\frac{1}{2}+\delta} f(x)] dx$$

with $0 < \delta < -C-1\frac{1}{2}$. Thus

$$Z_2(z) < X^{-\delta} z^{-\frac{1}{2}} \int_X^\infty |(zx)^{\frac{1}{2}} J_\nu(zx)| \,.\, |x^{\frac{1}{2}+\delta} f(x)| \, dx$$

where the integral is bounded for all $z > h > 0$ (any h). Then by a suitable choice of X we may make $Z_2(z)$ arbitrarily small. This shows that $F(z)$ is continuous for $z > 0$.

A review of the last few remarks shows that with trivial modifications we may prove that

(*a*) if $f(x) = 0(x^c)$, $\operatorname{Re} c < -2\frac{1}{2}$ as $x \to \infty$, then $F(z)$ is differentiable for all $z > 0$; and that

(*b*) if $f(x) = 0(x^c)$, $\operatorname{Re} c < -1\frac{1}{2}$ as $x \to \infty$, then $F(z)$ is continuous for all $z > 0$.

Considering Erdelyi (p. 47 (2) and p. 33 (5) corrected), we note that, in general, functions for which $-2\frac{1}{2} \leqslant \operatorname{Re} c < -1\frac{1}{2}$ have not differentiable images.

5

We will assume in this section that $C=-1\frac{1}{2}$. In order to present the results in the most convenient form, we will assume that

$$f(x)=Ax^c \cos(\beta x+\zeta)+f_1(x), \text{ for } x>1,\ \beta>0 \quad \ldots\ldots\ldots\ldots\ (5.1)$$

where $f_1(x)=0(x^k)$ as $x\to\infty$, $\operatorname{Re} k<-1\frac{1}{2}$.

We will derive some formulae needed later.

From the known formula

$$\int_0^\infty x^{p-1}\cos uxdx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p),\ 0<\operatorname{Re} p<1$$

we obtain

$$\int_1^\infty x^{p-1}\cos uxdx+\int_0^1 x^{p-1}(\cos ux-1)dx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p)-p^{-1},$$

which holds for $-1<\operatorname{Re} p<1$ provided that when $p=0$, we replace the right side by $\Gamma'(1)-\log u$.

Thus as $u\to 0+$,

$$\int_1^\infty x^{p-1}\cos uxdx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p)-p^{-1}+0(u^2)$$

if $-1<\operatorname{Re} p<1$ and $p\neq 0$, and

$$\int_1^\infty x^{-1}\cos uxdx=-\log u+\Gamma'(1)+0(u^2).$$

Similarly from

$$\int_0^\infty x^{p-1}\sin uxdx=u^{-p}\Gamma(p)\sin(\tfrac{1}{2}\pi p),\ -1<\operatorname{Re} p<1$$

we obtain that as $u\to 0+$

$$\int_1^\infty x^{p-1}\sin uxdx=u^{-p}\Gamma(p)\sin(\tfrac{1}{2}\pi p)+0(u)$$

if $-1<\operatorname{Re} p<1$ and $p\neq 0$, and

$$\int_1^\infty x^{-1}\sin uxdx=\tfrac{1}{2}\pi+0(u).$$

Combining the results, we have as $u\to 0+$

$$\int_1^\infty x^{p-1}\cos(ux+\alpha)dx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p+\alpha)-p^{-1}\cos\alpha+0(u) \quad \ldots\ (5.2a)$$

$-1<\operatorname{Re} p<1$, $p\neq 0$, and

$$\int_1^\infty x^{-1}\cos(ux+\alpha)dx=-\cos\alpha[\log u-\Gamma'(1)]-\tfrac{1}{2}\pi\sin\alpha+0(u). \quad \ldots\ (5.2b)$$

Referring back to equation (4.1), we write

$$\begin{aligned} Z_2(z)&=\int_X^\infty Ax^{c+1}\cos(\beta x+\zeta)J_\nu(zx)dz+\int_X^\infty xJ_\nu(zx)f_1(x)dx \\ &= \qquad Z_3(z) \qquad + \qquad Z_4(z) \qquad \ldots\ldots\ (5.3)\end{aligned}$$

in which $Z_4(z)$ is continuous (by §4).

By a suitable choice of X, we are enabled to write

$$(\tfrac{1}{2}\pi z)^{\frac{1}{2}} Z_3(z) = \int_X^\infty A x^{c+\frac{1}{2}} \cos(\beta x+\zeta)[\cos(xz-w)+p(zx)]dx$$

with $|p(zx)| < E(zx)^{-1}$, (E a constant). Then

$$(\tfrac{1}{2}\pi z)^{\frac{1}{2}} Z_3(z) = Z_5(z)+Z_6(z)+Z_7(z) \quad \ldots\ldots\ldots\ldots (5.4)$$

where

$$Z_5(z) = \tfrac{1}{2}A\int_X^\infty x^{c+\frac{1}{2}} \cos[(\beta-z)x+w+\zeta]dx \quad \ldots\ldots\ldots (5.5a)$$

$$Z_6(z) = \tfrac{1}{2}A\int_X^\infty x^{c+\frac{1}{2}} \cos[(\beta+z)x+w+\zeta]dx \quad \ldots\ldots\ldots (5.5b)$$

and

$$Z_7(z) = A\int_X^\infty x^{c+\frac{1}{2}} \cos(\beta x+\zeta)p(xz)dx. \quad \ldots\ldots\ldots (5.5c)$$

It is obvious that we may modify our choice of X to make $Z_7(z)$ arbitrarily small. $Z_6(z)$ is clearly continuous. $Z_5(z)$ is continuous for all $z\neq\beta$.

The results in equations (5.2a, b) now show that when $\gamma\neq 0$,

$$Z_5(z) = \tfrac{1}{2}A\Gamma(i\gamma)\cos(w+\zeta\mp\tfrac{1}{2}i\gamma)|z-\beta|^{-i\gamma} - \tfrac{1}{2}A(i\gamma)^{-1}X^{i\gamma}\cos(w+\zeta)+0(|z-\beta|) \quad \ldots (5.6)$$

as $z\to\beta\pm$.

when $\gamma=0$

$$Z_5(z) = -\tfrac{1}{2}A\cos(w+\zeta)[\log|X(z-\beta)|-\Gamma'(1)]\pm\tfrac{1}{4}A\pi\sin(w+\zeta)+0(|z-\beta|) \quad \ldots (5.7)$$

as $z\to\beta\pm$.

From these results we derive

Theorem 5 :—If

(*a*) (1.1), (1.2) hold and $z>0$;
(*b*) $f(x=Ax^c\cos(\beta x+\zeta)+f_1(x)$ for $x>1$, $\beta>0$; $f_1(x)=0(x^k)$ as $x\to\infty$ with Re $k<-1\tfrac{1}{2}$,
(*c*) $c=-1\tfrac{1}{2}+i\gamma$

then the only discontinuity of $F(z)$ is at $z=\beta$, and

(i) when $\gamma\neq 0$,

$$F(z)\sim(2\pi\beta)^{-\frac{1}{2}}A\Gamma(i\gamma)\cos(w+\zeta\mp\tfrac{1}{2}i\gamma)+P(\beta) \quad \ldots\ldots\ldots (5.8)$$

($P(\beta)$ being independent of z) as $z\to\beta\pm$;

(ii) when $\gamma=0$ and $\cos(w+\zeta)\neq 0$,

$$F(z)\sim-(2\pi\beta)^{-\frac{1}{2}}A\cos(w+\zeta)\log|z-\beta| \quad \ldots\ldots\ldots (5.9)$$

as $z\to\beta\pm$;

(iii) when $\gamma=0$ and $\cos(w+\zeta)=0$

$F(z)$ has saltus of $A(\pi/2\beta)^{\frac{1}{2}}\sin(w+\zeta)$ at $z=\beta$. .... (5.10)

Proof. We recall that X was chosen to make $Z_7(z)$ arbitrarily small. If we consider only $z>h>0$ where $h<\beta$, we may choose X independently of z. Then equation (5.8) follows from equations (5.6) and equations (5.9) and (5.10) follow from equation (5.7).

6

We now assume that $f(x)$ satisfies the assumptions of Theorem 5 except that now $-1\frac{1}{2}<\text{Re}\,c<-\frac{1}{2}$. The corresponding theorem is

Theorem 6 :—If in the assumptions of Theorem 5, (c) is replaced by $-1\frac{1}{2}<\text{Re}\,c<-\frac{1}{2}$, then the only discontinuity of $F(z)$ is at $z=\beta$, and

$$F(z)\sim(2\pi\beta)^{-\frac{1}{2}}A\Gamma(c+1\tfrac{1}{2})\cos(\tfrac{1}{2}c\pi+\tfrac{3}{4}\pi\mp w\mp\zeta)|z-\beta|^{-c-1\frac{1}{2}}+P(\beta)$$

as $z\to\beta\pm$, provided that at least one value of $\cos(\frac{1}{2}c\pi+\frac{3}{4}\pi\mp w\mp\zeta)$ does not vanish. If both values of $\cos(\frac{1}{2}c\pi+\frac{3}{4}\pi\mp w\mp\zeta)$ vanish then $F(z)$ is continuous for $z>0$.

The proof of this theorem differs only trivially from the derivation of equation (5.8) and will not be given.

For the same of completeness we observe that if $\beta=\zeta=0$, then $Z_3(z)$ may be written in the form

$$Z_3(z)=Az^{-c-1\frac{1}{2}}\int_{Xz}^{\infty} y^{c+\frac{1}{2}}J_\nu(y)dy$$

(from equation (5.2)). Thus $Z_3(z)$ is clearly continuous for $z>0$.

Then if, in the enunciations of Theorems 5 and 6 we assume that $\beta=0$, we may conclude that $F(z)$ is continuous for $z>0$.

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Distribution of Stress in the Neighbourhood of a Wedge Indenter

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ABSTRACT—Wedge indentation techniques play a prominent role in testing ductile materials for hardness. Elastic stress states within the indented materials are of interest as a pointer to elastic-plastic behaviour. This paper presents the solution of a new wedge indentation problem for the state of plane elastic strain.

Statement of the Problem

A semi-infinite elastic medium " occupies " the lower half (of the complex) plane. The tip of a wide-angled rigid wedge, the profile of which is shown in Fig. 1, is brought into contact with the elastic half-plane at the origin O. The sides of the wedge AD and BC are vertical and the face AOB is frictionless.

The equation of the face of the wedge before a force is applied is

$$y=-\varepsilon x \quad \text{for } -l \leqslant x \leqslant 0$$
$$y=\varepsilon x \quad \text{for } 0 \leqslant x \leqslant l \qquad \text{(1)}$$

and ε is small (this being a requirement of small deformation). A vertical force P_0 causes the wedge to move vertically and to indent the half plane, the force P_0 being sufficiently large to bring the corners A and B into contact with the boundary of the half-plane.

Solutions are obtained for

(i) the distribution of pressure along the face of the wedge,
(ii) the stress components within the elastic medium,
(iii) the lines of constant maximum shear stress within the elastic medium (isochromatic lines).

The special case when the force P_0 is insufficient to bring the corners A and B of the wedge into contact with the elastic half-plane is also considered. The solution obtained in this case agrees with an earlier solution obtained by other methods and the earlier solution is extended.

The methods used to obtain the solution of the present problem are based on the work of N. I. Muskhelishvili (1953*a*).

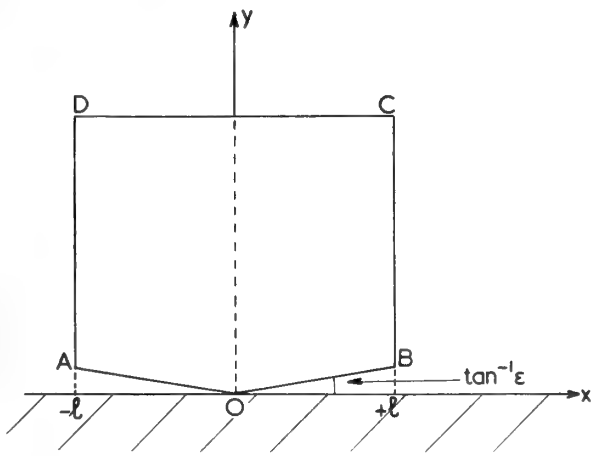

FIG. 1.

Basic Elastic Theory for the Half-Plane

We denote the upper half-plane by S^+, the lower half-plane by S^- and the real axis by L. The stress components X_x, Y_y, X_y and the displacement components u, v for the state of plane stress are given by Muskhelishvili's equations 112.1, 112.2, 112.3 (1953*a*), i.e.

$$X_x + Y_y = 2[\Phi(z) + \overline{\Phi(z)}] \quad \ldots \quad (2)$$

$$Y_y - X_x + 2iX_y = 2[\bar{z}\Phi'(z) + \Psi(z)] \quad \ldots \quad (3)$$

$$2\mu(u+iv) = \varkappa\varphi(z) - z\overline{\varphi'(z)} + \overline{\psi(z)} \quad \ldots \quad (4)$$

where $\Phi(z) = \varphi'(z) = \frac{d\varphi}{dz}$; $\Psi(z) = \psi'(z)$, are functions holomorphic in S^-. The functions $\varphi(z)$, $\psi(z)$ are arbitrary functions arising from the solution of the bi-harmonic equation, μ is the shear modulus, and $\varkappa = 3 - 4\sigma$, σ being Poisson's ratio. The bar denotes the complex conjugate.

The elastic region is stressed by forces acting on the boundary L. It is assumed that the resultant vector (X,Y) of the external forces acting on the boundary L is finite, and that the stresses and rotation vanish at infinity. Thus we have, for large $|z|$,

$$\Phi(z) = -\frac{X+iY}{2\pi z} + o\left(\frac{1}{z}\right) \quad \ldots \quad (5)$$

$$\Psi(z) = \frac{X-iY}{2\pi z} + o\left(\frac{1}{z}\right) \quad \ldots \quad (6)$$

By defining $\Phi(z)$ in the upper half-plane as

$$\Phi(z) = -\bar{\Phi}(z) - z\bar{\Phi}'(z) - \Psi(z) \text{ for } z \text{ in } S^+ \quad \ldots \quad (7)$$

(where $\bar{\Phi}(z) = \overline{\Phi(\bar{z})}$, etc.), the function $\Phi(z)$ is analytically continued from the lower half-plane into the upper half-plane through the unloaded parts of the boundary. (See Muskhelishvili, 1953*a*, § 112).

Using this analytic continuation we can write

$$\Psi(z) = -\Phi(z) - \bar{\Phi}(z) - z\Phi'(z) \text{ for } z \text{ in } S^- \quad \ldots \quad (8)$$

and hence equations (2) and (3) can be rewritten in terms of one arbitrary function $\Phi(z)$ thus:

$$X_x + Y_y = 2[\Phi(z) + \bar{\Phi}(\bar{z})] \quad \ldots \quad (9)$$

$$Y_y - X_x + 2iX_y = 2[(\bar{z} - z)\Phi'(z) - \Phi(z) - \bar{\Phi}(z)] \quad \ldots \quad (10)$$

Adding equations (9) and (10) and taking the complex conjugate, we have

$$Y_y - iX_y = \Phi(z) - \Phi(\bar{z}) + (z - \bar{z})\bar{\Phi}'(\bar{z}) \quad \ldots \quad (11)$$

Differentiating equation (4) partially with respect to x and substituting for $\Psi(z)$ given by equation (8) we obtain

$$2\mu(u' + iv') = \varkappa\Phi(z) + \Phi(\bar{z}) - (z - \bar{z})\bar{\Phi}'(\bar{z}) \quad \ldots \quad (12)$$

Equations (9), (10), (11), (12) are the formulae required in the sequel.

Boundary Conditions in the General Case

Assume that the profile of a rigid stamp, before being pressed into the elastic half-plane, has the equation $y = f(x)$. A force P_0 applied vertically (in such a way that the stamp moves vertically downward) brings the stamp into contact with the boundary of the elastic body along a segment *ab* of the real axis.

After the force has been applied the equation of the profile referred to axes O_x, O_y will be

$$y=f(x)+c,$$

where c is a real constant.

A point of the elastic body, occupying the position $(t,0)$ before deformation, $(a\leqslant t\leqslant b)$ and after deformation the position $(t+u,v)$ must lie on the curve $y=f(x)+c$. Thus neglecting small terms (assuming u and $f'(t)$ are small) we have

$$v=f(t)+c \quad \text{where } a\leqslant t\leqslant b \qquad (13)$$

Equation (13) gives the normal displacement v^- of points on the boundary of the elastic half-plane.

Since friction is absent along the face of the stamp, the shear stress is zero on the boundary underneath the stamp as well as on the unloaded parts of the boundary. Hence the boundary conditions may be written

$$X_y^-=0 \text{ everywhere on } L \qquad (14)$$

$$Y_y^-=0 \text{ on } L-ab \qquad (15)$$

$$v^-=f(t)+c \text{ on } ab \qquad (16)$$

Provided $\Phi(z)$ is defined in the upper half-plane as in equation (7) it is clear from equations (14) and (15) that $\Phi(z)$ is holomorphic in the entire plane cut along ab.
From equation (11), if $z\to t$ from S^-, and using equation (14) we have

$$Y_y^-=\Phi^-(t)-\Phi^+(t) \text{ on } L \qquad (17)$$

where $\Phi^+(t)$ and $\Phi^-(t)$ are the left and right boundary values of $\Phi(z)$. It follows from this equation (Muskhelishvili, 1953*a*, p. 473) that

$$\bar{\Phi}(z)=-\Phi(z) \qquad (18)$$

Equation (18) must be verified once $\Phi(z)$ has been found.

Now from equation (12), if $z\to t$ from S^-,

$$2\mu(u'^-+iv'^-)=\varkappa\Phi^-(t)+\Phi^+(t) \qquad (19)$$

Taking the complex conjugate of this expression we have

$$2(u'^- - iv'^-)=\varkappa\bar{\Phi}^+(t)+\bar{\Phi}^-(t) \qquad (20)$$

Subtracting equation (20) from equation (19) and using equation (18) yields

$$4\mu iv'^-=(\varkappa+1)\{\Phi^+(t)+\Phi^-(t)\}$$

and since $v'^-=f'(t)$ on ab we have

$$\Phi^+(t)+\Phi^-(t)=\frac{4\mu if'(t)}{\varkappa+1} \text{ on } ab \qquad (21)$$

(The assumption $v'^-=(v^-)'$ on ab used here may be verified if need be, after the solution has been constructed. We rely here on the " reasonableness " of the assumption.)

Equation (21) represents a special case of the Hilbert boundary value problem (Muskhelishvili, 1953*a*, § 107) in which $G(t)=-1$. $\Phi(z)$ can be determined from equation (21) and the general solution of the Hilbert problem (Muskhelishvili, 1953*a*, equation 110.33) provided $f'(t)$ satisfies certain conditions.

In § 115 Muskhelishvili (1953*a*, p. 473) requires that $f'(t)$ satisfy the Hölder condition (*idem*, p. 258) on the segment ab. In the problem to be considered, $f'(t)$ has a simple discontinuity at a given point of ab, so that the Hölder condition is not satisfied at all points of ab. However, this is of no consequence. The validity of the solution will remain for points on ab other than the point of simple discontinuity.

(For a discussion of this point see Woods (1958), Chapter 3, also Reichel (1958), § 2. For a description of $\Phi(z)$ at the point of simple discontinuity and at the ends of ab, see Muskhelishvili (1953*b*), § 33, also Reichel (1958), § 2.)

Because of the existence of the discontinuity in $f'(t)$ the Cauchy integral in the solution (see below) cannot be solved by the contour methods suggested by Muskhelishvili (1953*a*, p. 445).

Appropriate formal substitution in Muskhelishvili's equation 110.33 yields

$$\Phi(z)=\frac{2\mu}{\pi(\varkappa+1)(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}}\int_a^b \frac{\sqrt{(t-a)(t-b)}f'(t)dt}{t-z}+\frac{D}{(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}} \quad \ldots\ldots (22)$$

where D is a real constant.

The branch of the function $(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}$ is so chosen that

$$(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}=-i(z-a)^{\frac{1}{2}}(z-b)^{\frac{1}{2}} \quad \ldots\ldots (23)$$

The value of the constant D is determined from the fact that for large $|z|$ (equation (5))

$$\Phi(z)=\frac{iP_0}{2\pi z}+o\left(\frac{1}{z}\right) \quad \ldots\ldots (24)$$

where $-P_0$ is the given resultant vector of the external force.

Also from equation (23), for large $|z|$,

$$(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}=-iz+0(1).$$

Hence, for large $|z|$, equation (22) gives

$$\Phi(z)=\frac{D}{-iz}+0\left(\frac{1}{z^2}\right) \quad \ldots\ldots (25)$$

Comparison of equations (24) and (25) shows that $D=P_0/2\pi$.

The pressure $P(t)$ exerted by the stamp on the boundary ab underneath the stamp can be determined from equation (17) once $\Phi(z)$ has been found. In fact

$$P(t)=-Y_y^-=\Phi^+(t)-\Phi^-(t) \quad \ldots\ldots (26)$$

In order that a solution may be physically possible it is necessary that $P(t)$ be positive or zero for $a \leqslant t \leqslant b$.

We assume in the first instance that the segment ab of contact between the stamp and the elastic half-plane has the same given length whatever the value of P_0, i.e. as P_0 increases the segment of contact remains the same length. This corresponds to the case where the stamp has corners A and B in contact with the half-plane. In this case (in accordance with the behaviour of $\Phi(z)$ at the ends of ab and at the point of discontinuity of $f'(t)$ on ab) $P(t)$ will be unbounded at the ends of ab and at the point of discontinuity of $f'(t)$ on ab. This behaviour does not represent a valid part of the solution of the given boundary value problem. Near these points of contact the medium ceases to behave elastically.

If P_0 is less than the value required to bring the corners A and B of the stamp (wedge) into contact with the boundary of the half-plane, a smaller segment ab will be the region of contact and the pressure $P(t)$ remains bounded at the ends a, b (but not at any " corner point " of the stamp between a and b). The condition on P_0 for boundedness of $P(t)$ at the ends of ab will give the values of a and b for the given (diminished) P_0. Alternatively, if a and b are given (so that ab is less than " arc " AB) the condition for boundedness of $P(t)$ at the ends of ab will give the value of P_0 necessary to make contact along the given segment.

Solution of the Wedge Indentation Problem

We now apply the general results of the foregoing to the specific problem stated at the outset. The segment ab of the foregoing is now denoted by $(-l,l)$.

The normal displacement v^- of the boundary between $-l$ and l is given by

$$v^- = -\varepsilon t + c \text{ for } -l \leqslant t \leqslant 0$$
$$\text{and } v^- = +\varepsilon t + c \text{ for } 0 \leqslant t \leqslant l \quad \ldots\ldots (27)$$

The function $\Phi(z)$ can be determined from equation (22) in which we must put

$$f'(t) = -\varepsilon \quad \text{on} \quad -l \leqslant t < 0$$
$$= +\varepsilon \quad \text{on} \quad 0 < t \leqslant l.$$

Clearly $f'(t)$ satisfies the Hölder condition on $(-l,l)$ except at the origin.
Therefore

$$\Phi(z) = \frac{2\mu}{\pi(\varkappa+1)(l^2-z^2)^{\frac{1}{2}}} F(z) + \frac{P_0}{2\pi(l^2-z^2)^{\frac{1}{2}}} \quad \ldots\ldots (28)$$

where

$$F(z) = -\varepsilon \int_{-l}^{0} \frac{(l^2-t^2)^{\frac{1}{2}}}{t-z} dt + \varepsilon \int_{0}^{l} \frac{(l^2-t^2)^{\frac{1}{2}}}{t-z} dt \quad \ldots\ldots (29)$$

Consider the integrals for $F(z)$ first. To evaluate* (29) we first replace t by $-t$ in the first integral and combine with the second. Thus

$$\frac{F(z)}{\varepsilon} = \int_0^l \frac{(l^2-t^2)^{\frac{1}{2}} 2t\,dt}{t^2-z^2} \quad \ldots\ldots (30)$$

We let

$$z^2 = l^2 + \zeta^2 \quad \ldots\ldots (31)$$

and we make the change of variable

$$t^2 = l^2 - \zeta^2 u^2 \quad \ldots\ldots (32)$$

to obtain

$$\frac{F(z)}{\varepsilon} = \int_{l/\zeta}^{0} \frac{\zeta u . -2\zeta^2 u\,du}{-\zeta^2(1+u^2)} = -2\zeta \int_0^{l/\zeta} \frac{u^2 du}{1+u^2} = -2l + 2\zeta \tan^{-1}(l/\zeta) \quad \ldots\ldots (33)$$

The conformal transformation (31) transforms the z-plane cut along $(-l,l)$ of the real axis to the ζ-plane with a cut joining $+il$ and $-il$ of the imaginary axis (taking $\zeta = +il$ as the image of $z=0$). As ζ covers this cut plane l/ζ covers the complex plane cut along the whole imaginary axis except for the interval joining the branch points $+i$ and $-i$ of $\tan^{-1}(l/\zeta)$.

Expression (33) is clearly regular in this region.

Hence

$$F(z) = \varepsilon[-2l + 2(z^2-l^2)^{\frac{1}{2}} \tan^{-1}\{l(z^2-l^2)^{-\frac{1}{2}}\}] \quad \ldots\ldots (34)$$

is clearly regular in the z-plane cut along $(-l,l)$ of the real axis so that (34) is the required solution of (29). We require only that z should not lie on the segment $(-l,l)$ of the real axis. Equation (34) can be rewritten in logarithmic form, which is in some ways more convenient for later work. After some simplification we obtain

$$F(z) = \varepsilon\left[-2l + 2i(z^2-l^2)^{\frac{1}{2}} \log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} + \pi(z^2-l^2)^{\frac{1}{2}}\right] \quad \ldots\ldots (35)$$

* The author is grateful to Mr. W. B. Smith-White for this elegant evaluation. The author's own evaluation was much longer.

The boundary values $F^+(t)$ and $F^-(t)$ of $F(z)$ are obtained from equation (29) by applying the Plemelj formulae (Muskhelishvili, 1953*a*, equations 68.2, 68.3, 68.4). From Muskhelishvili's equation 68.4 we obtain

$$F^+(t)-F^-(t)=-2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } -l<t<0$$
$$+2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } 0<t<l \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(36)}$$

To find F^+t and $F^-(t)$ individually we must evaluate the integral

$$\overline{\int}=\frac{1}{2\pi i}\overline{\int}_{(-l,l)}\frac{f(t)dt}{t-t_0}$$

where

$$f(t)=-2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } -l<t<0$$
$$=+2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } 0<t<l.$$

(The bar over the summa indicates that the integral is to be taken in the sense of Cauchy Principal Value, since t_0 is any point on $(-l,l)$ excluding the origin and the ends.)

Consider first the case when $0<t_0<l$. Now

$$\overline{\int}=-\varepsilon\int_{-l}^{0}\frac{(l^2-t^2)^{\frac{1}{2}}}{t-t_0}dt+\varepsilon\overline{\int}_0^l\frac{(l^2-t^2)^{\frac{1}{2}}dt}{t-t_0}.$$

Replace t by $-t$ in the first integral and combine with the second, i.e.

$$\overline{\int}=\varepsilon\overline{\int}_0^l\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}$$
$$=\lim_{\delta\to 0}\varepsilon\int_0^{t_0-\delta}\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}+\lim_{\delta\to 0}\varepsilon\int_{t_0+\delta}^{l}\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}$$

Write $t_0-\delta=P$ and $t_0+\delta=Q$ and consider

$$I=\int_0^P\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}+\int_Q^l\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}.$$

Write $t_0^2=l^2-\zeta^2$ (ζ real) and make the substitution $t^2=l^2-\zeta^2u^2$.
Thus

$$I=\int_{l/\zeta}^{(l^2-P^2)^{\frac{1}{2}}/\zeta}\frac{\zeta u.-2\zeta^2udu}{\zeta^2(1-u^2)}+\int_{(l^2-Q^2)^{\frac{1}{2}}/\zeta}^{0}\frac{\zeta u.-2\zeta^2udu}{\zeta^2(1-u^2)}$$
$$=2\zeta\left[-\frac{l}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+l}{\zeta-l}\right]$$
$$-2\zeta\left[-\frac{(l^2-P^2)^{\frac{1}{2}}}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+(l^2-P^2)^{\frac{1}{2}}}{\zeta-(l^2-P^2)^{\frac{1}{2}}}\right]$$
$$+2\zeta\left[-\frac{(l^2-Q^2)^{\frac{1}{2}}}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+(l^2-Q^2)^{\frac{1}{2}}}{\zeta-(l^2-Q^2)^{\frac{1}{2}}}\right].$$

Using the results

$$(l^2-Q^2)^{\frac{1}{2}}<\zeta<(l^2-P^2)^{\frac{1}{2}}<l$$

and

$$\lim_{\delta\to 0}\frac{(l^2-P^2)^{\frac{1}{2}}-\zeta}{\zeta-(l^2-Q^2)^{\frac{1}{2}}}=1 \text{ (from de l'Hopital's Rule)}$$

we find finally, after allowing $\delta\to 0$, that

$$\lim_{\delta\to 0} \mathrm{I}=-2l+\zeta \log \frac{l+\zeta}{l-\zeta}.$$

Thus we may write

$$\overline{\int}=\varepsilon[-2l-2(l^2-t_0^2)^{\frac{1}{2}}\{\log [l-(l^2-t_0^2)^{\frac{1}{2}}]-\log t_0\}].$$

Thus applying Muskhelishvili's equations 68.2 (1953*a*) we have for $0<t<l$

$$F^+(t)=\varepsilon[-2l-2(l^2-t^2)^{\frac{1}{2}}\{\log [l-(l^2-t^2)^{\frac{1}{2}}]-\log t\}+i\pi(l^2-t^2)^{\frac{1}{2}}] \quad \ldots\ldots \quad (37)$$

In the case when $-l<t_0<0$, the integral

$$\overline{\int}=-\varepsilon\overline{\int_{-l}^{0}}\frac{(l^2-t^2)^{\frac{1}{2}}dt}{t-t_0}+\varepsilon\int_{0}^{l}\frac{(l^2-t^2)^{\frac{1}{2}}dt}{t-t_0}$$

may be evaluated by first replacing t by $-t$ in the second integral and combining with the first. The same methods as before yield, for $-l<t'<0$ and if $\log t'$ means $\log|t'|$,

$$F^+(t')=\varepsilon[-2l-2(l^2-t'^2)^{\frac{1}{2}}\{\log [l-(l^2-t'^2)^{\frac{1}{2}}[-\log t'\}-i\pi(l^2-t'^2)^{\frac{1}{2}}] \quad \ldots\ldots \quad (38)$$

The boundary values $F^-(t)$ and $F^-(t')$ may be written down from equation 68.3 (Muskhelishvili, 1953*a*) and the foregoing, thus

$$F^-(t)=\varepsilon[-2l-2(l^2-t^2)^{\frac{1}{2}}\{\log [l-(l^2-t^2)^{\frac{1}{2}}]-\log t\}-i\pi(l^2-t^2)^{\frac{1}{2}}] \quad \ldots\ldots \quad (39)$$

$$F^-(t')=\varepsilon[-2l-2(l^2-t'^2)^{\frac{1}{2}}\{\log [l-(l^2-t'^2)^{\frac{1}{2}}]-\log t'\}+i\pi(l^2-t'^2)^{\frac{1}{2}}] \quad \ldots\ldots \quad (40)$$

In the sequal the boundary values of $(z^2-l^2)^{\frac{1}{2}}$ are required. We define (see Fig. 2)

$$(z-l)^{\frac{1}{2}} \text{ as } r_1^{\frac{1}{2}}e^{i\alpha/2}$$
$$(z+l)^{\frac{1}{2}} \text{ as } r_2^{\frac{1}{2}}e^{i\beta/2} \quad \ldots\ldots \quad (41)$$

Then $\alpha=\pi$, $\beta=0$ for $z\to t$ on the left side of $(-l,l)$. (This is consistent with the behaviour of the chosen branch of $(z-a)^{\frac{1}{2}}(b-z)^{\frac{1}{2}}$ in similar circumstances. See equation (23).)
Thus at t^+ (i.e. $0<t<l$ for $z\to t$ on the left side of $-l,l$): $(z^2-l^2)^{\frac{1}{2}}=(l^2-t^2)e^{i\pi/2}$.

At t^- $(0<t<l)$: $(z^2-l^2)^{\frac{1}{2}}=(l^2-t^2)^{\frac{1}{2}}e^{-i\pi/2}$
At t'^+ $(-l<t'<0)$: $(z^2-l^2)^{\frac{1}{2}}=(l^2-t'^2)^{\frac{1}{2}}e^{i\pi/2}$.
At t'^- $(-l<t'<0)$: $(z^2-l^2)^{\frac{1}{2}}=(l^2-t'^2)^{\frac{1}{2}}e^{i3\pi/2}$.

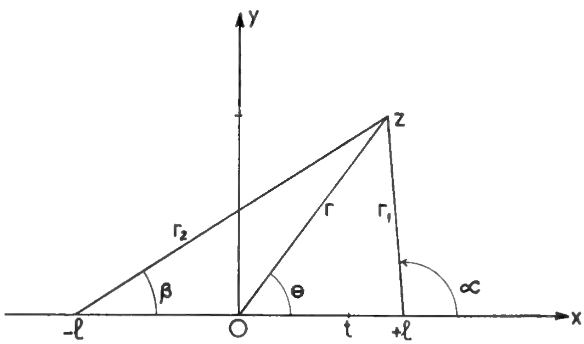

FIG. 2.

Returning now to equation (28), we can write

$$\Phi(z)=\frac{2\mu\varepsilon}{\pi(\varkappa+1)(l^2-z^2)^{\frac{1}{2}}}\left[-2l+2i(z^2-l^2)^{\frac{1}{2}}\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\}+\pi(z^2-l^2)^{\frac{1}{2}}\right]+\frac{P_0}{2\pi(l^2-z^2)^{\frac{1}{2}}} \quad \ldots\ldots (42)$$

Remembering that for the chosen branch of $(z^2-l^2)^{\frac{1}{2}}$ we have $(l^2-z^2)^{\frac{1}{2}}=-i(z^2-l^2)^{\frac{1}{2}}$, we can rewrite $\Phi(z)$ as

$$\Phi(z)=\left\{\frac{iP_0}{2\pi}-\frac{4\mu l\varepsilon i}{\pi(\varkappa+1)}\right\}\frac{1}{(z^2-l^2)^{\frac{1}{2}}}+\frac{2\mu\varepsilon i}{\varkappa+1}-\frac{4\mu\varepsilon}{\pi(\varkappa+1)}\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} \quad \ldots (43)$$

Pressure under Wedge and Stress Components

In the expression (43) for $\Phi(z)$ we let

$$A=\frac{iP_0}{2\pi}-\frac{4\mu l\varepsilon i}{\pi(\varkappa+1)}; \quad B=\frac{2\mu\varepsilon i}{\varkappa+1}; \quad C=\frac{4\mu\varepsilon}{\pi(\varkappa+1)}; \quad \ldots\ldots (44)$$

so that

$$\Phi(z)=\frac{A}{(z^2-l^2)^{\frac{1}{2}}}+B-C\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} \quad \ldots\ldots (45)$$

The left and right boundary values of $\Phi(z)$ can be written down using the left and right boundary values of $F(z)$ (equations 37, 38, 39, 40) and those of $(z^2-l^2)^{\frac{1}{2}}$.

Thus, for $0<t<l$,

$$\Phi^+(t)=\frac{A}{i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log[l-(l^2-t^2)^{\frac{1}{2}}]-\log t\} \quad \ldots\ldots (46)$$

$$\Phi^-(t)=\frac{A}{-i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log t-\log[l-(l^2-t^2)^{\frac{1}{2}}]\} \quad \ldots\ldots (47)$$

so that

$$\Phi^+(t)-\Phi^-(t)=\frac{2A}{i(l^2-t^2)^{\frac{1}{2}}}+2C\log\frac{t}{l-(l^2-t^2)^{\frac{1}{2}}} \quad \ldots\ldots (48)$$

For $-l<t<0$, if $\log t=\log|t|$,

$$\Phi^+(t)=\frac{A}{i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log[l-(l^2-t^2)^{\frac{1}{2}}]-\log t+i\pi\} \quad \ldots\ldots (49)$$

$$\Phi^-(t)=\frac{A}{-i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log t-\log[l-(l^2-t^2)^{\frac{1}{2}}]+i\pi\} \quad \ldots\ldots (50)$$

so that

$$\Phi^+(t)-\Phi^-(t)=\frac{2A}{i(l^2-t^2)^{\frac{1}{2}}}+2C\log\frac{t}{l-(l^2-t^2)^{\frac{1}{2}}} \quad \ldots\ldots (51)$$

Equations (48) and (51) give the pressure on the boundary underneath the wedge (equation 26). Thus we may write, for $-l\leqslant t\leqslant l$ and using (44),

$$P(t)=2\left[\frac{P_0}{2\pi}-\frac{4\mu l\varepsilon}{\pi(\varkappa+1)}\right]\frac{1}{(l^2-t^2)^{\frac{1}{2}}}+\frac{4\mu\varepsilon}{\pi(\varkappa+1)}\log\frac{t^2}{\{l-(l^2-t^2)^{\frac{1}{2}}\}^2} \quad \ldots\ldots (52)$$

This is clearly an even function of t.

The solution is physically possible if $P(t)\geqslant 0$ for $-l\leqslant t\leqslant l$, i.e. if

$$P_0\geqslant\frac{8\mu l\varepsilon}{\varkappa+1} \qquad (53)$$

$P(t)$ is infinite at $t=-l$, $t=+l$, and $t=0$, so that the solution corresponds to the case when the corners of the wedge come into contact with the elastic half-plane.

$P(t)$ is bounded near the ends $-l$ and l if

$$P_0=\frac{8\mu l\varepsilon}{\varkappa+1} \qquad (54)$$

If $P_0<\frac{8\mu l\varepsilon}{\varkappa+1}$, this corresponds to the special case in which a diminished length of the indenter comes into contact with the elastic half-plane. If the diminished length of the indenter is denoted by $2l'$ $(l'<l)$, then

$$P_0=\frac{8\mu l'\varepsilon}{\varkappa+1} \qquad (55)$$

and for a given P_0 less than the critical value given by (54)

$$l'=\frac{(\varkappa+1)P_0}{8\mu\varepsilon}.$$

This special case is dealt with in the sequel.

The stress components can be found by substitution of $\Phi(z)$ given by equation (45) in equations (9) and (10).

Now $$\bar{\Phi}(z)=\overline{\Phi(\bar{z})}=\frac{\bar{A}}{(z^2-l^2)^{\frac{1}{2}}}+\bar{B}-\bar{C}\log\left\{\frac{l-i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} \qquad (56)$$

Now $$-\bar{C}\log\left\{\frac{l-i(z^2-l^2)^{\frac{1}{2}}}{z}\right\}=+\bar{C}\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\}$$

and since $\bar{A}=-A$, $\bar{B}=-B$, $\bar{C}=+C$, we have

$$\bar{\Phi}(z)=-\Phi(z).$$

Hence the requirement (18) is satisfied.

Now, $$\bar{\Phi}(\bar{z})=\frac{-A}{(\bar{z}^2-l^2)^{\frac{1}{2}}}-B-C\log\left\{\frac{l-i(\bar{z}^2-l^2)^{\frac{1}{2}}}{\bar{z}}\right\},\text{ whence}$$

$$\Phi(z)+\bar{\Phi}(\bar{z})=A\left[\frac{1}{(z^2-l^2)^{\frac{1}{2}}}-\frac{1}{(\bar{z}^2-l^2)^{\frac{1}{2}}}\right]-C\log\left\{\frac{[l+i(z^2-l^2)^{\frac{1}{2}}][l-i(\bar{z}^2-l^2)^{\frac{1}{2}}]}{z\bar{z}}\right\}$$

Putting $(z^2-l^2)^{\frac{1}{2}}=r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}e^{i(\alpha+\beta)/2}$, $(\bar{z}^2-l^2)^{\frac{1}{2}}=r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}e^{-i(\alpha+\beta)/2}$,
and $z=re^{i\theta}$, $\bar{z}=re^{-i\theta}$ (Fig. 2)
we find, after substituting for A, B and C, that

$$X_x+Y_y=\frac{4}{r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}}\left[\frac{P_0}{2\pi}-\frac{4\mu l\varepsilon}{\pi(\varkappa+1)}\right]\sin\frac{\alpha+\beta}{2}-\frac{8\mu\varepsilon}{\pi(\varkappa+1)}\left\{\frac{l^2-2r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}\sin\frac{\alpha+\beta}{2}+r_1r_2}{r^2}\right\} \qquad (57)$$

Since $\bar{\Phi}(z)=-\Phi(z)$, equation (10) reduces to

$$Y_y-X_x+2iX_y=2(\bar{z}-z)\Phi'(z)$$

so that

$$Y_y-X_x+2iX_y=\frac{-2(\bar{z}-z)}{(z^2-l^2)^{\frac{1}{2}}}\left[\frac{Az}{z^2-l^2}+\frac{Cli}{z}\right].$$

We find, after some algebra, substituting for A, C, z, z^2-l^2, etc., as before, using elementary trigonometric formulae and separating real and imaginary parts, that

$$Y_y-X_x=\frac{-P_0r^2}{r_1^{3/2}r_2^{3/2}}\left[2\sin\theta\cos\frac{2\theta-3(\alpha+\beta)}{2}\right]+\frac{8\mu l^3\varepsilon}{\pi(\varkappa+1)r_1^{3/2}r_2^{3/2}}\left[2\sin\theta\cos\frac{2\theta+3(\alpha+\beta)}{2}\right] \quad \text{.................. (58)}$$

$$X_y=\frac{P_0r^2}{r_1^{3/2}r_2^{3/2}}\left[\sin\theta\sin\frac{3(\alpha+\beta)-2\theta}{2}\right]-\frac{8\mu l^3\varepsilon}{\pi(\varkappa+1)r_1^{3/2}r_2^{3/2}}\left[\sin\theta\sin\frac{3(\alpha+\beta)+2\theta}{2}\right] \quad \text{.................... (59)}$$

It must be remembered that α, β, and θ will have negative values in the lower half-plane. Expressions for X_x and Y_y can be obtained by combining equations (57) and (58).

The maximum shearing stress across any plane through the point (x,y) can be calculated from the formula

$$T_{\max}=[(\tfrac{1}{2}X_x-\tfrac{1}{2}Y_y)^2+X_y{}^2]^{\frac{1}{2}} \quad \text{...................... (60)}$$

Appropriate substitution yields

$$T_{\max}=\frac{\sin\theta}{\pi r_1^{3/2}r_2^{3/2}}\left[P_0^2r^4+\frac{64\mu^2l^6\varepsilon^2}{(\varkappa+1)^2}-\frac{16P_0r^2\mu l^3\varepsilon\cos 2\theta}{\varkappa+1}\right]^{\frac{1}{2}} \quad \text{.............. (61)}$$

The isochromatic lines are given by the curves $T_{\max}=$constant.

Special Cases and a Previously Known Solution

In the case when the applied vertical force P_0 is not large enough to bring the end corners of the wedge into contact with the elastic boundary, a diminished length $2l'$ of the boundary touches the face of the wedge. This diminished length is given by equation (55) for a given P_0. The distribution of pressure under the face of the wedge is given by putting $l=l'$ and

$$P_0=\frac{8\mu l'\varepsilon}{\varkappa+1}$$

in expression (52) for $P(t)$, i.e.

$$P(t)=\frac{4\mu\varepsilon}{\pi(\varkappa+1)}\log\frac{t^2}{\{l'-(l'^2-t^2)^{\frac{1}{2}}\}^2} \quad \text{.................. (62)}$$

for $-l'\leqslant t\leqslant l'$.

Expressions for the stress components and maximum shear stress within the elastic medium can be obtained by putting $l=l'$ and $P_0=\dfrac{8\mu l'\varepsilon}{\varkappa+1}$ in the previous results or by deriving them anew from the corresponding expression for $\Phi(z)$. In this case

$$\Phi(z)=\frac{2\mu\varepsilon i}{\varkappa+1}-\frac{4\mu\varepsilon}{\pi(\varkappa+1)}\log\left\{\frac{l'+i(z^2-l'^2)^{\frac{1}{2}}}{z}\right\} \quad \text{.............. (63)}$$

This function $\Phi(z)$ satisfies the conditions of the problem and we find

$$X_x+Y_y=-\frac{8\mu\varepsilon}{\pi(\varkappa+1)}\log\left\{\frac{l'^2-2r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}\sin\frac{\alpha+\beta}{2}+r_1r_2}{r^2}\right\} \quad \ldots\ldots\ldots\ldots (64)$$

$$Y_y-X_x=-\frac{8\mu l'\varepsilon}{\pi(\varkappa+1)r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}}\left\{2\sin\theta\cos\frac{\alpha+\beta+2\theta}{2}\right\} \quad \ldots\ldots\ldots\ldots (65)$$

and

$$X_y=\frac{8\mu l'\varepsilon}{\pi(\varkappa+1)r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}}\sin\theta\sin\frac{\alpha+\beta+2\theta}{2} \quad \ldots\ldots\ldots\ldots (66)$$

(In these expressions the lengths r_1. r_2 are measured from l', $-l'$ respectively.)

The maximum shearing stress across any plane through the point (x,y) is obtained from equation (60) and we find

$$T_{\max}=\frac{8\mu l'\varepsilon\sin\theta}{\pi(\varkappa+1)r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots (67)$$

The isochromatic lines are given by the formula

$$|\sin\theta|=kr_1^{\frac{1}{2}}r_2^{\frac{1}{2}} \quad \ldots\ldots\ldots\ldots (68)$$

where k is a constant parameter.

Certain results for this special case have been obtained previously by a different method. The results are given in Sneddon's book (1951) and are apparently based on the work of H. G. Hopkins in a paper which at that time (1951) was unpublished. The results are obtained using Fourier transforms (Sneddon, 1951, pp. 43€, et. seq.). The only result of interest here, quoted explicitly by Sneddon, is the stress distribution on the boundary under the wedge. The result is expressed in terms of dimensionless co-ordinates and a special units system and has to be translated into the notation of this paper. Appropriate substitution yields the author's result, equation (62).

A second special case is given by putting $\varepsilon=0$ in equation (43) to obtain

$$\Phi(z)=\frac{P_0}{2\pi(l^2-z^2)^{\frac{1}{2}}}$$

This solution corresponds to the problem of a stamp with a straight horizontal base, in contact with the segment $(-l,l)$ of the real axis and under the action of a vertical force P_0. This solution is given by Muskhelishvili (1953*a*, § 116*a*).

Note—This paper is part of a thesis entitled " Determination of a Sectionally Holomorphic Function from a Problem of Hilbert with an Application in the Plane Theory of Elasticity " by the present author, written in partial fulfilment of the requirements for the degree of Master of Science, University of Sydney.

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Annual Reports by the President and the Council

Presented at the Annual Meeting of the Society, April 1, 1959.

The President's Report

At the end of my Address, I will complete my year as President of the Royal Society of New South Wales. The year has not been by any means arduous due to the magnificent co-operation given to me by the Secretaries, Treasurer and other members of Council.

It is with extreme regret that I have to draw your attention to the retirement from the Council of Dr. Ida Browne. If my understanding of the position is correct, she has been a member of Council for fifteen of the last seventeen years. Almost every year has seen her occupying some executive position. As you know, an ordinary member of Council must retire at the end of four years unless he then occupies an executive position. It is only pressure of outside work that has caused Dr. Browne to retire from the position of Editorial Secretary, and this retirement has of necessity forced her to retire from Council. I have not the faintest doubt that her name will be somewhere on the nomination form in two years' time.

I would like to draw your attention to the four conjoint meetings held during the year. As you all know, many of the Scientific Societies in New South Wales were once sections of the Society. These sections became large and then broke away and formed separate societies. It is one of the major aims of the Royal Society to co-operate with these societies, thereby bringing a unifying influence to all these professional groups. We feel that we have achieved something and are continuing this type of meeting. In June we will have a meeting with the Linnean Society.

Now it is one of the expressed aims of the Australian Academy of Science to co-operate with the Royal Societies of the various States in assisting and stimulating scientific work. The first step has been taken, by which this Society has just completed the organization of a Soil Science Committee under the chairmanship of Professor Crocker.

This liaison position between the Academy and scientist is the position which a modern Royal Society must occupy and must work to retain.

I would recommend the Journal of the Society as a field for publishing to all members of the Society. This should be of particular interest to my Mathematical colleagues. The delay in printing is now less than six months. The Journal is sent directly to *Mathematical Reviews*, a copy of which is sent to us in exchange. The Journal is sent to all countries in which scientific work is being done and in addition to many others. If a review is satisfactory an author is assured that his paper will be easily available.

Dr. Browne is organizing the fourth part of this year's Journal, which will be a very large commemorative issue. A number of the first-ranking geologists of Australia are contributing technical articles.

I would like to express my congratulations to Mr. Heffron on his success at the recent elections. Mr. Heffron has been a strong supporter of the Society during his term of office as Minister of Education. The increased Government subsidy received by the Society is entirely due to his efforts. I know that his interest will continue in the coming years.

One of my saddest duties during the year was to attend the funeral of one of our oldest members, Dr. Woolnough. Dr. Woolnough had been a President of the Society in 1926 and joined the Society in 1906. His interest in the Society did not diminish with his retirement. His astounding knowledge of a large number of languages was placed at the service of the Society. He cannot be replaced by any one man; and his passing was and still is a loss to the Society and to the community.

I must also make special comment of the loss of Dr. George Harker, who joined the Society in 1905. Dr. Harker had not been able over the last few years to attend the meetings of the Society as often as formerly. He left a bequest of £100, for which I express our appreciation.

During this year, I have had full co-operation from Miss Ogle, our only full-time member of staff, who has carried on with her usual efficiency, and from Mrs. Huntley, our librarian. Mrs. Huntley, after two years of very hard work, has now put the cataloguing in a reasonable condition. She informs me that there is still much to be done.

You will see that the retiring Council can be proud of its efforts. The Society's funds show a surplus and no loss of capital. It has co-operated more than ever with kindred societies, has taken steps to implement the aims of the Academy and has arranged the publication of its first commemorative part of the Journal. I feel that the Society is in a very happy position.

JAMES L. GRIFFITH,
President.

Report of the Council for the Year ended 31st March, 1959

At the end of the period under review the composition of *the membership* was 311 ordinary members, 4 associate members, 8 honorary members; 6 new members were elected and 15 members resigned. Four names were removed from the list of members under Rule XVIII. It is with regret that we announce the loss by death of Mr. Arthur J. Bedwell, Father Thomas N. Burke-Gaffney, Mr. George Z. Dupain, Mr. Roy H. Goddard, Mr. Charles A. Loney, Mr. Herbert J. Sullivan and Dr. Walter G. Woolnough.

Nine monthly *meetings* were held. The Proceedings of these meetings have been published in the notice papers and appear elsewhere in this issue of the "Journal and Proceedings". The members of Council wish to express their sincere thanks and appreciation to the 15 speakers who contributed to the addresses, symposia and commemorations, and also to the members who read papers at the November monthly meeting.

The meeting on 2nd July was devoted to a Commemoration of the centenary of the birth of Professor Sir T. W. Edgeworth David.

A feature of this year's activities was the holding of three meetings conjointly with other scientific societies. The Commemoration of the Centenary of the birth of Sir George Handley Knibbs was celebrated on 31st July with the Statistical Society of New South Wales, a symposium on " Food " was held with the Royal Australian Chemical Institute on 6th August, " Evaporation and the Water Cycle " was the subject of a meeting held on 1st October with the Institute of Physics, and on 19th March a lecture entitled " Why is it Dark at Night ", sponsored by the Society and the Institute of Physics, was delivered by Professor H. Bondi.

The *Annual Sherry Party and Buffet Tea* was held in the Holme and Sutherland Rooms, Sydney University Union, on 23rd March, at which the attendance was 41.

The *Clarke Medal* for 1959 was awarded to Mr. Tom Iredale for distinguished contributions in the field of zoology.

The *Society's Medal* for service to science and to the Royal Society of New South Wales was awarded to Mr. Frank R. Morrison.

The *Edgeworth David Medal* for 1958 was awarded to Dr. Paul I. Korner for outstanding work in the field of physiology.

The *Archibald D. Olle Prize* was awarded to Mr. Alex Reichel for his paper entitled " Boundary Stresses in an Infinite Hub of Special Shape " published in volume 91 of the Society's " Journal and Proceedings ".

The *Liversidge Research Lecture* for 1958 entitled " Modern Structural Inorganic Chemistry " was delivered by Dr. A. D. Wadsley.

Council is pleased to announce that the *Government subsidy* has been increased from £500 to £750. The Government's interest in the work of the Society is much appreciated.

The Society's *financial statement* shows a surplus of about £100.

During the year four parts of *the Journal* were published. Eleven papers have been accepted for reading and for publication in the first three parts of volume 92. Part 4, devoted to the commemoration of the centenary of the birth of Professor Sir T. W. Edgeworth David, will include invited papers from about twelve senior geologists who were associated with Professor David.

The *Section of Geology* held five meetings during the year. Dr. T. G. Vallance was Chairman and Dr. L. E. Koch was Honorary Secretary. The average attendance was about 22 members and visitors.

Council held eleven ordinary meetings. The attendance of members of Council was as follows: Mr. J. L. Griffith 11, Mr. H. A. J. Donegan 4, Mr. F. N. Hanlon 7, Mr. A. F. A. Harper 9, Mr. F. D. McCarthy 8, Dr. Ida A. Browne 10, Mr. H. W. Wood 11, Mr. C. L. Adamson 9, Dr. A. Bolliger 2, Mr. B. A. Bolt 9, Dr. F. W. Booker 3, Dr. A. A. Day 6, Dr. J. A. Dulhunty 5, Dr. R. M. Gascoigne 4, Mr. E. J. Harrison 1, Prof. D. P. Mellor 1, Mr. W. H. G. Poggendorff 8, Prof. G. Taylor 4, Mr. H. F. Whitworth 7.

At the meeting held 27th August, 1958, Dr. A. A. Day was appointed a Member of Council to fill the vacancy left when Dr. Bolliger resigned due to his departure for overseas.

The Society's representatives on *Science House Management Committee* were Mr. Griffith and Mr. Donegan; Mr. Harper and Mr. Poggendorff were substitute representatives.

The President and Honorary Secretary were both present at the Official Opening of the Atomic Research Establishment at Lucas Heights on 18th April, 1958.

The Society was represented by Professor Taylor at the Laying of the Foundation Stone of the Australian Academy of Science, 24th April, 1958.

The President attended the Commemoration of the 188th Anniversary of the Landing of Captain Cook at Kurnell.

The President attended the meeting of the Board of Visitors of the Sydney Observatory and the meeting of the Donovan Astronomical Trust.

The Library—Periodicals were received by exchange from 383 societies and institutions. In addition, the amount of £150 was expended on the purchase of 14 periodicals.

Among the institutions which made use of the Library through the inter-library loan scheme were :—

N.S.W. Govt. Depts.—Department of Health; Department of Mines; Forestry Commission; Soil Conservation Service; Water Conservation and Irrigation Commission; The Australian Museum.

Commonwealth Govt. Depts.—C.S.I.R.O. (Division of Animal Genetics, Sydney; Library, Canberra; Coal Research Section, Sydney; Division of Fisheries and Oceanography, Cronulla; National Standards Laboratory, Sydney; Sheep Biology Laboratory, Parramatta; Division of Industrial Chemistry, Melbourne; Plant and Soils Laboratory, Brisbane; Veterinary Parasitology Laboratory, Queensland; Division of Food Preservation, Homebush; Wool Textile Research Laboratory, Ryde); Australian Atomic Energy Commission; Bureau of Mineral Resources, Canberra.

Universities and Colleges—Sydney Technical College; Wollongong Technical College; University of New England; University of New South Wales; University College, Newcastle; University of Sydney; University of Melbourne; University of Queensland.

Public Libraries—Library Board of Western Australia; Public Library of Western Australia; Public Library of South Australia.

Companies—Austral Bronze Co., Sydney; Broken Hill Proprietary Co., Shortland; Colonial Sugar Refining Co., Sydney; Polymer Corporation, Sydney; Standard Telephones and Cables, Sydney.

Research Institutes—Bread Research Institute, Sydney; Institute of Dental Research, Sydney; N.S.W. State Cancer Council.

HARLEY WOOD,
Hon. Secretary.

Financial Statement

BALANCE SHEET AS AT 28th FEBRUARY, 1959

LIABILITIES

1958 £		£ s. d.	£ s. d.
23	Subscriptions Paid in Advance		14 14 0
195	Life Members' Subscriptions — Amount carried forward		186 0 0
	Trust and Monograph Capital Funds (detailed below)—		
	Clarke Memorial	1,857 16 3	
	Walter Burfitt Prize	1,141 10 3	
	Liversidge Bequest	680 11 1	
	Monograph Capital Fund	4,185 3 4	
	Ollé Bequest	132 13 1	
7,865			7,997 14 0
23,474	Accumulated Funds		23,547 8 1
	Contingent Liability (in connection with Perpetual Lease).		
£31,557			£31,745 16 1

ASSETS

1958 £		£ s. d.	£ s. d.
143	Cash at Bank and in Hand		852 14 2
	Investments—		
	Commonwealth Bonds and Inscribed Stock—		
	At Face Value—held for:		
	Clarke Memorial Fund	1,800 0 0	
	Walter Burfitt Prize Fund	1,000 0 0	
	Liversidge Bequest	700 0 0	
	Monograph Capital Fund	3,000 0 0	
	General Purposes	1,960 0 0	
8,960			8,460 0 0
	Debtors for Subscriptions	105 0 0	
	Less Reserve for Bad Debts	105 0 0	
—			—
14,835	Science House—One-third Capital Cost		14,835 4 4
6,800	Library—At Valuation		6,800 0 0
800	Furniture and Office Equipment—At Cost, *less* Depreciation		779 14 7
18	Pictures—At Cost, *less* Depreciation		17 3 0
1	Lantern—At Cost, *less* Depreciation		1 0 0
£31,557			£31,745 16 1

TRUST AND MONOGRAPH CAPITAL FUNDS

	Clarke Memorial			Walter Burfitt Prize			Liversidge Bequest			Monograph Capital Fund			Ollé Bequest		
	£	s.	d.	£	s.	d.	£	s.	d.	£	s.	d.	£	s.	d.
Capital at 28th February, 1959	1,800	0	0	1,000	0	0	700	0	0	3,000	0	0	—		
Revenue—															
Balance at 28th February, 1958	90	6	6	103	13	7	11	9	2	1,069	3	5	90	3	7
Income for twelve months	68	2	2	37	16	8	26	9	5	115	19	11	42	9	6
	158	8	8	141	10	3	37	18	7	1,185	3	4	132	13	1
Less Expenditure ..	100	12	5	—			57	7	6	—			—		
Balance at 28th February, 1959	£57	16	3	£141	10	3	*£19*	*8*	*11*	£1,185	3	4	£132	13	1

ACCUMULATED FUNDS

	£	s.	d.	£	s.	d.
Balance at 28th February, 1958				23,474	2	1
Add Surplus for twelve months				103	15	0
				23,577	17	1
Less—						
Loss on Sale of Stock	0	9	0			
Increase in Reserve for Bad Debts ..	2	14	0			
Bad Debts written off	27	6	0			
				30	9	0
Balance at 28th February, 1959				£23,547	8	1

Auditors' Report

The above Balance Sheet has been prepared from the Books of Account, Accounts and Vouchers of the Royal Society of New South Wales, and is a correct statement of the position of the Society's affairs on 28th February, 1959, as disclosed thereby. We have satisfied ourselves that the Society's Commonwealth Bonds and Inscribed Stock are properly held and registered.

HORLEY & HORLEY,
Chartered Accountants (Aust.).

Prudential Building
39 Martin Place, Sydney
19th March, 1959

(Sgd.) C. L. ADAMSON,
Honorary Treasurer.

INCOME AND EXPENDITURE ACCOUNT

1st March, 1958, to 28th February, 1959

1958 £			£ s. d.
12	Annual Social Function		—
31	Audit		31 10 0
104	Cleaning		117 5 0
43	Depreciation		41 18 9
43	Electricity		50 4 3
2	Entertainment		6 7 0
39	Insurance		39 14 11
106	Library Purchases		150 15 5
133	Miscellaneous		115 4 0
135	Postages and Telegrams		124 16 9
	Printing Journal—		
	Vol. 90, Binding	£23 0 0	
	Vol. 91, Part 1 (block)	4 8 0	
	Vol. 91, Parts 3–4	564 17 7	
	Vol. 92, Parts 1–2	336 12 3	
1,548			928 17 10
109	Printing—General		102 5 3
9	Removal Expenses		—
63	Rent—Science House Management		140 6 0
4	Repairs		4 2 8
10	Reprints		—
1,116	Salaries		1,164 3 1
29	Telephone		28 16 3
—	Surplus for twelve months		103 15 0
£3,536			£3,150 2 2

1958 £			£ s. d.
838	Membership Subscriptions		812 14 0
10	Proportion of Life Members' Subscriptions		9 9 0
217	Subscriptions to Journal		221 13 2
750	Government Subsidy		750 0 0
996	Science House Management—Share of Surplus		951 3 3
46	Rentals Received—Reception Room		35 1 2
—	Annual Social Function		3 11 0
—	Bequest—Estate G. Harker		100 0 0
88	Interest on General Investments		74 3 2
	Reprints—		
	Expenditure	£262 17 9	
	Receipts	334 15 0	
—			71 17 3
482	Sale of Periodicals *ex* Library		37 0 0
24	Sale of Back Numbers of the Journal		83 10 2
50	Publication Grant		—
35	Deficit for twelve months		—
£3,536			£3,150 2 2

Obituary, 1958-1959

Arthur John Bedwell, a member of the Society since 1933, died on 5th July, 1958.

Mr. Bedwell, who was born in Sydney in 1877, was a pioneer of the eucalyptus oils industry in New South Wales and contributed substantially to the opening up of new areas of eucalyptus in the southern part of the State.

Thomas Noel Burke-Gaffney was born in Dublin on 26th December, 1893. He entered the Jesuit order in 1913, and, after studying in Jersey and at the National University of Ireland, was ordained in 1926. He came to Australia in 1928 (after an earlier visit in 1921) as a science master at St. Ignatius' College, Riverview, Sydney.

He was appointed Assistant Director of the Riverview College Observatory in 1946, and Director (as successor to Fr. D. J. K. O'Connell) in 1952, a post which he held with distinction until his death in Sydney on 14th September, 1958. He was Convenor of the Australian national sub-committee on Seismology both for the I.G.Y. and the International Union of Geodesy and Geophysics. He also served on the Council of the Society for four years and contributed two papers to the Society's Journal.

His published work included seven seismological papers on the seismicity of Australia, the detection of transverse waves in the Earth's inner core, special phases from New Zealand earthquakes, and seismic data from nuclear explosions.

The papers on nuclear explosions, published jointly with Professor K. E. Bullen, received considerable attention overseas. They depended upon the careful collection of data from routine seismological reports from other observatories, many of which were then unaware that they had recorded the explosions.

Father Burke-Gaffney was devoted to his work and he more than maintained the reputation which Riverview has held since 1910 as one of the world's most reliable observatories.

George Z. Dupain died on 18th December, 1958, at the age of 77. He studied chemistry at the Sydney Technical College, and was an original member of the Australian Chemical Institute and of the Sydney Technical College Chemical Society. He served on the Council of the latter and was President in 1926–27. He founded the Dupain Institute of Physical Education, Sydney, in 1900, and thereafter devoted his life to establishing the concept that health meant more than mere freedom from disease; rather was it a force for effective living. His unobtrusive manner, together with a pleasant and cheerful temperament, was a source of inspiration and encouragement to his associates, his patients and students.

He wrote a number of books dealing with physical education, nutrition and diet and many articles on similar subjects flowed from his facile pen.

He was elected to membership of the Royal Society of New South Wales in 1924.

Roy H. Goddard died on 15th April, 1958. He was elected to membership of the Society in 1945.

Charles A. Loney, who was elected to membership in 1906, died on 5th February, 1959.

Herbert J. Sullivan, a member since 1918, died on 13th July, 1958.

By the death of **Dr. Walter George Woolnough** on 28th September, 1958, at the age of 82, Australia lost one of its most versatile and distinguished geologists. Graduating in 1898 after a brilliant course at the University of Sydney, where he came under the influence of T. W. E. David, he filled university lectureships in Adelaide and Sydney and in 1913 became the first Professor of Geology in the University of W.A. After 21 years of academic life, he entered the service of Brunner, Mond Alkali Company, and in 1927 was appointed Geological Adviser to the Commonwealth Government, a position from which he retired in 1941. He had an extensive and unrivalled knowledge of the geology of the Australian continent and was the pioneer in this country of the use of aircraft as an aid to geological reconnaissance, especially in the search for structures favourable to the accumulation of oil.

An original thinker and a lucid writer, he contributed many valuable papers to Australian and overseas scientific journals. In 1941 the American Association of Petroleum Geologists conferred on him Honorary Membership, a rare honour for a non-American. In his later years his remarkable knowledge of foreign languages was made freely available to research workers in science.

He joined this Society in 1906, was President in 1926, and Clarke lecturer in 1936. He was awarded the Clarke Medal (1933) and the Society's Medal (1955).

Members of the Society, April 1959

The year of election to membership and the number of papers contributed to the Society's Journal are shown in brackets, thus: (1934; P8). * indicates Life Membership.

Honorary Members

BURNET, Sir Frank Macfarlane, O.M., Kt., D.Sc., F.R.S., F.A.A., Director of the Walter and Eliza Hall Research Institute, Melbourne. (1949)

FAIRLEY, Sir Neil Hamilton, C.B.E., M.D., D.Sc., F.R.S., 73 Harley Street, London, W.1. (1951)

FIRTH, Raymond William, M.A., Ph.D., Professor of Anthropology, University of London, London School of Economics, Houghton Street, Aldwych, W.C.2, England. (1952)

FLOREY, Sir Howard, M.B., B.S., B.Sc., M.A., Ph.D., F.R.S., Professor of Pathology, Oxford University, England. (1949)

JONES, Sir Harold Spencer, K.B.E., M.A., D.Sc., F.R.S., 40 Hesper Mews, London, S.W.5, England. (1946)

O'CONNELL, Rev. Daniel J., S.J., D.Sc., Ph.D., F.R.A.S., Director, The Vatican Observatory, Rome, Italy. (1953)

OLIPHANT, Sir Marcus L., K.B.E., Ph.D., B.Sc., F.R.S., F.A.A., Professor of Physics, Australian National University, Canberra, A.C.T. (1948)

ROBINSON, Sir Robert, M.A., D.Sc., F.R.S., F.C.S., F.I.C., Professor of Chemistry, Oxford University, England. (1948)

Members

ADAMSON, Colin Lachlan, B.Sc., 9 Dewrang Avenue, North Narrabeen. (1944)

*ALBERT, Adrien, D.Sc., Professor of Medical Chemistry, Australian National University, Canberra, A.C.T. (1938; P2)

*ALBERT, Michael Francois, " Boomerang ", Billyard Avenue, Elizabeth Bay. (1935)

ALEXANDER, Albert Ernest, Ph.D., Professor of Chemistry, University of Sydney. (1950)

*ALLDIS, Victor le Roy, Box 37, Orange, N.S.W. (1941)

ANDERSON, Geoffrey William, B.Sc., c/o Box 30, P.O. Chatswood. (1948)

ANDREWS, Paul Burke, B.Sc., 5 Conway Avenue, Rose Bay. (1948; P2)

ASTON, Ronald Leslie, Ph.D., Associate Professor of Geodesy and Surveying, University of Sydney. (1930; P1; **President 1948**)

*AUROUSSEAU, Marcel, M.C., B.Sc., 229 Woodland Street, Balgowlah. (1919; P2)

*BAILEY, Victor Albert, D.Phil., F.A.A., 80 Cremorne Road, Cremorne. (1924; P2)

BAKER, Stanley Charles, Ph.D., Department of Physics, Newcastle University College. (1934; P2)

BALDICK, Kenric James, B.Sc., 19 Beaconsfield Parade, Lindfield. (1937)

BANKS, Maxwell Robert, B.Sc., Department of Geology, University of Tasmania, Hobart, Tas. (1951)

*BARDSLEY, John Ralph, 29 Walton Crescent, Abbotsford. (1919)

BASDEN, Keith Spencer, B.Sc., School of Mining and Applied Geology, University of New South Wales, Kensington. (1951)

BAXTER, John Philip, O.B.E., Ph.D., F.A.A., Vice-Chancellor and Professor of Chemical Engineering, University of New South Wales, Kensington. (1950)

BECK, Julia Mary (Mrs.), B.Sc., Department of Geophysics, University of Western Ontario, London, Ont., Canada. (1950)

BENTIVOGLIO, Sydney Ernest, B.Sc.Agr., 42 Telegraph Road, Pymble. (1926)

*BISHOP, Eldred George, 26A Wolseley Road, Mosman. (1920)

BLANKS, Fred Roy, B.Sc., 583 Malabar Road, Maroubra. (1948)

BLASCHKE, Ernest Herbert, 6 Illistron Flats, 63 Carabella Street, Kirribilli. (1946)

BOLLIGER, Adolph, D.Sc., Gordon Craig Urological Research Laboratory, Department of Surgery, University of Sydney. (1933; P30; **President 1945**)

BOLT, Bruce Alan, Ph.D., Department of Applied Mathematics, University of Sydney. (1956; P3)

BOOKER, Frederick William, D.Sc., Government Geologist, c/o Geological Survey of N.S.W., Mines Department, Sydney. (1951; P4)

BOOTH, Brian Douglas, Ph.D., 37 Highfield Road, Lindfield. (1954)

*BOOTH, Edgar Harold, M.C., D.Sc., 29 March Street, Bellevue Hill. (1920; P9; **President 1936**)

BOSSON, Geoffrey, M.Sc., Professor of Mathematics, University of New South Wales, Kensington. (1951; P2)

BOSWORTH, Richard Charles Leslie, D.Sc., Associate Professor, School of Physical Chemistry, University of New South Wales, Kensington. (1939; P26; **President 1951**)

BREYER, Bruno, M.D., Ph.D., Department of Agricultural Chemistry, University of Sydney. (1946; P1)

BRIDGES, David Somerset, 19 Mount Pleasant Avenue, Normanhurst. (1952)

*BRIGGS, George Henry, D.Sc., 13 Findlay Avenue, Roseville. (1919; P1)

BROWN, Desmond J., Ph.D., Department of Medical Chemistry, Australian National University, Canberra, A.C.T. (1942)

BROWNE, Ida Alison, D.Sc., 363 Edgecliff Road, Edgecliff. (1935; P12; **President 1953**)

*BROWNE, William Rowan, D.Sc., F.A.A., 363 Edgecliff Road, Edgecliff. (1913; P23; **President 1932**)

BRYANT, Raymond Alfred Arthur, M.E., School of Mechanical Engineering, University of New South Wales, Kensington. (1952)

BUCHANAN, Gregory Stewart, B.Sc., School of Physical Chemistry, Sydney Technical College. (1947)

BUCKLEY, Lindsay Arthur, B.Sc., 30 Wattle Street, Killara. (1940)

BULLEN, Keith Edward, Sc.D., F.R.S., F.A.A., Professor of Applied Mathematics, University of Sydney. (1946; P2)

CAMERON, John Craig, M.A., 15 Monterey Street, Kogarah. (1957)

CAMPBELL, Ian Gavin Stuart, B.Sc., c/o Wesley College, Prahran, Victoria. (1955)

*CAREY, Samuel Warren, D.Sc., Professor of Geology, University of Tasmania, Hobart, Tas. (1938; P2)

CAVILL, George William Kenneth, Ph.D., Associate Professor of Organic Chemistry, University of New South Wales. (1944)

*CHAFFER, Edric Keith, 27 Warrane Road, Roseville. (1954)

CHALMERS, Robert Oliver, A.S.T.C., Australian Museum, College Street, Sydney. (1933; P1)

CHAMBERS, Maxwell Clark, B.Sc., 58 Spencer Road, Killara. (1940)

CHRISTIE, Thelma Isabel, B.Sc., Chemistry School, University of New South Wales. (1953)

CLANCY, Brian Edward, M.Sc., 21 London Drive, West Wollongong. (1957)

COHEN, Samuel Bernard, M.Sc., 35 Spencer Road, Killara. (1940)

COLE, Edward Ritchie, B.Sc., 7 Wolsten Avenue, Turramurra. (1940; P2)

COLE, Joyce Marie (Mrs.), B.Sc., 7 Wolsten Avenue, Turramurra. (1940; P1)

COLE, Leslie Arthur, 61 Kissing Point Road, Turramurra. (1948)

COLEMAN, Patrick Joseph, Ph.D., Geology Department, University of Sydney. (1955)

COLLETT, Gordon, B.Sc., 27 Rogers Avenue, Haberfield. (1940)

COOK, Cyril Lloyd, Ph.D., c/o Propulsion Research Laboratories, Box 1424H, G.P.O., Adelaide. (1948)

COOK, Rodney Thomas, Buckley's Road, Old Toongabbie. (1946)

*COOMBS, F. A., Bannerman Crescent, Rosebery. (1913; P5)

CORBETT, Robert Lorimer, c/o Intaglio Pty. Ltd., Box 3749, G.P.O., Sydney. (1933)

CORTIS-JONES, Beverley, M.Sc., 65 Peacock Street, Seaforth. (1940)

*COTTON, Leo Arthur, D.Sc., Emeritus Professor, 113 Queen's Parade East, Newport Beach. (1909; P7; **President 1929**)

CRAIG, David Parker, Ph.D., Department of Theoretical Chemistry, University College, London, W.C.1, England. (1941; P1)

CRAWFORD, Edwin John, B.E., "Lynwood", Bungalow Avenue, Pymble. (1955)

CRAWFORD, Ian Andrew, 73 Wyadra Avenue, Manly. (1955)

*CRESSWICK, John Arthur, 101 Villiers Street, Rockdale. (1921; P1)

CROFT, James Bernard, 8 Malahide Street, Pennant Hills. (1956)

CROOK, Keith Alan Waterhouse, Ph.D., Geology Department, University of Melbourne. (1954; P4)

DADOUR, Anthony, B.Sc., 25 Elizabeth Street, Waterloo. (1940)

DARVALL, Anthony Roger, M.B., B.S., 119 Marsden Street, Parramatta. (1951)

DAVIES, George Frederick, 57 Eastern Avenue, Kingsford. (1952)

DAY, Alan Arthur, Ph.D., Department of Geology and Geophysics, University of Sydney. (1952)

DE LEPERVANCHE, Beatrice Joy, 29 Collins Street, Belmore. (1953)

DENTON, Leslie A., Bunarba Road, Miranda. (1955)

DONEGAN, Henry Arthur James, M.Sc., 18 Hillview Street, Sans Souci. (1928)

DRUMMOND, Heather Rutherford, B.Sc., 2 Gerald Avenue, Roseville. (1950)

DULHUNTY, John Allan, D.Sc., Department of Geology, University of Sydney. (1937; P16; **President 1947**)

DUNLOP, Bruce Thomas, B.Sc., 77 Stanhope Road, Killara. (1948)

DURIE, Ethel Beatrix, M.B., Ch.M., Institute of Medical Research, Royal North Shore Hospital, St. Leonards. (1955)

DWYER, Francis P. J., D.Sc., Department of Chemistry, Australian National University, Canberra, A.C.T. (1934; P62)

EADE, Ronald Arthur, Ph.D., School of Organic Chemistry, University of New South Wales. (1945)

EDGAR, Joyce Enid (Mrs.), B.Sc., 22 Slade Avenue, Lindfield. (1951)

EDGELL, Henry Stewart, Ph.D., c/o Iranian Oil Exploration and Producing Co., Masjid-i-Sulaiman, via Abadan, Iran. (1950)

ELKIN, Adolphus Peter, Ph.D., Emeritus Professor, 15 Norwood Avenue, Lindfield. (1934; P2; **President 1940**)

ELLISON, Dorothy Jean, M.Sc., 51 Tryon Road, Lindfield. (1949)

EMMERTON, Henry James, B.Sc., 37 Wangoola Street, East Gordon. (1940)

ERHART, John Charles, c/o "Ciba" Company, Basle, Switzerland. (1944)

*ESDAILE, Edward William, 42 Hunter Street, Sydney. (1908)

EVANS, Silvanus Gladstone, 6 Major Street, Coogee. (1935)

FALLON, Joseph James, 1 Coolong Road, Vaucluse. (1950)

*FAWSITT, Charles Edward, D.Sc., Emeritus Professor, 14A Darling Point Road, Edgecliff. (1909; P7; **President 1919**)

FISHER, Robert, B.Sc., 3 Sackville Street, Maroubra. (1940)

FLEISCHMANN, Arnold Walter, 8/25 Guilfoyle Avenue, Double Bay. (1956)

FLETCHER, Harold Oswald, M.Sc., The Australian Museum, College Street, Sydney. (1933)

FORMAN, Kenn P., 52 Pitt Street, Sydney. (1932)

FREEMAN, Hans Charles, Ph.D., 43 Newcastle Street, Rose Bay. (1950)

FRENCH, Oswald Raymond, 66 Nottinghill Road, Lidcombe. (1951)

FRIEND, James Alan, Ph.D., Department of Chemistry, University of Tasmania, Hobart, Tas. (1944; P2)

FURST, Hellmut Friedrich, D.M.D. (Hamburg), 158 Bellevue Road, Bellevue Hill. (1945)

GARAN, Teodar, c/o Geology Branch, Warragamba Dam, N.S.W. (1952)
GARRETTY, Michael Duhan, D.Sc., " Surrey Lodge ", Mitcham Road, Mitcham, Victoria. (1935 ; P2)
GASCOIGNE, Robert Mortimer, Ph.D., Department of Organic Chemistry, University of N.S.W. (1939 ; P4)
GIBSON, Neville Allan, Ph.D., 103 Bland Street, Ashfield. (1942 ; P6)
GILL, Naida Sugden, Ph.D., 45 Neville Street, Marrickville. (1947)
*GILL, Stuart Frederic, 45 Neville Street, Marrickville. (1947)
GLASSON, Kenneth Roderick, M.Sc., 70 Beecroft Road, Beecroft. (1948)
GOLDING, Henry George, M.Sc., School of Mining Engineering and Applied Geology, University of N.S.W., Kensington. (1953 ; P3)
GOLDSTONE, Charles Lillington, B.Agr.Sc., University of N.S.W., Kensington. (1951)
GOLDSWORTHY, Neil Ernest, Ph.D., 118 Ryde Road, West Pymble. (1947)
GORDON, William Fraser, B.Sc., 58 Abingdon Road, Roseville. (1949)
GRAY, Charles Alexander Menzies, B.E., Professor of Engineering, University of Malaya, Malaya. (1948 ; P1)
GRAY, Noel Mackintosh, B.Sc., 6 Twenty-fourth Street, Warragamba Dam, N.S.W. (1952)
GRIFFIN, Russell John, B.Sc., c/o Department of Mines, Sydney. (1952)
GRIFFITH, James Langford, M.Sc., School of Mathematics, University of N.S.W., Kensington. (1952 ; P9 ; **President 1958**)
GRODEN, Charles Mark, M.Sc., School of Mathematics, University of N.S.W., Kensington. (1957 ; P1)
GUTMANN, Felix, Ph.D., University of N.S.W., Kensington. (1946 ; P1)
HALL, Norman Frederick Blake, M.Sc., 15A Wharf Road, Longueville. (1934)
HAMPTON, Edward John William, 1 Hunter Street, Waratah, N.S.W. (1949)
HANCOCK, Harry Sheffield, M.Sc., 21 Constitution Road, Dulwich Hill. (1955)
HANLON, Frederick Noel, B.Sc., 4 Pearson Avenue, Gordon. (1940 ; P16 ; **President 1957**)
HARPER, Arthur Frederick Alan, M.Sc., National Standards Laboratory, University Grounds, City Road, Chippendale. (1936 ; **President 1959**)
HARRINGTON, Herbert Richard, 28 Bancroft Avenue, Roseville. (1934)
HARRIS, Clive Melville, Ph.D., School of Inorganic Chemistry, University of N.S.W. (1948 ; P6)
HARRISON, Ernest John Jasper, B.Sc., c/o N.S.W. Geological Survey, Mines Department, Sydney. (1946)
HAWKINS, Cedric Arthur, B.Sc.Agr., Chemists' Branch, N.S.W. Department of Agriculture, Sydney. (1956 ; P2)
HEARD, George Douglas, B.Sc., Crows Nest Boys' High School, Pacific Highway, Crows Nest. (1951)
*HENRIQUES, Frederick Lester, Billyard Avenue, Elizabeth Bay. (1919)
HIGGS, Alan Charles, c/o Colonial Sugar Refining Co. Ltd., Building Material Division, 1–7 Bent Street, Sydney. (1945)
HILL, Dorothy, D.Sc., F.A.A., Department of Geology, University of Queensland, St. Lucia, Brisbane. (1938 ; P6)
HLA, U., Chief Planning Officer, Ministry of Mines, Rangoon, Burma. (1957)
HOGARTH, Julius William, B.Sc., University House, Canberra, A.C.T. (1948 ; P6)
HOLM, Thomas John, 524 Wilson Street, Redfern. (1952)
*HYNES, Harold John, D.Sc.Agr., Director, N.S.W. Department of Agriculture, Sydney. (1923 ; P3)
IREDALE, Thomas, D.Sc., Chemistry Department, University of Sydney. (1943)
JAEGER, John Conrad, D.Sc., F.A.A., Geophysics Department, Australian National University, Canberra, A.C.T. (1942 ; P1)
JAMIESON, Helen Campbell, 3 Hamilton Street, Coogee. (1951)
JENKINS, Thomas Benjamin Huw, Ph.D., c/o A.O.G. Corp. Ltd., Box 5048, G.P.O., Sydney. (1956)
JENSEN, Harald Ingemann, D.Sc., Geologist, Caboolture, Queensland. (1958)
JOPLIN, Germaine Anne, D.Sc., Geophysics Department, Australian National University, Canberra, A.C.T. (1935 ; P8)
KEANE, Austin, Ph.D., School of Mathematics, University of N.S.W., Kensington. (1955 ; P2)
KELLY, Caroline Tennant (Mrs.), Dip.Anthr., " Silvermists ", Robertson, N.S.W. (1935)
*KENNY, Edward Joseph, 65 Park Avenue, Ashfield. (1924 ; P1)
KIMBLE, Frank Oswald, 31 Coronga Crescent, Killara. (1948)
KIMBLE, Jean Annie, B.Sc., 383 Marrickville Road, Marrickville. (1943)
*KIRCHNER, William John, B.Sc., 18 Lyne Road, Cheltenham. (1920)
KNIGHT, Oscar Le Maistre, B.E., 10 Mildura Street, Killara. (1948)
KOCH, Leo E., D.Phil.Habil., University of N.S.W., Kensington. (1948)
LAMBETH, Arthur James, B.Sc., " Talanga ", Picton Road, Douglas Park, N.S.W. (1939 ; P3)
LANG, Thomas Arthur, M.C.E., c/o Mr. Roger Rhoades, 101 California Street, San Francisco 11, California, U.S.A. (1955)
LAWRENCE, Laurence James, Ph.D., School of Geology, University of N.S.W., Kensington. (1951 ; P1)
LEACH, Stephen Laurence, B.Sc., c/o Taubman's Industries Ltd., Box 82A, P.O., North Sydney. (1936)
LEECHMAN, Frank, 51 Willoughby Street, Kirribilli. (1957)
LE FEVRE, Raymond James Wood, D.Sc., F.R.S., F.A.A., Professor of Chemistry, University of Sydney. (1947)
LEMBERG, Max Rudolph, D.Phil., F.R.S., F.A.A., Assistant Director, Institute of Medical Research, Royal North Shore Hospital, St. Leonards. (1936 ; P3 ; **President 1955**)
*LIONS, Francis, Ph.D., Department of Chemistry, University of Sydney. (1929 ; P56 ; **President 1946**)
LIONS, Jean Elizabeth (Mrs.), B.Sc., 160 Alt Street, Haberfield. (1940)
LLOYD, James Charles, B.Sc., c/o N.S.W. Geological Survey, Mines Department, Sydney. (1947)
LOCKWOOD, William Hutton, B.Sc., c/o Institute of Medical Research, Royal North Shore Hospital, St. Leonards. (1940 ; P1)
LOVERING, John Francis, Ph.D., Department of Geophysics, Australian National University Canberra, A.C.T. (1951 ; P3)

LOW, Angus Henry, M.Sc., School of Mathematics, University of N.S.W., Kensington. (1950; P1)

*LUBER, Daphne (Mrs.), B.Sc., 98 Lang Road, Centennial Park. (1943)

LYONS, Lawrence Ernest, Ph.D., Chemistry Department, University of Sydney. (1948; P2)

MACCOLL, Allan, M.Sc., Department of Chemistry, University College, Gower Street, London, W.C.1, England. (1939; P4)

McCARTHY, Frederick David, Dip.Anthr., Australian Museum, College Street, Sydney. (1949; P1; **President 1956**)

McCOY, William Kevin, c/o Mr. A. J. McCoy, 23 Victoria Road, Pennant Hills. (1943)

McCULLAGH, Morris Behan, 23 Wallaroy Road, Edgecliff. (1950)

McELROY, Clifford Turner, B.Sc., " Bithongabel ", Bedford Road, Woodford, N.S.W. (1949; P2)

McGREGOR, Gordon Howard, 4 Maple Avenue, Pennant Hills. (1940)

McINNES, Gordon Elliott, B.Sc., Cranbrook School, Bellevue Hill. (1948)

McKAY, Maxwell Herbert, M.A., School of Mathematics, University of N.S.W., Kensington. (1956; P1)

McKENZIE, Peter John, M.Sc., 33 Harbour Street, Mosman. (1953)

McKERN, Howard Hamlet Gordon, M.Sc., Senior Chemist, Museum of Applied Arts and Sciences, Harris Street, Broadway, Sydney. (1943; P9)

McMAHON, Patrick Reginald, Ph.D., Professor of Wool Technology, University of N.S.W., Kensington. (1947)

McNAMARA, Barbara Joyce (Mrs.), M.B., B.S., 82 Millwood Avenue, Chatswood. (1943)

McPHEE, Stuart Duncan, 14 Lennon Street, Gordon. (1956)

McPHERSON, John Charters, 14 Sarnar Road, Greenwich. (1946)

MAGEE, Charles Joseph, D.Sc.Agr., Chief Biologist, N.S.W. Department of Agriculture, Sydney. (1947; P1; **President 1952**)

MALES, Pamela Ann, 13 Gelding Street, Dulwich Hill. (1951)

MANDL, Lothar Max, Dipl.Ing., Senior Technical Officer, C.S.I.R.O., National Standards Laboratory, University Grounds, City Road, Chippendale. (1955)

MARSHALL, Charles Edward, D.Sc., Professor of Geology, University of Sydney. (1949)

MARSDEN, Joan Audrey, 203 West Street, Crows Nest. (1955)

MAZE, William Harold, M.Sc., Deputy Principal, University of Sydney. (1935; P1)

MEARES, Harry John Devenish, Technical Librarian, Colonial Sugar Refining Co. Ltd., Box 483, G.P.O., Sydney. (1949)

*MELDRUM, Henry John, B.Sc., 116 Sydney Road, Fairlight. (1912)

MELLOR, David Paver, D.Sc., Professor of Inorganic Chemistry, University of N.S.W. (1929; P25; **President 1941**)

MILLERSHIP, William, M.Sc., 18 Courallie Avenue, Pymble. (1940)

MINTY, Edward James, B.Sc., Cooyong Road, Terrey Hills, N.S.W. (1951)

*MORRISON, Frank Richard, Director, Museum of Applied Arts and Sciences, Harris Street, Broadway, Sydney. (1922; P34; **President 1950**)

MORRISSEY, Matthew John, M.B., B.S., 46 Auburn Street, Parramatta. (1941)

MORT, Francis George Arnot, 110 Green's Road, Fivedock. (1934)

MOSHER, Kenneth George, B.Sc., c/o Joint Coal Board, 66 King Street, Sydney. (1948)

MOSS, Francis John, M.B., B.S., 15 Ormonde Road, Roseville Chase, N.S.W. (1955)

MOYE, Daniel George, B.Sc., Chief Geologist, c/o Snowy Mountains Hydro Electric Authority, Cooma, N.S.W. (1944)

MULHOLLAND, Charles St. John, B.Sc., Under-Secretary, Mines Department, Sydney. (1946)

*MURPHY, Robert Kenneth, Dr.Ing.Chem., 68 Pindari Avenue, North Mosman. (1915)

MURRAY, James Kenneth, B.Sc., 464 William Lane, Broken Hill, N.S.W. (1951)

MURRAY, Patrick Desmond Fitzgerald, D.Sc., F.A.A., Professor of Zoology, University of Sydney. (1950)

MUTTON, Anne Ruth, c/o Ascham, 188 New South Head Road, Edgecliff. (1959)

NASHAR, Beryl, Ph.D., 23 Morris Street, Mayfield West, 2N, N.S.W. (1946; P1)

NAYLOR, George Francis King, Ph.D., Department of Psychology and Philosophy, University of Queensland, Brisbane. (1930; P7)

*NEUHAUS, John William George, 32 Bolton Street, Guildford. (1943)

NEWMAN, Ivor Vickery, Ph.D., Botany Department, University of Sydney. (1932)

NOAKES, Lyndon Charles, B.A., c/o Bureau of Mineral Resources, Canberra, A.C.T. (1945; P1)

*NOBLE, Robert Jackson, Ph.D., 32A Middle Harbour Road, Lindfield. (1920; P4; **President 1934**)

NORDON, Peter, Ph.D., 42 Milroy Avenue, Kensington. (1947)

NYHOLM, Ronald Sydney, D.Sc., F.R.S., Professor of Inorganic Chemistry, University College, Gower Street, London, W.C.1, England. (1940; P26; **President 1954**)

*O'DEA, Daryl Robert, Box 14, P.O., Broadway, Sydney. (1951)

OLD, Adrian Noel, B.Sc.Agr., 4 Springfield Avenue, Potts Point. (1947)

OXENFORD, Reginald Augustus, B.Sc., 10 Fry Street, Grafton. (1950)

PACKHAM, Gordon Howard, Ph.D., Department of Geology and Geophysics, University of Sydney. (1951; P3)

*PENFOLD, Arthur Ramon, Flat 40, 3 Greenknowe Avenue, Potts Point. (1920; P82; **President 1935**)

PERRY, Hubert Roy, B.Sc., 74 Woodbine Street, Bowral, N.S.W. (1948)

PHILLIPS, Marie Elizabeth, Ph.D., Soil Conservation Section, S.M.H.E.A., Cooma. p.r.: 4 Morella Road, Clifton Gardens. (1938)

PINWILL, Norman, B.A., The Scots College, Victoria Road, Bellevue Hill. (1946)

*POATE, Sir Hugh Raymond Guy, M.B., Ch.M., 225 Macquarie Street, Sydney. (1919)

POGGENDORFF, Walter Hans George, B.Sc.Agr., Chief, Division of Plant Industry, N.S.W. Department of Agriculture, Sydney. (1949)

*POWELL, Charles Wilfred Roberts, " Wansfell ", Kirkoswald Avenue, Mosman. (1921; P2)

POWELL, John Wallis, c/o Foster Clark (Aust.) Ltd., 17 Thurlow Street, Redfern. (1938)

PRICE, William Linsday, B.Sc., School of Physics, Sydney Technical College, Sydney. (1927)

PRIDDLE, Raymond Arthur, B.E., 7 Rawson Crescent, Pymble. (1956)

*PRIESTLEY, Henry, M.D., 54 Fuller's Road, Chatswood. (1918; P1; **President 1942**)

PROKHOVNIK, Simon Jacques, B.Sc., School of Mathematics, University of N.S.W., Kensington. (1956)

*PROUD, John Seymour, B.E., Finlay Road, Turramurra. (1945)

PYLE, John Herbert, B.Sc., Analyst, Mines Department, Sydney. (1958)

*QUODLING, Florrie Mabel, B.Sc., Geology Department, University of Sydney. (1935; P4)

RADE, Janis, M.Sc., 69A Broadway, Nedlands, Perth, W.A. (1953; P4)

*RAGGATT, Harold George, C.B.E., D.Sc., F.A.A., Secretary, Department of National Development, Acton, Canberra, A.C.T. (1922; P8)

*RANCLAUD, Archibald Boscawen Boyd, B.E., 57 William Street, Sydney. (1919; P3)

RAY, Reginald John, "Treetops", Wyong Road, Berkeley Vale. (1947)

RAYNER, Jack Maxwell, B.Sc., Director, Bureau of Mineral Resources, Canberra, A.C.T. (1931; P1)

REICHEL, Alex, M.Sc., School of Mathematics, University of N.S.W., Kensington. (1957; P1)

REUTER, Fritz Henry, Ph.D., Associate Professor of Food Technology, University of N.S.W., Kensington. (1947)

RITCHIE, Arthur Sinclair, A.S.T.C., Department of Mineralogy and Geology, Newcastle University College, Newcastle. (1947; P2)

RITCHIE, Ernest, D.Sc., Chemistry Department, University of Sydney. (1939; P19)

ROBBINS, Elizabeth Marie (Mrs.), M.Sc., Waterloo Road, North Ryde. (1939; P3)

ROBERTS, Herbert Gordon, 3 Hopetoun Street, Hurlstone Park. (1957)

ROBERTSON, Rutherford Ness, Ph.D., F.A.A., Senior Plant Physiologist, C.S.I.R.O., c/o Botany Department, University of Sydney. (1940)

ROBERTSON, William Humphrey, B.Sc., c/o Sydney Observatory, Sydney. (1949; P13)

ROBINSON, David Hugh, 39 Molton Road, Beecroft. (1951)

ROSENBAUM, Sidney, 23 Strickland Avenue, Lindfield. (1940)

ROSENTHAL–SCHNEIDER, Ilse, Ph.D., 48 Cambridge Avenue, Vaucluse. (1948)

ROUNTREE, Phyllis Margaret, D.Sc., Royal Prince Alfred Hospital, Sydney. (1945)

*SCAMMELL, Rupert Boswood, B.Sc., 10 Buena Vista Avenue, Clifton Gardens. (1920)

SEARL, Robert Alexander, B.Sc., Rio Australian Exploration Pty. Ltd., 20 Queen's Road, Melbourne. (1950)

SEE, Graeme Thomas, B.Sc., School of Mining Engineering and Geology, University of N.S.W., Kensington. (1949)

SELBY, Edmond Jacob, Box 175D, G.P.O., Sydney. (1933)

*SHARP, Kenneth Raeburn, B.Sc., c/o S.M.H.E.A., Cooma, N.S.W. (1948)

SHERRARD, Kathleen Margaret (Mrs.), M.Sc., 43 Robertson Road, Centennial Park. (1936; P5)

SIMMONS, Lewis Michael, Ph.D., c/o The Scots College, Victoria Road, Bellevue Hill. (1945; P3)

SIMONETT, David Stanley, Ph.D., Assistant Professor of Geography, University of Kansas, Lawrence, Kansas, U.S.A. (1948; P3)

SIMPSON, John Kenneth Moore, "Browie", Old Castle Hill Road, Castle Hill. (1943)

SIMS, Kenneth Patrick, B.Sc., 24 Catherine Street, St. Ives. (1950; P7)

SLADE, George Hermon, B.Sc., "Raiatea", Oyama Avenue, Manly. (1933)

SLADE, Milton John, B.Sc., 10 Elizabeth Street, Raymond Terrace. (1952)

SMITH, Eric Brian Jeffcoat, D.Phil., 74 Webster Street, Nedlands, W.A. (1940)

SMITH–WHITE, William Broderick, M.A., Department of Mathematics, University of Sydney. (1947; P2)

*SOUTHEE, Ethelbert Ambrook, O.B.E., M.A., Trelawney Street, Eastwood. (1919)

SPARROW, Gerald William Alfred, B.Sc., Geography Department, University of New England, Armidale. (1958)

STANTON, Richard Limon, Ph.D., Geology Department, University of New England, Armidale. (1949; P2)

STAPLEDON, David Hiley, B.Sc., c/o Engineering Geology Branch, S.M.H.E.A., Cooma, N.S.W. (1954)

*STEPHEN, Alfred Ernest, c/o Box 1158HH, G.P.O., Sydney. (1916)

*STEPHENS, Frederick G. N., M.B., Ch.M., 133 Edinburgh Street, Castlecrag. (1914)

STEVENS, Neville Cecil, Ph.D., Geology Department, University of Queensland, Brisbane. (1948; P5)

STEVENS, Robert Denzil, B.Sc., 219 Coleford Place, Ottawa, Ontario, Canada. (1951; P2)

*STONE, Walter George, 26 Rosslyn Street, Bellevue Hill. (1916; P1)

STUNTZ, John, B.Sc., 511 Burwood Road, Belmore. (1951)

*SUTHERLAND, George Fife, A.R.C.Sc., 47 Clanwilliam Street, Chatswood. (1919)

*SUTTON, Harvey, O.B.E., M.D., 27 Kent Road, Rose Bay. (1920)

SWANSON, Thomas Baikie, M.Sc., c/o Technical Service Department, I.C.I.A.N.Z., Box 1911, G.P.O., Melbourne. (1941; P2)

SWINBOURNE, Ellice Simmons, c/o Chemistry Department, University College, Gower Street, London, W.C.1, England. (1948)

TAYLOR, Griffith, D.Sc., F.A.A., Emeritus Professor, 28 Alan Avenue, Seaforth. (1954 and previous membership 1921–1928; P5)

*TAYLOR, Brigadier Harold B., M.C., D.Sc., 12 Wood Street, Manly. (1915; P3)

THEW, Raymond Farly, 88 Braeside Street, Wahroonga. (1955)

THOMAS, Penrhyn Francis, Suite 22, 3rd Floor, 29 Market Street, Sydney. (1952)

THOMSON, David John, B.Sc., Geologist, c/o Boree Shire Council, Cudal, N.S.W. (1956)

THORLEY, Geraldine Lesley, B.A., 1290 Pacific Highway, Turramurra. (1955)

THORNTON, Barry Stephen, M.Sc., School of Mathematics, University of N.S.W., Kensington. (1957)

TOMPKINS, Denis Keith, B.Sc., 24 The Crescent, Lane Cove. (1954)

TOW, Aubrey James, M.Sc., c/o Community Hospital, Canberra, A.C.T. (1940)

TREBECK, Prosper Charles Brian, 12A Chester Street, Woollahra. (1949)

TUGBY, Elise Evelyn (Mrs.), M.Sc., c/o Department of Anthropological Sociology, Australian National University, Canberra, A.C.T. (1951)

UNGAR, Andrew, Dipl.Ing., 6 Ashley Grove, Gordon. (1952)

VALLANCE, Thomas George, Ph.D., Geology Department, University of Sydney. (1949; P1)

VAN DIJK, Dirk Cornelis, D.Sc.Agr., 2 Lobelia Street, O'Connor, Canberra, A.C.T. (1958)

VEEVERS, John James, Ph.D., Bureau of Mineral Resources, Canberra, A.C.T. (1953)

VERNON, Ronald Holden, B.Sc., Minerographic Investigations Section, C.S.I.R.O., c/o Geology Department, University of Melbourne. (1958)

*VICARS, Robert, "Yallambee", The Crescent, Cheltenham. (1921)

VICKERY, Joyce Winifred, D.Sc., 17 The Promenade, Cheltenham. (1935)

VOISEY, Alan Heywood, D.Sc., Professor of Geology and Geography, University of New England, Armidale. (1933; P10)

*VONWILLER, Oscar U., B.Sc., Emeritus Professor, "Silvermists", Robertson, N.S.W. (1903; P10; **President 1930**)

WALKER, Donald Francis, 13 Beauchamp Avenue, Chatswood. (1948)

WALKER, Patrick Hilton, M.Sc.Agr., Research Officer, C.S.I.R.O., Division of Soils, c/o School of Agriculture, University of Sydney. (1956; P2)

*WALKOM, Arthur Bache, D.Sc., 45 Nelson Road, Killara. (1919 and previous membership 1910–13; P2; **President 1943**)

WARD, Judith (Mrs.), B.Sc., 50 Bellevue Parade, New Town, Hobart, Tasmania. (1948)

*WARDLAW, Hy. Sloane Halcro, D.Sc., 71 McIntosh Street, Gordon. (1913; P5; **President 1939**)

*WATERHOUSE, Lionel Lawry, B.E., 42 Archer Street, Chatswood. (1919; P1)

*WATERHOUSE, Walter L., C.M.G., M.C., D.Sc.Agr., F.A.A., "Hazelmere", Chelmsford Avenue, Lindfield. (1919; P7; **President 1937**)

*WATT, Robert Dickie, M.A., Emeritus Professor, 5 Gladswood Gardens, Double Bay. (1911; P1; **President 1925**)

*WATTS, Arthur Spencer, "Araboonoo", Glebe Street, Randwick. (1921)

WEST, Norman William, B.Sc., c/o Department of Main Roads, Sydney. (1954)

WESTHEIMER, Gerald, Ph.D., c/o Perpetual Trustee Co. Ltd., 33 Hunter Street, Sydney. (1949)

WHITLEY, Alice, Ph.D., 39 Belmore Road, Burwood. (1951)

WHITWORTH, Horace Francis, M.Sc., Mining Museum, Sydney. (1951; P4)

WILLIAMS, Benjamin, 14 Francis Street, Artarmon. (1949)

WILLIAMSON, William Harold, M.Sc., 6 Hughes Avenue, Ermington. (1949)

WOOD, Clive Charles, B.Sc., c/o Bank of N.S.W., 47 Berkeley Square, London, W.1, England. (1954)

WOOD, Harley Weston, M.Sc., Government Astronomer, Sydney Observatory, Sydney. (1936; P14; **President 1949**)

WYNN, Desmond Watkin, B.Sc., c/o Mines Department, Sydney. (1952)

Associates

BOLT, Beverley (Mrs.), M.Sc., 3/17 Alexander Street, Coogee. (1959)

DONEGAN, Elizabeth S. (Mrs.), 18 Hillview Street, Sans Souci. (1956)

GRIFFITH, Elsie A. (Mrs.), 9 Kanoona Street, Caringbah. (1956)

SMITH, Glennie Forbes, 2 Mars Road, Lane Cove. (1958)

Obituary, 1958–59

Arthur J. Bedwell (1933)
Rev. Thomas N. Burke-Gaffney (1952)
George Z. Dupain (1924)
Roy H. Goddard (1935)
Charles A. Loney (1906)
Herbert J. Sullivan (1918)
Walter G. Woolnough (1906)

Medals, Memorial Lectureships and Prizes awarded by the Society

The James Cook Medal

A bronze medal awarded for outstanding contributions to science and human welfare in and for the Southern Hemisphere.

1947 J. C. Smuts (South Africa)
1948 B. A. Houssay (Argentina)
1950 Sir N. H. Fairley (U.K.)
1951 N. McA. Gregg (Australia)
1952 W. L. Waterhouse (Australia)
1953 Sir D. Rivett (Australia)
1954 Sir F. M. Burnet (Australia)
1955 A. P. Elkin (Australia)
1956 Sir I. Clunies Ross (Australia)

The Walter Burfitt Prize

A bronze medal and money prize of £75 awarded at intervals of three years to the worker in pure and applied science, resident in Australia or New Zealand, whose papers and other contributions published during the preceding six years are deemed of the highest scientific merit, account being taken only of investigations described for the first time, and carried out by the author mainly in those Dominions. Established as a result of generous gifts to the Society of Dr. and Mrs. W. F. Burfitt.

1929 N. D. Royle (Medicine)
1932 C. H. Kellaway (Medicine)
1935 V. A. Bailey (Physics)
1938 F. M. Burnet (Medicine)
1941 F. W. Whitehouse (Geology)
1944 H. L. Kesteven (Medicine)
1947 J. C. Jaeger (Mathematics)
1950 D. F. Martyn (Ionospheric Physics)
1953 K. E. Bullen (Geophysics)
1956 J. C. Eccles (Medicine)

The Clarke Medal

Awarded from time to time for distinguished work in the Natural Sciences done in or on the Australian Commonwealth and its territories ; the person to whom the award is made may be resident in the Australian Commonwealth or its territories or elsewhere. Established by the Society soon after the death of the Rev. W. B. Clarke in appreciation of his character and services " as a learned colonist, a faithful minister of religion, and an eminent scientific man ".

The recipients from 1878 to 1929 were given in this Journal, vol. 89, p. xv, 1955.

1930 L. Keith Ward (Geology)
1931 R. J. Tillyard (Entomology)
1932 F. Chapman (Palaeontology)
1933 W. G. Woolnough (Geology)
1934 E. S. Simpson (Mineralogy)
1935 G. W. Card (Geology)
1936 Sir Douglas Mawson (Geology)
1937 J. T. Jutson (Geology)
1938 H. C. Richards (Geology)
1939 C. A. Sussmilch (Geology)
1941 F. Wood Jones (Zoology)
1942 W. R. Browne (Geology)
1943 W. L. Waterhouse (Botany)
1944 W. E. Agar (Zoology)
1945 W. N. Benson (Geology)
1946 J. M. Black (Botany)
1947 H. L. Clark (Zoology)
1948 A. B. Walkom (Palaeobotany)
1949 Rev. H. M. R. Rupp (Botany)
1950 I. M. Mackerras (Entomology)
1951 F. L. Stillwell (Geology)
1952 J. G. Wood (Botany)
1953 A. J. Nicholson (Entomology)
1954 E. de C. Clarke (Geology)
1955 R. N. Robertson (Botany)
1956 O. W. Tiegs (Zoology)
1957 Irene Crespin (Geology)
1958 T. G. B. Osborn (Botany)
1959 T. Iredale (Zoology)

The Society's Medal

A bronze medal awarded from **1884** until **1896** for published papers. The Award was revived in **1943** for scientific contributions and services to the Society.

1884 W. E. Abbott
1886 S. H. Cox
1887 J. Seaver
1888 Rev. J. E. Tenison-Woods
1889 T. Whitelegge
Rev. J. Mathew
1891 Rev. J. Milne Curran
1892 A. G. Hamilton
1894 J. V. De Coque
R. H. Mathews
1895 C. J. Martin
1896 Rev. J. Milne Curran
1943 E. Cheel (Botany)
1948 W. L. Waterhouse (Agriculture)
1949 A. P. Elkin (Anthropology)
1950 O. U. Vonwiller (Physics)
1951 A. R. Penfold (Applied Chemistry)
1953 A. B. Walkom (Palaeobotany)
1954 D. P. Mellor (Chemistry)
1955 W. G. Woolnough (Geology)
1956 W. R. Browne (Geology)
1957 R. C. L. Bosworth (Physical Chemistry)
1958 F. R. Morrison (Applied Chemistry)

The Edgeworth David Medal

A bronze medal awarded to Australian research workers under the age of thirty-five years for work done mainly in Australia or its territories, or contributing to the advancement of Australian science.

1948 R. G. Giovanelli (Astrophysics)
E. Ritchie (Organic Chemistry)
1949 T. B. Kiely (Plant Pathology)
1950 R. M. Berndt (Anthropology)
Catherine H. Berndt (Anthropology)
1951 J. G. Bolton (Radio Astronomy)
1952 A. B. Wardrop (Botany)
1954 E. S. Barnes (Mathematics)
1955 H. B. S. Womersley (Botany)
1957 J. M. Cowley (Chemical Physics)
J. P. Wild (Radio Astronomy)
1958 P. I. Korner (Physiology)

Clarke Memorial Lectureship

The lectureship is awarded for the purpose of the advancement of Geology. The practice of publishing the lectures in the Journal began in **1936**.

1903 T. W. E. David
1906 E. W. Skeats (two lectures)
1907 T. W. E. David (two lectures)
W. G. Woolnough
E. F. Pittman
W. S. Dun
1918 R. J. A. Berry
1919 T. W. E. David
1936 W. G. Woolnough
1937 H. C. Richards
1938 C. T. Madigan
1939 Sir John S. Flett
1940 E. J. Kenny
1941 C. A. Sussmilch
1942 E. C. Andrews
1943 H. G. Raggatt
1944 W. H. Bryan
1945 E. S. Hills
1946 L. A. Cotton
1947 H. S. Summers
1948 Sir Douglas Mawson
1949 W. R. Browne
1950 F. W. Whitehouse
1951 A. B. Edwards
1953 M. F. Glaessner
1955 R. O. Chalmers
1957 A. H. Voisey
1959 D. E. Thomas

Liversidge Research Lectureship

The lectureship is awarded at intervals of two years for the purpose of encouragement of research in Chemistry. It was established under the terms of a bequest to the Society by Professor Archibald Liversidge. The lectures are published in the Journal.

1931 H. Hey
1933 W. J. Young
1940 G. J. Burrows
1942 J. S. Anderson
1944 F. P. Bowden
1946 L. H. Briggs
1948 I. Lauder
1950 Hedley R. Marston
1952 A. L. G. Rees
1954 M. R. Lemberg
1956 G. M. Badger
1958 A. D. Wadsley

Pollock Memorial Lectureship

Sponsored by the University of Sydney and the Royal Society of New South Wales in memory of Professor J. A. Pollock.

1949 T. M. Cherry
1952 H. S. W. Massey
1955 R. v. d. R. Woolley
1959 Sir Harold Jeffreys

The Archibald D. Olle Prize

Awarded from time to time at the discretion of the Council to the member of the Society who has submitted the best paper in any year. Established under the terms of a bequest by Mrs. A. D. Olle.

1956 R. L. Stanton
1958 Alex Reichel

The Society's Money Prize

A prize of £25 awarded for published papers (awarded in 1882 only).

1882 J. Fraser and A. Ross

Abstract of Proceedings, 1958

2nd April, 1958

The annual general meeting and seven hundred and thirty-seventh monthly meeting were held in the Hall of Science House at 7.45 p.m.

The President, Mr. F. N. Hanlon, was in the chair. Thirty-seven members and visitors were present. The following business was conducted in accordance with the printed notice paper: the annual awards were made; the annual report was read and the financial statement presented; the election of office-bearers and auditors was made; and one paper was read by title only.

The deaths of the following were announced: George Petersen, a member since 1956, and Peter Beckmann, a member since 1947.

The following resignations were accepted: Arthur R. Coombs and George E. Mapstone.

The retiring President, Mr. F. N. Hanlon, read his presidential address entitled "The Relationship of Geology to Transport".

The office-bearers for 1958–59 will be:

Patrons: His Excellency the Governor-General of the Commonwealth of Australia, Field-Marshal Sir William Slim, G.C.B., G.C.M.G., G.C.V.O., G.B.E., D.S.O., M.C.
His Excellency the Governor of New South Wales, Lieutenant-General Sir Eric W. Woodward, K.C.M.G., C.B., C.B.E., D.S.O.

President: J. L. Griffith, B.A., M.Sc.

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Auditors: Horley & Horley.

7th May, 1958

The seven hundred and thirty-eighth general monthly meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. J. L. Griffith, was in the chair. Twenty-eight members and visitors were present. The minutes of the previous meeting were read and confirmed.

The Chairman announced the death of Roy Hamilton Goddard, 15th April, 1958, a member since 1935.

The following were elected members of the Society: Dirk Cornelis van Dijk, John Herbert Pyle and Ronald Holden Vernon.

The evening was devoted to the commemoration of the centenary of Sydney Observatory. The Government Astronomer, Mr. Harley Wood, addressed the audience on "Sydney Observatory and its One Hundred Years of Work". Exhibits of the early instruments used at the Sydney Observatory were on display.

4th June, 1958

The President, Mr. J. L. Griffith, was in the chair. Twenty-nine members and visitors were present. The minutes of the previous meeting were read and confirmed.

Roger Chapman Thorne was elected a member of the Society.

The Chairman announced that Professor R. S. Nyholm had recently been elected to Fellowship of the Royal Society. It was also announced that this month was the centenary of the birth of George Handley Knibbs and notes prepared by Professor O. U. Vonwiller were read to the audience.

The following paper was read by title only: "Precise Observations of Minor Planets at Sydney Observatory During 1955 and 1956", by W. H. Robertson.

The evening was devoted to an address entitled "Colours by Numbers", which was delivered by Mr. W. R. Blevin, Research Officer, C.S.I.R.O. Division of Physics, National Standards Laboratory, Sydney.

2nd July, 1958

The seven hundred and fortieth general monthly meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.30 p.m.

The President, Mr. J. L. Griffith, was in the chair. One hundred and five members and visitors were present. The minutes of the previous meeting were read and confirmed.

The meeting was devoted to the commemoration of the centenary of the birth of Professor Sir T. Edgeworth David, and the following addresses were delivered:

"Professor David—The Man Himself", by Professor L. A. Cotton, Emeritus Professor of Geology, University of Sydney.

"Professor T. Edgeworth David—His Antarctic Research", by Professor Griffith Taylor, Emeritus Professor of Geography, University of Toronto.

"David and the Development of Coal Research", by Professor C. E. Marshall, Department of Geology, University of Sydney.

At the conclusion of the addresses the following resolution from the minutes of the Council meeting held on 29th August, 1934, was read: "The members of the Council of the Royal Society of New South Wales record their profound sorrow at the death of their beloved colleague, Sir T. W. Edgeworth David, K.B.E., C.M.G., D.S.O., F.R.S., Vice-President. The Council records its appreciation of his innumerable services rendered to the Society over a period of forty-eight years of membership, including many terms as a member of Council and two terms as President. His contributions to the cause of scientific research, both directly through his own labours and indirectly through the inspiration of his work and personality, have been incalculable. By his colleagues he was justly held in honour for his pre-eminence in the scientific field, and no less for his tact, ripe wisdom, sound judgment and scrupulous fairness; and to all he endeared himself by his unfailing courtesy and kindly consideration, and by the spirit of selflessness and service that marked his whole life. Among the scientific workers of Australia his name will ever be held in grateful and affectionate remembrance."

6th August, 1958

The President, Mr. J. L. Griffith, was in the chair. Forty-two members and visitors were present.

The Chairman announced the deaths of Arthur Johnson Bedwell, a member since 1933, and Herbert Jay Sullivan, a member since 1918.

The following paper was read by title only: " Flexure of a Slab on an Elastic Foundation ", by G. Bosson.

The meeting took the form of a conjoint meeting with the Royal Australian Chemical Institute. The subject for discussion was " Food " and the following addresses were given: " The Responsibility of the Food Producer to the Consumer ", by Mr. J. F. Kefford, Acting Officer in Charge, Canning Section, C.S.I.R.O. Division of Food Preservation and Transport, Homebush; " Some Economic Aspects of Food Production ", by Mr. C. King, Chief of Marketing and Agricultural Economy, N.S.W. Department of Agriculture, Sydney; " Advances in Food Production Methods ", by Mr. W. H. G. Poggendorff, Chief, Division of Plant Industry, N.S.W. Department of Agriculture; " Discussion of the Contributions of Food Science and Food Technology to the Development of Modern Foods ", by Associate Professor F. H. Reuter, School of Food Technology, N.S.W. University of Technology, Kensington.

3rd September, 1958

The seven hundred and forty-second general monthly meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. J. L. Griffith, was in the chair. Twenty-four members and visitors were present. The minutes of the previous meeting were read and confirmed.

The following was elected a member of the Society: Gerald William Alfred Sparrow.

The following paper was read by title only: " A Note on the possible Sedimentary Origin of Some Amphibolites from the Cooma Area, N.S.W.", by N. J. Snelling.

The evening was devoted to an address entitled " Fossil Insects ", delivered by Dr. J. W. Evans, Director, The Australian Museum, Sydney.

1st October, 1958

The President, Mr. J. L. Griffith, was in the chair. Thirty-four members and visitors were present. The minutes of the previous meeting were read and confirmed.

The Chairman announced the deaths of Thomas Noel Burke-Gaffney, a member since 1952, and Walter George Woolnough, a member since 1906.

It was announced that a bequest of £100 had been received by the Society from the estate of the late Dr. George Harker.

The following paper was read by title only: " On the Genetic and Structural Relations between Contact Metamorphic Mineralization and a Hydrothermal Vein at Walang, N.S.W.", by L. J. Lawrence.

The meeting took the form of a conjoint meeting with the Institute of Physics, and an address entitled " Evaporation and the Water Cycle " was delivered by Dr. A. J. Dyer, C.S.I.R.O. Division of Meteorological Physics.

5th November, 1958

The President, Mr. J. L. Griffith, was in the chair. Thirty members and visitors were present. The minutes of the previous meeting were read and confirmed.

The following was elected a member of the Society: Harald Ingemann Jensen.

In accordance with Rule XVIII, the following names were removed from the list of members: Robert F. Holmes and Kevin J. Lancaster.

In commemoration of the centenary of the birth of Max Planck, the following address was given by Dr. Ilse Rosenthal-Schneider, " Max Planck, His Epoch-Making Work and His Personality ".

The following papers were presented: " Seismic Travel-Times in Australia ", by B. A. Bolt, M.Sc., F.R.A.S.; " Flexure of a Slab on an Elastic Foundation ", by G. Bosson, M.Sc. (Lond.).

The following paper was read by title only: " Minor Planets Observed at Sydney Observatory during 1957 ", by W. H. Robertson.

3rd December, 1958

The seven hundred and forty-fifth general monthly meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. J. L. Griffith, was in the chair. Fifty-one members and visitors were present.

The following papers were read by title only: " An Investigation of Metal Gluconate Complexes ", by W. F. Pickering and J. Miller (communicated by Prof. D. P. Mellor); " Macro- and Micro-Floras of North-eastern New South Wales ", by N. J. de Jersey (communicated by C. T. McElroy).

The evening was devoted to a symposium on " Progress of the Geophysical Year " and the following addresses were given: " Whistlers and the Outer Ionosphere ", by Dr. G. R. Ellis, C.S.I.R.O., National Standards Laboratory, Division of Radiophysics, Sydney; " Solar Activity ", by S. F. Smerd, C.S.I.R.O., National Standards Laboratory, Division of Radiophysics, Sydney; " Exploration of the Upper Atmosphere by Rockets ", by Mr. W. G. Stroud, visiting American scientist.

Section of Geology

CHAIRMAN: T. G. VALLANCE, PH.D., B.SC.; HON. SECRETARY: L. E. KOCH, D.PHIL.HABIL.

Abstract of Proceedings, 1958

Five meetings were held during the year, alternating with every second meeting of the Geological Society of Australia, New South Wales Division. The average attendance was about 22 members and visitors.

March 21st (Annual meeting): Election of office-bearers:—Chairman: Dr. T. G. Vallance; Hon. Secretary: Dr. L. E. Koch.

Business:—Notes and Exhibits. The following contributions were made: Dr. T. G. Vallance: contact-metamorphic rocks from near London Bridge, 11 miles south of Queanbeyan, containing axinite, clinozoisite, tremolite. Also, vesuvianite from Duckmaloi, Oberon district, and chiastolite from north-west of Dunkeld, N.S.W., were exhibited.

Mr. R. O. Chalmers exhibited specimens of stillwellite from the Mary Kathleen district, N.T., associated with epidote, allanite, diopside, garnet. He also exhibited a scoriaceous material from Narrandera, N.S.W.

Mr. G. H. Packham exhibited plant remains of probably Permian age from a locality eight miles west of Mudgee, N.S.W.

Mr. W. Baker reported briefly on his investigations on hinsdalite from Tasmania and its relations to svanbergite.

May 16th: Address by Dr. A. A. Day: "Geology at Sea (with Special Reference to the North-East Atlantic)". Dr. Day reported on the under-water survey of the sea bed south-west of Britain as well as in the English Channel. Sampling by means of free-fall corers revealed the distribution of pre-Tertiary and late-Tertiary sedimentary deposits. Pebbles originating from glacial drift were characteristic for Pleistocene sediments. The investigations were supplemented by a seismic and echo-sounding survey carried out from the research vessels "Discovery II" and "Sarsia".

July 18th: Short Notes: "Some Aspects of Lateritization" (F. C. Loughnan), "Infra-red Spectra of Minerals" (G. T. See). Mr. F. C. Loughnan discussed the mineralogy of the Fuller's earth deposit at Dubbo, N.S.W., and pointed out the probably Jurassic origin of the material produced by lateritization of probably arkosic sediments. Composition and probable mode of origin of this material were compared with the "Chocolate Shales" of the Narrabeen Group and a similar mode of origin was suggested for the latter.

Mr. G. T. See reviewed recent investigations of the constitution of certain alumosilicates by means of the absorption spectra of infra-red radiation. The method can be used for the determination of the Ab-An content of plagioclases.

September 19th: Address by Mr. H. G. Golding: "Observations on Quarried Sandstones of the Sydney and Gosford Areas." Mr. Golding reported on his investigations on the relations between petrographic characteristics and physical properties of quarried sandstones (Hawkesbury Sandstone) from Piles Creek, Gosford, Paddington, and Maroubra, N.S.W. Gosford sandstone was found to contain a clay plus carbonate bonding, whereas sandstones from Piles Creek contained zones of microstylolites alternating with silica-cemented macro-porous zones. Carbonates are absent. Rates of water absorption, bulk and grain densities (but not porosities) vary significantly with variations in composition and texture.

November 21st: Address by Mr. G. H. Packham: "Observations on Zeolites in Sedimentary Rocks from New South Wales and Other Occurrences", of which the following is an abstract.

"Zeolites formed at or near the surface in sediments are derived either from detrital volcanic material, in particular, volcanic glass, or, in the presence of high concentrations of alkali salts, from other minerals, notably clay minerals. High concentrations of alkali salts favour the formation of analcite from volcanic glass. Studies in Southland, New Zealand, by Coombs (1954) have given evidence of a depth-zoning of zeolites, laumontite being the most significant at lower levels. Other sedimentary occurrences of this mineral fall into the same pattern. Less hydrated calcium silicates occur at greater depths. Studies in hydrothermal areas reveal mineral successions which are comparable in general features, but differ in details. The features which are characteristic of this zoning are increase in lime content and decrease in degree of hydration with depth. A depth-zoning comparable to the Southland occurrence is found in the Carboniferous and Permian rocks extending from the Hunter Valley at least as far north as Bingara, N.S.W."

L. E. KOCH,
Hon. Secretary Section of Geology.

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The typescript should be double-spaced, preferably on quarto paper, with generous side margins. Headings should be typed without underlining; if a paper is long, the headings should also be given in a table of contents typed on a separate sheet, for the guidance of the Editor.

The approximate positions of Figures, Plates and Tables should be indicated in the text between parallel ruled lines. Captions of Figures and Plates should be typed on a separate sheet.

The author's institutional or residential address should be given at the conclusion of the paper, the relevant author's initials being attached in brackets to the appropriate address in cases of papers written jointly.

Abstract. An *informative* abstract should be provided at the commencement of each paper for the guidance of readers and for use in abstracting journals.

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References. References are to be cited in the text by giving the author's name and the year of publication, e.g.: Vick (1934); at the end of the paper they should be arranged alphabetically giving the author's name and initials, the year of publication, the title of the paper (if desired), the abbreviated title of the journal, volume number and pages, thus:

VICK, C. G., 1934. *Astr. Nach.*, **253**, 277.

The abbreviated form of the title of this journal is: *J. Proc. Roy. Soc. N.S.W.*

Line Diagrams. Line diagrams should be made with dense black ink on either white bristol board, blue linen or pale-blue ruled graph paper. Tracing paper is unsatisfactory because it is subject to attack by silverfish and also changes its shape in sympathy with the atmospheric humidity. The thickness of lines and the size of letters and numbers should be such as to permit photographic reduction without loss of detail.

Whenever possible dye-line or photographic copies of each diagram should be sent so that the originals need not be sent to referees, thus eliminating possible damage to the diagrams while in the mail.

Photographs. Photographs should be included only where essential, should be glossy, preferably mounted on white card, and should show as much *contrast* as possible. Particular attention should be paid to contrast in photographs of distant scenery and of geological subjects.

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AUSTRALASIAN MEDICAL PUBLISHING CO. LTD.
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JOURNAL AND PROCEEDINGS

OF THE

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VOLUME 93

PART 3

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Royal Society of New South Wales

OFFICERS FOR 1959-1960

NOTICE

The Royal Society of New South Wales originated in 1821 as the "Philosophical Society of Australasia"; after an interval of inactivity it was resuscitated in 1850 under the name of the "Australian Philosophical Society", by which title it was known until 1856, when the name was changed to the "Philosophical Society of New South Wales". In 1866, by the sanction of Her Most Gracious Majesty Queen Victoria, the Society assumed its present title, and was incorporated by Act of Parliament of New South Wales in 1881.

Journal and Proceedings, Royal Society of New South Wales, Vol. 93, pp. 99–103, 1959

Dykes in the Port Stephens Area

Beryl Nashar and C. Catlin

(*Received* 30 *July*, 1959)

Abstract—A swarm of some 60 non-olivine bearing basaltic dykes of probable Tertiary age is recorded as outcropping along the coastline in the Port Stephens District. The rocks intruded are Carboniferous lavas. The dykes fall into two natural groups, namely, those striking approximately north-south and those striking approximately east-west.

Introduction

Throughout the literature, mention is made of dykes which outcrop along the coastal region of N.S.W. That the dykes are unequally distributed has been shown by Morrison (1904), who has described the dykes of the Sydney District. In that District, the area of concentration is between Port Jackson and Botany Bay. Harper (1915) has described some 270 dykes along the coast between Broken Bay and Nowra, while Raggatt and Whitworth (1930) have described at least 40 dykes in the Muswellbrook-Singleton area. However, Hills (1955, p. 12, Fig. 6) indicated that there are at least 200 dykes between Nowra and Port Hacking, 103 in the Sydney District, and 48 in the Newcastle District. In literature on the coal-fields, for example, Lonie (1957) and Wilson *et al.* (1958), mention is made of the presence and distribution of similar dykes.

The area considered in this paper lies along the coastline between Cemetery Point and Tomaree on the coast and Tomaree and Corlette Point on the southern shore of Port Stephens—

Table I

East-West Dykes			North-South Dykes		
Dyke No.	Thickness	Direction	Dyke No.	Thickness	Direction
1	9″–18″	E 23° N	6	9″	S 10° E
2	24″	E 30° N	8	48″	S 4° E
3	162″	E-W	9	36″	S 4° E
4		E-W	16	48″	S 22° E
5	24″	E 8° N	17	54″	S 13° E
7	18″–120″	E 3° N	18	27″	S 13° E
10	12″	E 18° N	19	120″	S 15° E
11	12″	E 10° N	20	120″	S 15° E
12	18″	E-W	23	22″	S 15° E
13	204″	E 7° S	24	12″	S 15° E
14	192″	E 10° N	25	18″	S 15° E
15		E 19° N	26	72″	S 10° E–S 15° E
21	36″	E-W	28	24″	S 2° E
22	84″	E-W	29	24″	S 13° E
27	6″	E 9° N	30		
31	84″	E 13° N	33	24″	S 2° E
32		E 11° N	34	24″	S 2° E
39	10″	E-W	35	45″	S 2° E
42		E 6° N	36	81″	S 19° E
46		E 18° N	37	12″	S 19° E
47		E-W	38	72″	S 19° E
50	36″	E 15° N	38*a*		S 15° E
51		E 15° N	40		S 19° E
52	18″	E-W	41	6″	S 19° E
53	18″	E-W	43	24″	S 2° E
55	24″	E 20° N	44	24″	S 2° E
56	24″	E 20° N	45	45″	S 2° E
57	72″	E 33° N	48		S 20° W
			49	30″	S 20° W
			54	24″	S 7° W

Note: Where no thickness and/or direction are/is given the dyke has probably been eroded or lies submerged under the water.

a distance of approximately 24 miles. Again, in this district the dykes are unequally distributed, the area of concentration lying between Cemetery Point and Morna Point—a distance of about seven miles.

The dykes intrude volcanic rocks belonging to the Kuttung Series of the Carboniferous System. The volcanic rocks include rhyolite, toscanite and andesite, but for some reason, not yet clear, the dykes intrude, for the most part, the rhyolite. They are exposed best in the rock platforms and are soon lost after cutting back into the cliff because of superficial deposits of dune sand, soil and undergrowth.

Nature of Intrusion and Direction

The dykes number about 60 and, in keeping with the other dykes along the coast, those in the Port Stephens District fall into two distinct groups—those that trend approximately north-south (range of strike S. 19° E. to S. 20° W.) and those that trend approximately east-west (range of strike E. 33° N. to E. 7° S.). See Table I. The number of dykes in each group is about equal.

For distribution of dykes between Cemetery Point and Fingal Bay, see Figs. 1, 1A and 1B. Actually, two more dykes which are not shown in the text-figures occur to the north, one just south of Tomaree and the other at Nelson's Head.

Although the dyke outcrops have been numbered individually, it is probable that some of the outcrops belong to the same dyke as indicated by the dotted lines, in the above-mentioned figures. This would, of course, reduce the total number of dykes.

The dykes vary in thickness from a few inches to about 17 feet, and in all cases seem to have been intruded along the joints of the older lavas. Mostly they are quite regular, but some show effects of side-stepping as a result of moving from one joint to another. In some places this involves a lateral shift of only a few inches, while at others it is in the order of 12 to 18 inches. See Fig. 2. Side-stepping may be noted both in plan and in vertical section. Xenoliths of rhyolite, the country rock, are present in some of the dykes. The wider dykes often show jointing parallel to both sides of the dyke for a width of about six inches, while within the dykes joints are developed perpendicular to the sides.

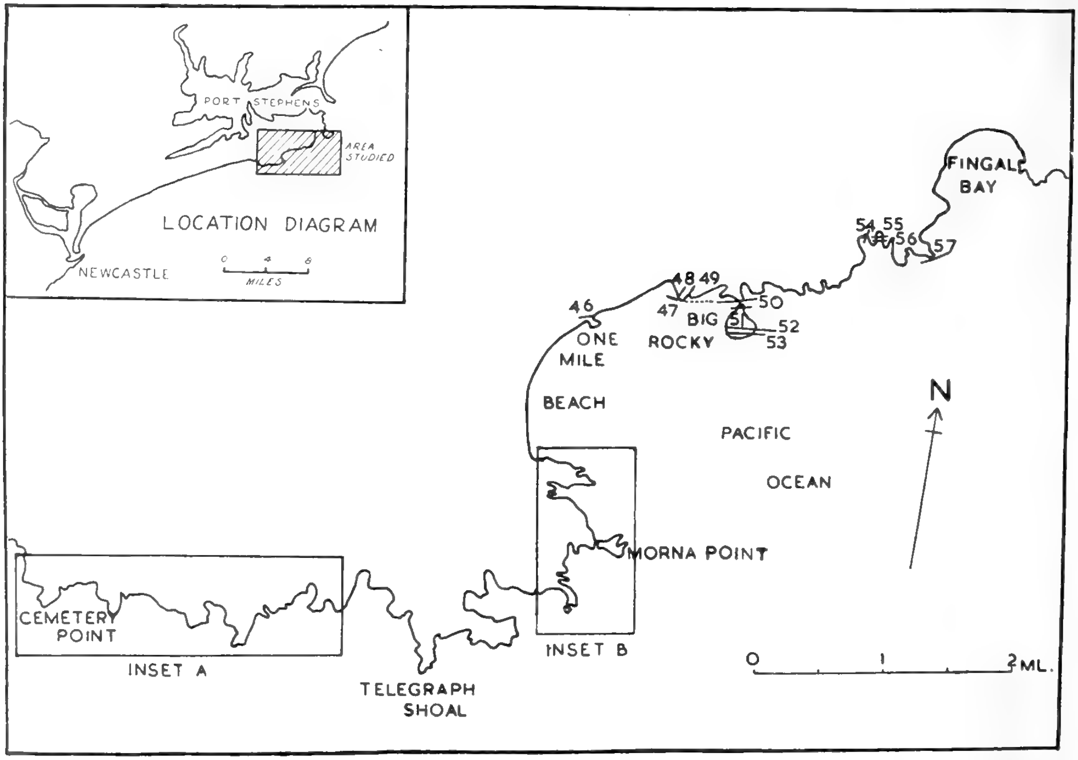

FIG. 1

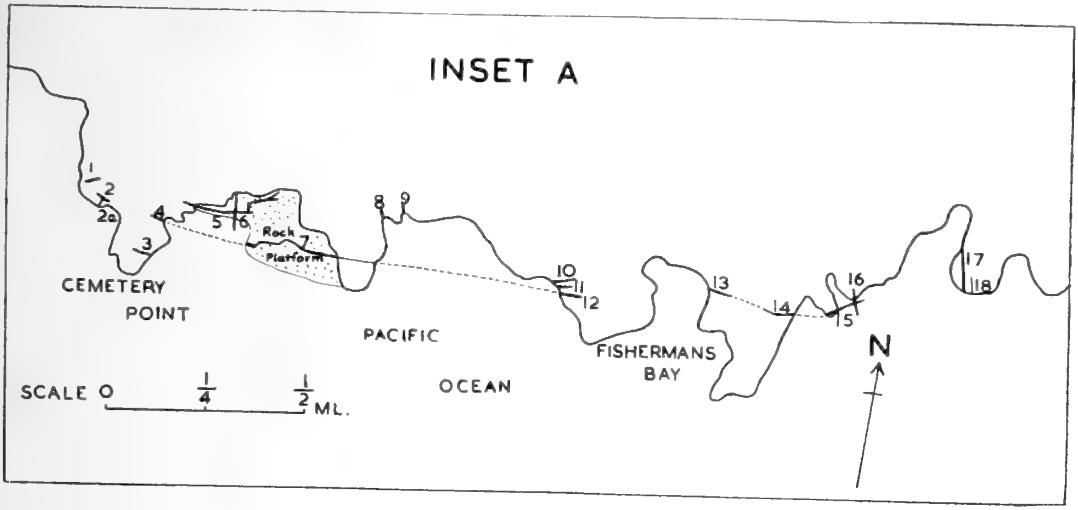

Fig. 1a

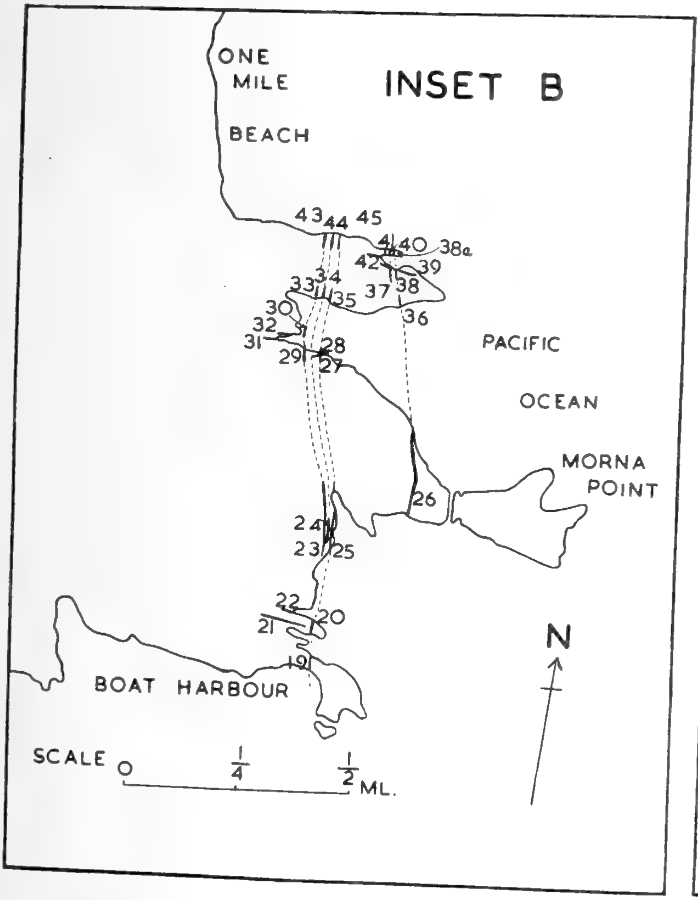

Fig. 1b

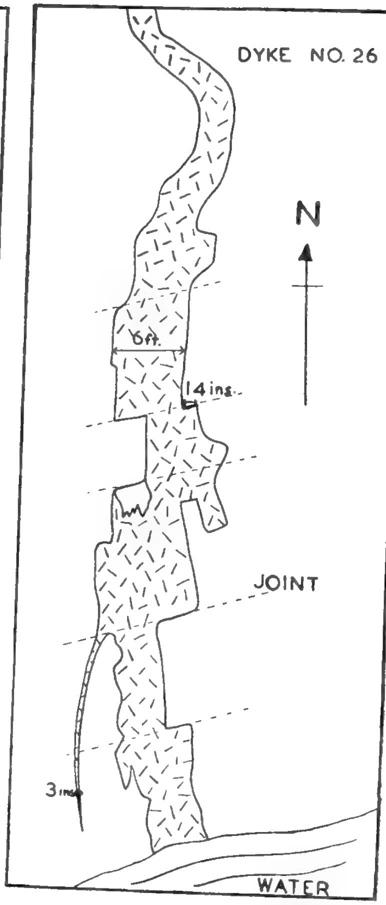

Fig. 2

Age

All that may be stated definitely about the age of the dykes under consideration is that they are post-Carboniferous. However, most writers have ascribed a Tertiary age to similar dykes elsewhere, for they intrude rocks of Permian age as at Newcastle and rocks of Triassic age as in the Sydney District. Because of differences in rock types and the fact that some dykes are intersected by others, Harper (1915) thought that they did not fall in the same epoch of volcanic activity. However, the present writers, on petrological evidence, namely, the similarity of rock type, believe that the dykes of the Port Stephens District belong to the one epoch but some of the north-south dykes may have been emplaced slightly before the others. Evidence for this is obtained at the southern end of One Mile Beach. There, north-south dykes, numbers 38*a* and 40, are slightly offset by east-west dyke number 42, which obviously was intruded a little later. However, the rock type in all three dykes is identical.

The geographical relationship of the Older basalts to the Port Stephens dykes is shown in figure 6 of Hills (1955). If these dykes are feeders to the basalts, then they must be the same age.

David (1950) states that although the age of all the coastal dykes is not known they are, for the most part, assigned to the Older volcanic series on the grounds of physiographic relations and geographical association with Older flows and partly on petrological character. He regards the Older volcanics as being pre-Miocene in age.

Weathering

The dykes afford an excellent example of differential weathering. The mechanical weathering by the ocean is negligible in comparison with the effect of the chemical weathering by ground water. The mechanical effect has been in some cases to reduce the dykes to the level of the surrounding volcanic rock, while in others the dykes are eroded away, leaving a trench. Because of the strong relationship between jointing and dykes, it is often difficult to tell if some of the trenches were originally hosts to dyke material since eroded away or have been joints widened by erosion. However, remnants of dyke rock are to be found in some eroded joints. Where the dykes are seen to cut back into the cliff, ground water has kaolinized the dyke rock and further mechanical weathering has caused the dyke to recede for some distance into the cliff.

Petrography

Unlike some of the dykes elsewhere, the dykes of the Port Stephens District are rather constant in mineralogical composition. Neither monchiquites nor any other lamprophyres as recorded from the South Coast dykes have been found. The rocks are olivine free felspathic basalts/dolerites which range in grain size from fine grained basalts to medium grained dolerites.

The mineral constituents are as follows:

Plagioclase: The composition appears to be labradorite ($Ab_{45}An_{55}$). The laths vary in length from 0·1 mm. to 1·5 mm., averaging 0·2 mm. in the finer grained rocks and 0·7 mm. in the coarser. Occasional rocks contain plagioclase as phenocrysts when the size is approximately 1·5 mm. Sometimes this mineral is kaolinized, and the larger laths may show partial replacement by chlorite. The phenocrysts, when present, occasionally show replacement by calcite and chlorite.

Augite: This mineral varies from being finely granular (0·05 mm.) to occurring as small prismatic crystals which average 0·1 mm. in the finer grained rocks. Occasional idiomorphic phenocrysts may range up to 1 mm. in length and the augite in the coarser rocks may average 0·5 mm. The average content in the rocks would be about 20%. The alteration product, when present, is chlorite.

Ilmenite: For the most part, this mineral occurs as fine grains, although in some rocks, particularly the coarser, it may occur as skeletal crystals. The frequent alteration product is leucoxene, grains of which are scattered throughout the rocks.

Apatite: Fine needles of this mineral are fairly abundant as an accessory constituent in the rocks.

Chlorite: This mineral occurs abundantly, mostly interstitially between the felspar laths. It was noted that the more abundant the chlorite, the more abundant are the granules of iron ore, indicating that some of the latter may be secondary in origin.

Analcite and Calcite: These minerals have been observed in some rocks. They are not abundant and when they do occur they are interstitial and often outlined by chlorite.

Acknowledgement

Thanks are extended to Mr. A. S. Ritchie of Newcastle University College who introduced the authors to the area and for his co-operation in the field.

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School of Mining Engineering and Applied Geology
Newcastle University College

Journal and Proceedings, Royal Society of New South Wales, Vol. 93, pp. 105–120, 1959

Deuteric Alteration of Volcanic Rocks

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Abstract—A review is presented of common types of deuteric alteration of volcanic rocks and of the effects of alteration on physical properties, mineralogy and bulk chemical composition. It is shown that some quantities, such as the $(FeO+Fe_2O_3)/(FeO+Fe_2O_3+MgO)$ ratio, which are taken as guides to stages of magmatic differentiation are affected by alteration and that, in general, changes due to alteration are parallel with those produced by magmatic differentiation within such broad groups as basic, intermediate and acid volcanic rocks. There is evidence that solid state replacement of basic rocks may give rise to extreme acid differentiates by deuteric alteration so that the processes are convergent. This replacement probably requires introduction of alkalis and extensive leaching of mafic minerals. Changes in fabric are likely, and convergence with magmatic processes is expressed in mineralogy, bulk chemical composition, and a trend towards the low-temperature trough of the system nepheline-kaliophilite-silica. Some conclusions based on the erroneous assumption that alteration has little or no effect on bulk composition are reviewed, and some problems in classification are pointed out. The origin and composition of deuteric solutions is discussed, and it is shown that volatiles and their dissolved constituents may be concentrated, and ultimately cause alteration, by several mechanisms of which fractional crystallization of anhydrous minerals is only one. The complementary effects of loss of deuteric fluids before alteration is briefly considered.

Introduction

Volcanic rocks are susceptible to alteration in a wide variety of environments and it is likely that such diversified processes as low-grade regional metamorphism, diagenetic alteration, weathering, deuteric alteration and hydrothermal alteration accompanying ore deposition can produce much the same secondary mineral assemblages from rocks of the same composition. Not all of the processes are mutually exclusive; for example, some ore deposits within lava flows or shallow intrusions are of internal origin and associated hydrothermal alteration may be classed as deuteric. In addition, fumarolic alteration may in certain circumstances be considered as deuteric alteration. Designation of the process responsible for alteration is not simple and usually requires knowledge of all post-consolidation events in the history of the rocks. Many of the criteria set forth by Ross and Shannon (1926) adequately distinguish between alterations produced by solutions of internal and external origin in undeformed rocks, but do not take into account modifications of deuteric alteration products by weathering. The best criterion supporting an origin by deuteric alteration is restricted distribution of alteration products within a particular flow or intrusion. Where large areas of volcanic rocks, including a number of lithologic or structural units, have been altered, an external source of hydrothermal solutions is probable. An example of such alteration is propylitization, common among undeformed members of calc-alkaline volcanic suites. The secondary mineral assemblage—clay, carbonate, epidote, quartz, albite—produced by this type of alteration is similar to that produced by deuteric alteration in rocks of the same composition. Where the rocks are interbedded with marine sediments (e.g. spilites) or have been deformed, the process of alteration may be difficult to ascertain.

Deuteric alteration was originally defined (Sederholm, 1916) as metasomatic changes taking place " in direct continuation of the consolidation of the magma of the rock itself ". Singewald (1932) proposed that the term " deuteric " be restricted to reactions in a closed system, thus excluding alteration produced by fluids derived from more deep-seated magmatic sources than represented by the altered rocks themselves. Sederholm (1929), in an effort to clarify controversial points of usage raised by Gillson (1929) and Osborne (1929), stated that the term was intended to be descriptive of changes in primary minerals and not of the process. For present purposes, Sederholm's meaning is most useful and takes the emphasis off qualitative arguments about how much alteration is consistent with an internal source of aqueous solutions. Singewald's usage has the additional disadvantage of the many misleading implications of a " closed system ". If this precluded loss of volatiles and their dissolved constituents from the altered rocks, or concentration of fluids in certain parts of flows or intrusions, the term deuteric would have few natural occurrences under its name. In considering the formation of complementary rocks or liquids by loss of volatile constituents, however, the source of deuteric fluids is of importance.

There is nothing in Sederholm's definition which gives a guide to the types of minerals formed by deuteric alteration or to the effects of metasomatism, and there is room for legitimate doubt about separating magmatic from post-magmatic events (Ross, 1928). The distinction becomes important, however, in considering the distribution of elements by crystal-liquid reactions on the one hand and by solid state reactions on the other. In the first instance chemical evolution of the rocks may be controlled by relative movement of crystals and liquid and in the second instance by addition and/or removal of constituents from an already solid rock. For the most part consideration of metasomatism in deuteric alteration has been confined to introduction of constituents, especially H_2O, CO_2 and alkalis, while selective leaching has not been accorded an important role by igneous petrologists although this is an essential part of Lindgren's (1925) definition of metasomatism. The main purpose of this paper is to show, from data available in the literature, the magnitude of changes which may be effected by solid state replacements and to discuss the implications of these changes in classification of volcanic rocks and petrogenetic considerations.

Physical Changes

The variety of physical changes caused by deuteric alteration are practically the same as those described by Schwartz (1939, 1959). Altered rocks may be either lighter or darker in colour than their unaltered equivalents, and are usually less dense. Where alteration results in filling of vesicles, the bulk density may increase, but alteration of holocrystalline rocks nearly always causes a reduction in density. For the most part the original fabric of altered rocks is well preserved (Day, 1925, 1930*a*; Wilshire, 1958, 1959), which clearly indicates equal volume replacement. In some cases parts of the original fabric may be destroyed by alteration (Day, 1930*a*, 1930*b*), but those parts which are preserved generally indicate equal volume replacement. In a few cases the author has observed brecciation along narrow veins of secondary minerals, but this is exceptional.

Because of density variation, the distinction between passive and actual chemical changes due to alteration requires measurement of densities of altered and unaltered equivalents (Lindgren, 1900). Calculations of changes are straightforward with holocrystalline rocks, but in the case of deuteric solutions of internal origin an additional problem arises, for segregation of volatiles before alteration may give rise to open cavities. If such rocks are compared with those in which volatiles were not segregated, conversion of weight percents to gms./cc. will show unreal changes. In general it will be difficult to distinguish between cavities formed in this manner and those formed by solution. If the two cannot be distinguished or occur together, it is best to obtain both bulk and powder densities which will provide maximum and minimum passive changes respectively.

Mineral Alteration

Three principal types of deuteric alteration may be designated as: (1) dominantly clay mineral alteration; (2) dominantly carbonate alteration; and (3) dominantly zeolite alteration. Various combinations of the three are, of course, common, but where one group of secondary minerals dominates over others the effects of alteration on bulk composition may differ as shown in a subsequent section.

The susceptibility of primary minerals to alteration is a complex matter, governed at least in part by the factors outlined by Schwartz (1959) and Hemley (1959). In dominantly carbonate alteration, mafic minerals are commonly pseudomorphed by granular aggregates of carbonate and quartz with variable amounts of clay. In some examples of carbonate alteration plagioclase remains fresh although mafic minerals are completely altered (Wilkinson, 1958; Bailey *et al.*, 1924; Wilshire, 1959), but in others (Day, 1930*a*; Day and Stenhouse, 1930) plagioclase may also be altered to carbonate. In hydrous alteration feldspars are frequently replaced by zeolites of a variety of compositions or by members of the kaolinite and mica groups (Buddington, 1923; Chapman, 1950; Duschatko and Poldervaart, 1955; Muilenburg and Goldich, 1933; Wilkinson, 1958). Where associated mafic minerals are altered to clay, plagioclase is not infrequently replaced by trioctahedral montmorillonite or chlorite. Olivine and orthopyroxene are usually altered to trioctahedral clay minerals (Wilshire, 1958) and are the only minerals which commonly show structural inheritance in alteration products (Brown and Stephen, 1959). Clinopyroxene is sometimes remarkably resistant to alteration (Browne, 1925; M'Lintock, 1915), but may be altered to carbonate and chlorite

(Campbell, Day and Stenhouse, 1934) and is susceptible to composition change from salite to diopside (Shannon, 1924) or aegerine (Gillson, 1927 ; Larsen and Pardee, 1929) in the deuteric stage. Biotite and hornblende are both susceptible to chlorite-carbonate-sericite-epidote alteration, while nepheline and leucite are sometimes altered to sericite or zeolites. Unfortunately, little information is available on alteration of opaque minerals, but some records of conversion of titanomagnetite and ilmenite to leucoxene, sphene or hematite are available (Campbell, Day and Stenhouse, 1934 ; Cornwall, 1951*a*).

Clay Minerals—Members of all the major phyllosilicate clay mineral groups have been reported as products of deuteric alteration, the more common of which include: saponite (=bowlingite) (Cailliere and Henin, 1951 ; Mackenzie, 1958), common as pseudomorphs after mafic minerals, and as joint and vesicle filling ; vermiculite (Bradley, 1945) as vesicle filling ; nontronite (Prider and Cole, 1942 ; Allen and Scheid, 1946) as pseudomorphs after olivine and fracture filling ; regularly interstratified montmorillonite-chlorite (Earley and Milne, 1956) as vesicle filling ; random mixed-layer montmorillonite-chlorite (Wilshire, 1958) as pseudomorphs after mafic minerals and as joint and vesicle filling ; caladonite (Campbell, Day and Stenhouse, 1934 ; Hendricks and Ross, 1941) as vesicle filling ; and chlorophaeite (=allophane) (Peacock and Fuller, 1938 ; Fermor, 1928 ; Ming-Shan Sun, 1957 ; Smedes and Lang, 1955 ; Wilshire, 1958) as pseudomorphs after mafic minerals and as joint and vesicle filling.

Others, possibly less common, clay minerals which may occur as mechanical mixtures with the above include serpentine, talc and mica. Dioctahedral members of the kaolin and mica groups have often been reported as alteration products of feldspars and zeolites. It is noteworthy that none of the common clays are Ca-bearing (except as absorbed cations). Determination, at least qualitatively, of clay mineral composition is important, for such common clay alterations as replacement of plagioclase adjacent to altered mafic minerals by trioctahedral montmorillonite requires redistribution of Ca and Al originally combined in plagioclase. For reasons given in a later section, clay minerals often do not reflect directly the composition of the primary minerals which they replace.

Many of the optically homogeneous clay products of deuteric alteration are mixtures of both clay and non-clay materials. Because of this the use of mineral names or specification of composition is not warranted unless adequate identification techniques are used. As mineral species, iddingsite and bowlingite have been discredited, and there is probably considerable variation in types and proportions of minerals making up these aggregates. Iddingsite probably consists chiefly of montmorillonite or vermiculite and goethite (Brown and Stephen, 1959) or of goethite and allophane (Ming-Shan Sun, 1957). Bastite in basic lavas is commonly the same as iddingsite, but has a lower Fe^3/Fe^2 ratio and more commonly contains magnetite than goethite (Wilshire, 1958). All four principal types occur in lavas and hypabyssal intrusions, but " iddingsite ", " bastite " and chlorophaeite are more common in lavas, " bowlingite " in intrusions. With the presently available data there is a large difference in composition, depending on occurrence, but " iddingsite " from intrusions (e.g. Wilkinson, 1958) has not been analysed. Average analyses are given in Table I and are divided into five groups : (I) " iddingsite " pseudomorphs after mafic minerals ; (II) " iddingsite " vesicle filling ; (III) chlorophaeite vesicle filling ; (IV) " bowlingite " joint filling ; and (V) celadonite vesicle filling (possibly the same as II).

Carbonates—Carbonates commonly accompany clay minerals in deuterically altered rocks and sometimes make up the bulk of alteration products. Identification and composition deter-

TABLE I

Average Composition of Some Deuteric Clay Mineral Aggregates

	I	II	III	IV	V
SiO_2	41·20	52·45	45·02	44·56	53·59
TiO_2	0·14	0·05	0·30	0·20	—
Al_2O_3	3·81	7·17	6·25	7·69	6·10
Fe_2O_3	35·42	14·27	19·35	7·25	15·28
FeO	0·38	2·43	6·93	3·82	3·93
MnO	0·05	0·03	0·34	—	0·17
MgO	6·85	7·15	9·65	22·86	6·33
CaO	2·35	2·01	2·95	2·14	0·89
Na_2O	0·12	0·87	0·59	—	0·74
K_2O	0·10	5·43	0·16	—	6·87
H_2O^+	9·30	5·81	7·71	8·17	7·67
H_2O^-	9·84	3·94	17·89	12·06	

All analyses except those of celadonite recalculated to 100% excluding H_2O^- before averages were computed.

Column I represents 10 analyses (Wilshire, 1958) ; Column II represents 3 analyses (*Min. Abs.*, v. 13, pp. 186, 393) ; Column III represents 6 analyses (Wilshire, 1958 ; *Min. Abs.*, v. 13, pp. 185, 393) ; Column IV represents 5 analyses (Wilshire, 1958 ; Mackenzie, 1958) ; Column V represents 12 analyses (Hendricks and Ross, 1941 ; *Min. Abs.*, v. 13, pp. 59, 180).

mination are easier than with clay minerals, but in spite of this compositions are often inferred from rock analyses or the carbonate is simply called calcite. As with clay minerals, the composition of carbonates does not directly reflect the composition of primary minerals which they replace. Ca-rich carbonates as frequently replace magnesian olivine as plagioclase, and of course a redistribution of silica and alumina is implied by carbonate alteration.

Zeolites—The zeolites comprise a chemically and structurally complex group of minerals which are very abundant in deuterically altered volcanic rocks. For the most part these are hydrated silicates of lime, alkalis, and alumina with few members containing significant amounts of Fe and Mg. Among the more common deuteric zeolites are members of the natrolite, pectolite, and prehnite groups and analcite, but such minerals as heulandite, thomsonite, chalybite and others are locally abundant. Again, such replacements as plagioclase by analcite or by prehnite effectively exclude certain elements originally combined in the primary mineral.

Other Secondary Minerals—Among the most important anhydrous deuteric minerals are alkali feldspars and quartz which have frequently been recorded as products of deuteric alteration of plagioclase (Bailey and Grabham, 1909; M'Lintock, 1915; Colony, 1923; Shannon, 1924; Bailey *et al.*, 1924; Browne, 1924; Gillson, 1927; Clough *et al.*, 1925; Campbell *et al.*, 1932; Shand, 1943; Walker and Poldervaart, 1949; Cornwall, 1951*b*; Duschatko and Poldervaart, 1955). The alkali feldspar is generally called albite, but the properties given often do not warrant so specific a designation. Less common as alteration products in undeformed lavas and shallow intrusions are epidote, amphiboles, pumpellyite, garnet, sphene and sulphides.

Metasomatic Character of Mineral Alteration

It was suggested above that the composition of secondary minerals need not directly reflect the composition of primary minerals which they replace. Duschatko and Poldervaart (1955) consider this selectivity to be one of the most important characteristics of secondary minerals, and exclusion of elements which were combined in altered primary minerals is a defining characteristic of the most important class of pseudomorphs in Naumann's classification (Lindgren, 1900). Unfortunately, there is not a great deal of quantitative information on metasomatic alterations, but in such cases as replacement of olivine by calcite leaching of silica and magnesia is self-evident. Especially with clay mineral aggregates and some zeolites, it is difficult to determine compositions of secondary minerals, but in general equal volume replacement of primary minerals by less dense secondary minerals as well as addition of H_2O and CO_2 clearly suggest that material must be leached in the replacement. That leaching is selective is implied by gross differences in composition between primary minerals and alteration products. Examples of the types of chemical changes which are involved in the alteration of olivine to "iddingsite" (Ross and Shannon, 1926; Ming-Shan Sun, 1957) and in sericitization of plagioclase (Muilenburg and Goldich, 1933) are shown in Table II. These are the only quantitative data pertaining to metasomatic mineral alteration which the author has found, and even these calculations involve some assumptions. As pointed out by Ross and Shannon (1926), alteration of olivine to "iddingsite" involves leaching of MgO, oxidation of Fe, and addition of H_2O. Relatively small amounts of Fe and Al are also added, and silica removed. The changes involved in sericitization of plagioclase illustrate the possible effects of alteration on K_2O/alkali and alkali/CaO+alkali ratios, ratios which also increase with progressive magmatic differentiation. Many authors have commented on the probability of such metasomatic changes (Tyrrell, 1928; Wilkinson, 1958; Peacock and Fuller, 1938; Shannon, 1924; and others), but it is often difficult to obtain reliable data, especially in fine-grained volcanic rocks. Reliance on optical determination of composition is suspect

TABLE II

Chemical Variation in Equal Volume Replacement of Olivine and Plagioclase

	1	2	3
SiO_2	— 313	— 595	— 52
Al_2O_3 ..	+ 47	+ 106	— 44
Fe_2O_3 ..	+ 861	+1113	—
FeO	— 778	— 778	—
MgO ..	—1153	—1064	—
CaO	+ 74	+ 26	—173
Na_2O ..	—	—	— 28
K_2O	—	—	+ 94
H_2O	+ 466	+ 417	+ 89
CO_2	—	—	+ 14

1=gains and losses (milligram/cc.) in replacement of olivine by iddingsite (Ross and Shannon, 1926); **2**=gains and losses in replacement of olivine by iddingsite (Ming-Shan Sun, 1957); **3**=gains and losses in partial sericitization of plagioclase (Muilenburg and Goldich, 1933).

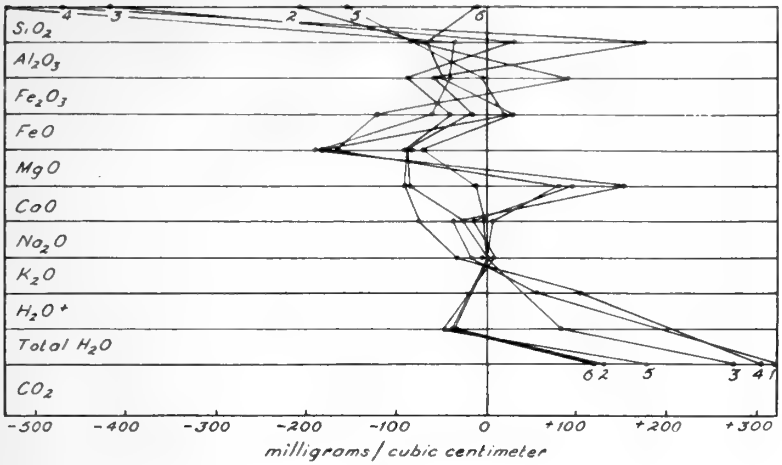

FIG. 1

Straight line variation diagram illustrating compositional changes in basic volcanic rocks due to dominantly carbonate alteration. 1=analyses 1–2, Table III. 2=anals. 3–4; 3=anals. 5–6; 4=anals. 7–8; 5=anals. 9–10; 6=anals. 9–11.

for many alteration products, and aggregates of different minerals pseudomorphing single crystals of primary minerals introduce errors into mineral calculations.

The data tabulated in Table II deal only with the distribution of major elements. Inasmuch as alteration of primary minerals involves complete structural reorganization and selective leaching, redistribution of trace elements is likewise to be expected. To the author's knowledge, this problem has not been dealt with on a mineralogical basis.

Dispersal of Alteration Products

The best criterion for the secondary origin of the minerals under discussion is, of course, pseudomorphism of primary minerals. If the considerations outlined above are correct, this alteration involves leaching of material which must be deposited elsewhere if the volume occupied by primary minerals is to remain the same. Hence, it is not surprising to find the same types of minerals occurring in vesicles, joints and porous wall rock. That constituents leached from primary minerals may be entirely removed from the rock is evident from generally lower bulk densities of altered rocks compared with their fresh equivalents. This does not mean, however, that every occurrence of these common secondary minerals in vesicles and joints is to be attributed to alteration, for the same conditions which permit migration of these materials will also permit movement of interstitial liquid residues formed by fractional crystallization and under appropriate conditions these may crystallize directly to any of the abovementioned minerals. Where equal volume deuteric alterations do occur, however, leaching and redeposition are to be expected.

Bulk Chemical Changes

The data now available representing altered and unaltered equivalents is meagre, and the value of much of that is considerably reduced by lack of specific gravity data. In addition, where supposed altered and unaltered equivalents are separated by some distance and variations in granularity occur the lack of modal analyses renders some analyses suspect. Most of the data available represent altered basic rocks, and it is generally extreme alterations which have attracted sufficient attention for analyses to be made. Some of these have probably been further modified by weathering and others represent various stages of alteration with no fresh equivalent.

Figs. 1 and 2 are a modification of the straight line variation diagrams used by Leith and Mead (1915). In these diagrams absolute compositional changes are represented in terms of milligrams/cc., assuming equal volume replacement. Inasmuch as many petrological calculations are based on weight percentages, the analyses used in Figs. 1 and 2 as well as others used in subsequent calculations are given in Table III.

TABLE III

Chemical Analyses of Fresh and Altered Rocks

	1	2	3	4	5	6	7	8	9	10
SiO_2 ..	46·01	31·91	42·02	38·80	43·05	32·97	46·31	32·01	43·52	40·65
TiO_2 ..	2·46	2·92	2·75	2·60	2·63	2·87	1·82	2·19	1·69	2·03
Al_2O_3 ..	13·13	13·41	14·19	12·88	14·23	17·54	16·91	25·33	13·95	11·75
Fe_2O_3 ..	2·84	1·64	1·04	4·62	4·00	1·01	3·25	1·25	5·01	5·19
FeO ..	10·09	9·01	9·98	6·31	7·07	6·43	6·46	6·23	6·70	7·87
MnO ..	0·18	1·39	—	—	0·17	0·17	0·17	0·19	0·22	0·13
MgO ..	8·90	2·86	10·65	5·56	8·62	5·05	6·01	3·15	10·84	4·52
CaO ..	9·08	15·87	10·83	16·15	10·55	8·64	9·33	6·71	8·74	13·13
Na_2O ..	3·03	2·04	2·82	3·35	2·36	1·48	3·08	0·34	2·72	2·22
K_2O ..	0·96	0·42	0·59	0·66	0·98	1·05	1·33	0·15	1·29	1·54
H_2O^+ ..	2·58	4·82	4·58	3·60	4·65	8·54	4·31	8·76	4·82	3·37
H_2O^- ..	0·30	1·30								
P_2O_5 ..	0·49	0·48	0·79	0·53	0·82	1·03	0·45	0·68	0·40	0·62
CO_2 ..	0·06	11·88	0·11	4·99	1·18	12·33	0·36	12·32	0·05	6·72
FeS_2 ..	—	—	—	—	0·28	0·44	0·22	0·42	0·39	0·62
Total ..	100·11	99·95	100·35	100·05	100·59	99·55	100·01	99·73	100·34	100·36
S.G.* ..	3·03	2·67	2·9	2·6	2·89	2·5	2·78	2·55	2·79	2·6

TABLE III—*Continued*

	11	12	13	14	15	16	17	18	19	20
SiO_2 ..	46·29	36·95	40·84	33·33	44·21	36·53	49·86	38·83	45·63	42·07
TiO_2 ..	2·08	3·05	2·68	5·57	2·24	1·80	1·33	nil	2·04	2·57
Al_2O_3 ..	12·44	17·88	32·13	18·97	9·11	14·08	12·75	15·25	14·54	11·24
Fe_2O_3 ..	3·48	5·84	2·21	7·00	3·77	5·63	3·36	4·33	1·98	5·08
FeO ..	8·18	12·12	1·05	9·32	8·07	6·26	11·38	13·83	10·21	7·92
MnO ..	0·12	—	—	—	—	—	—	—	0·19	0·18
MgO ..	5·04	5·45	0·90	3·91	7·84	7·20	4·39	4·18	9·18	8·81
CaO ..	8·88	3·39	2·60	1·20	7·60	8·51	8·71	3·92	9·83	8·53
Na_2O ..	2·85	—	nil	nil	1·29	1·70	5·25	0·97	3·46	3·66
K_2O ..	1·26	—	nil	nil	4·73	1·18	0·57	0·42	1·04	0·32
H_2O^+ ..	3·77	6·14	10·14	9·82	0·38	1·05	2·56	11·01	1·09	5·12
H_2O^- ..		6·99	9·06	11·18	3·01	5·70			0·56	3·77
P_2O_5 ..	0·51	—	—	—	2·77	4·13	0·58	nil	0·50	0·57
CO_2 ..	4·74	—	—	—	4·99	6·14	nil	9·32	nil	0·21
FeS_2 ..	0·63	—	—	—	—	—	—	—	—	—
Total ..	100·27	97·81	101·61	100·30	100·01	99·91	100·74	102·06	100·25	100·05
S.G. ..	2·6	2·63	2·04	2·54	2·72	2·60	2·91	2·6	3·00	2·66

TABLE III—*Continued*

	21	22	23	24	25	26	27	28	29
SiO_2 ..	52·72	51·06	51·75	49·96	48·69	33·04	34·91	37·98	31·81
TiO_2 ..	1·20	0·55	1·60	1·63	2·06	2·08	4·28	3·0	3·98
Al_2O_3 ..	16·19	18·66	15·91	16·47	16·02	25·53	7·80	11·39	10·88
Fe_2O_3 ..	4·80	4·15	0·76	5·33	4·18	2·51	1·01	1·32	2·13
FeO ..	4·14	4·91	9·71	4·68	6·91	1·81	5·77	6·03	5·43
MnO ..	0·07	0·09	—	—	0·19	0·11	0·59	0·10	—
MgO ..	4·12	3·55	7·36	5·10	3·82	3·24	11·25	12·10	8·79
CaO ..	8·10	5·64	8·08	8·30	5·58	8·73	8·68	5·49	8·51
Na_2O ..	3·31	3·75	2·82	2·10	4·17	0·47	1·90	2·86	1·41
K_2O ..	2·45	3·84	1·52	1·02	2·73	0·24	5·68	3·08	3·53
H_2O^+ ..	1·56	2·88	0·65	2·41	4·17	10·08	0·25	0·47	0·29
H_2O^- ..	0·92	0·18	0·09	3·08			0·49	0·92	0·13
P_2O_5 ..	0·48	0·41	—	—	0·90	1·68	4·81	3·45	4·75
CO_2 ..	0·07	0·36	nil	nil	0·75	10·30	12·03	11·86	18·41
FeS_2 ..	—	—	—	—	0·43	0·39	—	—	—
Total ..	100·13	100·03	100·25	100·08	100·60	100·21	99·45	100·05	100·05
S.G. ..	2·77	2·76	2·71	2·61	2·69	2·09	2·82	2·96	2·86

TABLE III—*Continued*

	30	31	32	33	34	35	36	37	38
SiO_2 ..	28·31	44·87	28·13	45·93	20·81	33·01	36·48	45·83	49·40
TiO_2 ..	tr	3·41	2·51	3·47	1·21	1·84	1·64	—	—
Al_2O_3 ..	10·81	25·55	10·00	23·24	3·12	11·03	13·36	18·92	16·12
Fe_2O_3 ..	2·97	2·41	6·82	0·53	4·31	1·62	1·36	6·02	11·51
FeO ..	6·85	0·56	10·36	0·85	13·02	10·51	9·44	6·24	2·13
MnO ..	0·27	0·12	0·25	0·04	0·31	0·34	0·26	—	—
MgO ..	5·99	1·30	5·79	1·27	6·17	4·79	3·14	8·49	3·52
CaO ..	13·39	4·25	10·69	5·04	18·28	10·83	10·06	9·28	10·90
Na_2O ..	0·56	0·49	0·49	0·61	2·72	4·27	3·34	2·10	3·02
K_2O ..	5·45	3·99	3·13	6·43	0·12	0·19	0·28	0·32	0·58
H_2O^+ } ..	2·88	7·80	5·55	6·28	1·31	1·52	3·14	2·70	2·30
H_2O^- }								0·50	0·10
P_2O_5 ..	0·09	1·11	0·79	1·94	0·26	0·39	0·39	—	—
CO_2 ..	21·17	4·04	15·49	3·27	28·65	19·57	16·53	0·10	0·59
FeS_2 ..	1·55	0·28	0·48	0·75	0·29	0·29	0·73	—	—
Total ..	100·29	100·18	100·48	99·65	100·58	100·20	100·15	100·50	100·17
S.G. ..	2·51	2·14	2·52	2·31	2·71	2·71	2·81	—	—

TABLE III—*Continued*

	39	40	41	42	43	44
SiO_2 ..	46·78	46·66	47·74	42·71	45·70	46·22
TiO_2 ..	—	—	1·02	1·29	1·10	0·95
Al_2O_3 ..	17·04	16·97	16·75	14·93	20·44	10·22
Fe_2O_3 ..	7·95	9·52	2·55	7·45	9·50	12·88
FeO ..	6·31	4·16	6·31	3·45	8·95	7·45
MnO ..	—	—	0·52	0·22	—	—
MgO ..	6·31	5·02	8·32	2·70	2·24	0·84
CaO ..	6·94	9·37	11·40	22·76	7·46	15·56
Na_2O ..	3·44	4·08	1·93	0·54	0·80	0·18
K_2O ..	1·10	0·44	0·14	0·04	0·28	1·04
H_2O^+ ..	3·62	2·79 }	2·73	3·56	{ 2·78	3·91
H_2O^- ..	0·66	0·91 }			{ 0·35	0·58
P_2O_5 ..	—	—	—	—	—	—
CO_2 ..	0·08	0·02	—	—	—	—
FeS_2 ..	—	—	—	—	—	—
Total ..	100·23	99·94	99·41	99·65	99·60	99·83
S.G. ..	—	—	—	—	—	—

* All specific gravity data quoted only to the first decimal are assumed values. **1-2** (Wilshire, 1959). **3-4** (Day, 1925). **5–6** (Day, 1930*a*). **7-8** (Day, 1930*b*). **9-11** (Day and Stenhouse, 1930). **12-14** (Fox, 1914). **15-16** (Gee, 1932). **17-18** (Fox, 1914). **19-20** (Wilshire, unpublished). **21-22** (Browne and White, 1928). **23-24** (Wilshire, 1958). **25-26** (Day, 1930*a*). **27-29** (Fox, 1930). **30-36** (Day, 1930*a*). **37-44** (Butler and Burbank, 1929).

Fig. 1 illustrates compositional changes in basic volcanic rocks which were caused by a dominantly carbonate alteration. Most of them show large losses of SiO_2 which is also obviously expressed in weight percentages. The average silica percentage is that of ultrabasic rocks, although most of them are derivatives of normal basalts. Al_2O_3 and total iron show moderate gains or losses, but the Fe^3/Fe^2 ratio generally increases. CaO, on the average, shows an increase and MgO and alkalis are generally lost in moderate to large amounts, but the K/Na ratio often increases. Campbell, Day and Stenhouse (1934) have noted that an increase of CaO during carbonation is accompanied by a decrease in MgO.

Fig. 2 represents changes due to a dominantly clay alteration and mixed clay-carbonate alteration of basic rocks. Those illustrating clay alteration all show losses of SiO_2, but this is not always expressed in weight percentages. Al_2O_3 changes are erratic but show an average increase. Total iron is remarkably constant, but again there is usually an increase in the Fe^3/Fe^2 ratio. In contrast to carbonate alteration, CaO shows only moderate changes and an average loss in dominantly clay alteration. MgO is generally leached and alkalis show small losses or gains with a general increase in the K/Na ratio.

There is very little data representing altered and unaltered equivalents of intermediate and acid rocks which can be attributed with certainty to deuteric alteration, but the close similarity of changes in deuterically altered basic rocks with those produced by hydrothermal alteration

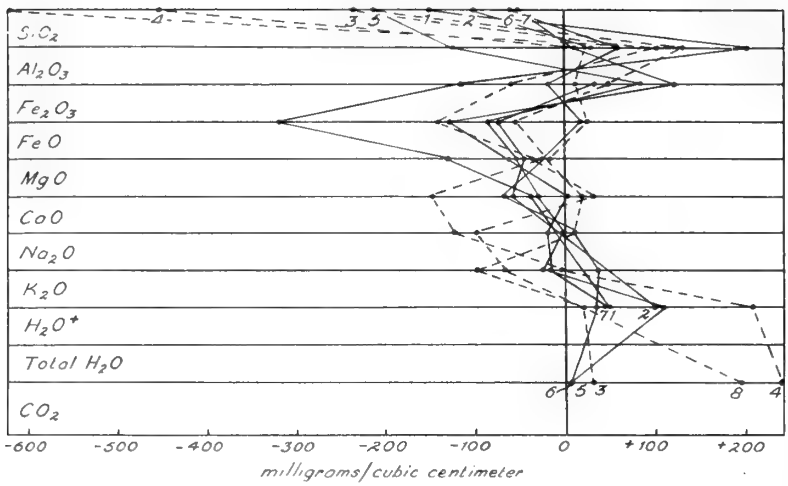

FIG. 2

Straight line variation diagram illustrating compositional changes in basic volcanic rocks due to dominantly clay alteration (solid lines) and to clay-carbonate alteration. 1=analyses 12–13, Table III; 2=anals. 12–14; 3=anals. 15–16; 4=anals. 17–18; 5=anals. 19–20; 6=anals. 21–22; 7=anals. 23–24; 8=anals. 25–26.

related to ore deposition warrants a brief summary of data presented by Schwartz (1939, 1959). Both acid and intermediate rocks show little change in SiO_2 and Al_2O_3, but passive increases in SiO_2 weight percentages may be significant. Both Fe_2O_3 and FeO are lost and the Fe^3/Fe^2 ratio is generally reduced because of a high pyrite content. MgO, CaO and Na_2O decrease in the majority of examples, while K_2O shows little change. In terms of weight percentages, Na_2O generally drops and K_2O shows large passive increases. Although Lindgren and Ransome (1906) maintain that one of the most important processes is the replacement of soda by potash, Schwartz's data (1939) do not support this where albitization of feldspars is important.

Richards (1922) cited a number of examples of kaolinite-quartz deuteric alterations of rhyolites in which large increases in SiO_2 resulted from alteration. Although these are readily distinguished from normal rhyolites because of their low alumina and alkalis, Fenner (1936) suggested that metasomatically altered rhyolites and dacites of Yellowstone Park would probably be regarded as fairly normal rocks in the absence of obvious surface evidence of hot spring activity. In this particular example, magmatic emanations dissolved in groundwater caused the formation of secondary quartz, orthoclase, clay minerals, carbonates and zeolites with the most notable effects being addition of silica and replacement of Na and Ca of feldspars by K.

Similar changes produced by fumarolic alteration of trachyte and dacite were cited by Lovering (1957). Although SiO_2 weight percentages show large increases in the altered rocks, these are entirely passive and silica is actually leached in the process. Iron, magnesia and alkalis are likewise leached, but intermediate stages of alteration could not be easily distinguished chemically from unaltered rocks notwithstanding pronounced changes in SiO_2, iron and MgO. Increase in SiO_2, reduction of total iron and MgO and increase in the Fe/Mg ratio produced by the alteration are changes which characterize silica variation diagrams representing basic, intermediate and acid rocks.

Macdonald (1944) has described extreme effects of solfataric alteration at Kilauea in which basalt was converted to a rock composed largely of opal with perfect preservation of the original fabric. Macdonald noted, in comparison with other examples of solfataric alteration, that alteration products were similar whatever the original rock type. Much the same thing was noted by Lindgren (1897), who found that in extreme cases of alteration basalts were difficult to distinguish from rhyolites, a convergence which has been stressed by Schwartz (1939, 1950, 1959) and Fenner (1931). The most common types of deuteric alteration, however, are not the result of throughgoing fluids of limitless supply, but rather of volatiles dissolved in the magma of a particular lava flow or intrusion (Sederholm, 1929). The possible effects of similar metasomatic alteration in volcanic conduits is outside the scope of this study.

Some Petrogenetic Implications of Metasomatic Alteration

The stage reached by differentiation among related basaltic rocis is usually measured by the ratios $(FeO + Fe_2O_3)/FeO + Fe_2O_3 + MgO)$; $Fe_2O_3/(FeO+Fe_2O_3)$; and $K_2O/(K_2O+Na_2O)$; see Walker (1953). Because deuteric alteration often causes selective leaching of MgO, oxidation of iron, and increase in the K/Na ratio of basic rocks, changes in these ratios may occur solely through solid state alteration, and the changes may parallel those produced by magmatic differentiation. The effects of alteration on these ratios are set out in Table IV. It is noteworthy that the magnitude of change is not correlative with degree of alteration. For comparison, the changes in these ratios between dolerite host rock and pegmatite differentiates (Walker, 1953) and among teschenites from various levels of a differentiated sill (Wilkinson, 1958) are set out in the same table. While the changes produced by alteration are somewhat erratic, the same may be said for those attributed to magmatic differentiation, a feature which Walker (1953) attributes to analytical difficulties in determining iron and alkalis.

Again, because of bulk composition changes produced by alteration, displacement on standard three-component diagrams illustrating magmatic differentiation may occur and may parallel the changes produced by magmatic differentiation. Effects of carbonate alteration when plotted on the (total Fe)-(total alkali)-MgO diagram are shown in Fig. 3, the effects of clay alteration in Fig. 4, and the effects of zeolite-clay-carbonate alteration in Fig. 5. A few reversals

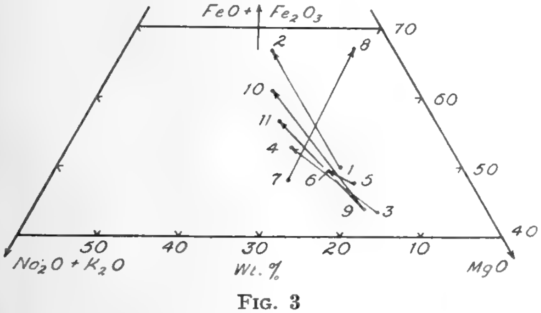

FIG. 3

Three-component diagram illustrating the effects of carbonate alteration. Altered rock lies at arrow point and is joined to its unaltered equivalent. Numbers correspond to numbers of analyses in Table III.

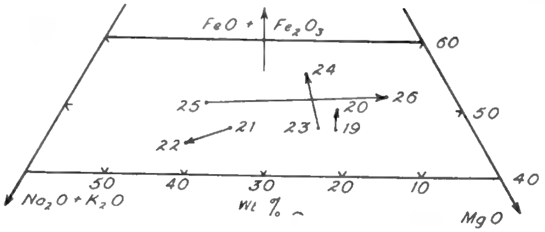

FIG. 4

Three-component diagram illustrating the effects of clay alteration. Altered rock lies at arrow point and is joined to its unaltered equivalent. Numbers correspond to numbers of analyses in Table III.

of normal trends occur, especially among the carbonated rocks, due to strong leaching of alkalis and less extensive leaching of MgO. Fig. 6 illustrates changes among equivalent rocks, all of which are altered, and data from Walker and Poldervaart (1949) and Walker (1953) on dolerite and associated dolerite pegmatites are shown in Fig. 7 for comparison.

It seems evident that, in general, alteration is capable of producing pronounced selective changes in composition and in petrologically important ratios. In many differentiated intrusions in which relatively fresh exposures are available, this may be deduced from field observations which indicate the abundance of magnesian clays and lime carbonates and zeolites in joints and amygdules (see, for example, Shannon, 1924). These are not con-

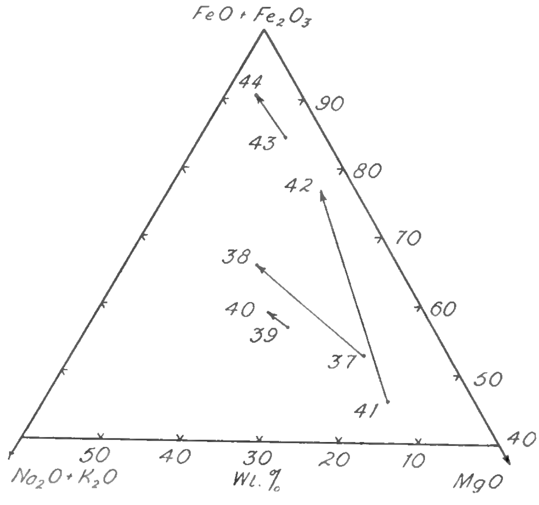

FIG. 5

Three-component diagram illustrating the effects of zeolite-clay-carbonate alteration. Altered rock lies at arrow point and is joined to its unaltered equivalent. Numbers correspond to numbers of analyses in Table III.

TABLE IV

Effects of Alteration on Petrologically Important Ratios

	1–2*	3–4	5–6	7–8	9–10	9–11	12–13	12–14	17–18	19–20	21–22	23–24	25–26	37–38	39–40	41–42	43–44
$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	+19·6	+15·4	+3·3	+8·8	+22·3	+18·1	+1·5	+4·1	+4·2	+2·6	+3·4	+7·4	+17·3	+20·4	+3·8	+28·6	+6·9
$\frac{Fe_2O_3}{FeO+Fe_2O_3}$ ..	—6·5	+32·9	—12·6	—16·7	—3·1	—12·9	+35·6	+9·8	+1·0	+22·9	—7·9	+46·0	—21·3	+35·3	+13·9	+39·5	+11·8
$\frac{K_2O}{K_2O+Na_2O}$ ..	—7·0	—0·9	+12·2	+0·5	+8·7	—1·5	—	—	+20·4	—15·1	+8·1	—2·5	+5·8	+2·9	—14·5	+0·2	+59·3

		1–2	3–4	3–5	6–8	7–8	9–10	11–12	13–14	13–15	16–17	18–19	20–21
Walker (1953)	$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	+22·8	+19·9	+18·3	+11·7	+8·5	+6·9	+12·3	+6·8	+21·5	+8·9	+4·2	+12·2
	$\frac{Fe_2O_3}{FeO+Fe_2O_3}$	+23·8	+9·3	+32·5	+1·0	+14·4	—6·5	+19·6	+7·8	+16·4	+12·2	+4·5	—10·3
	$\frac{K_2O}{K_2O+Na_2O}$	+1·2	—6·7	—3·7	+4·7	+0·7	+10·5	+16·9	+3·1	+25·7	+5·4	+6·4	—3·0

		1	3	4	5	6	7	8
Wilkinson (1958)	$\frac{FeO+Fe_2O_3}{FeO+Fe_2O_3+MgO}$	58·3	69·7	62·5	69·8	73·4	78·1	82·2
	$\frac{Fe_2O_3}{FeO+Fe_2O_3}$	31·2	23·6	25·1	25·5	28·9	25·2	30·3
	$\frac{K_2O}{K_2O+Na_2O}$	34·9	30·6	32·3	31·6	32·3	38·5	37·2

* Numbers correspond to analyses in Table III. + signs indicate increase in ratio produced by alteration. For Walker's data (1953; Table 3, p. 50), + signs indicate increase in ratio from host dolerite to dolerite pegmatite. Wilkinson's data (1958; Table 6, p. 22) illustrate changes in ratios with increasing height (left to right) in the Black Jack sill and represent progressively later stages of differentiation.

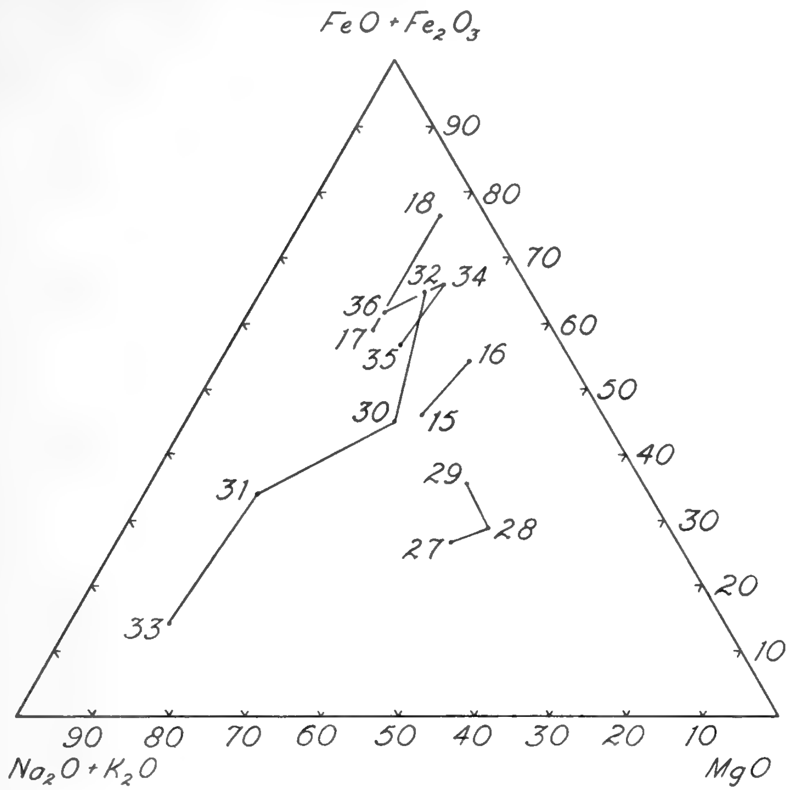

FIG. 6

Three-component diagram illustrating the effects of different degrees of alteration on equivalent rocks (each set joined by lines) all of which are altered. Numbers correspond to numbers of analyses in Table III.

stitutents which may be expected to concentrate in residual liquids, but they are the ones which are leached from early formed primary minerals in common types of alteration. At the same time it is these constituents which are lost in crystal-liquid processes to move a magma along the line of liquid descent, so that in a qualitative way parallelism between the processes may occur. This feature is important, for it is sometimes contended that alteration has little or no effect on bulk composition (Walker, 1952). Walker set forth a test of his conclusion by showing that an altered rock sequence followed the same differentiation trend as a comagmatic, unaltered basalt and its glassy mesostasis. This could be an adequate test only if alteration had some effect which is not parallel with that of fractional crystallization. Because of the apparent absence of olivine and variations in the Fe/Mg and other ratios, Wilkinson (1958, 1959) concluded that badly carbonated feeder dikes to a teschenite intrusion was emplaced at varying stages of differentiation. It seems more likely that the apparent absence of olivine is due to partial destruction of the original fabric, a feature which is not uncommon in carbonate alteration (Day, 1930*a*). If this were not the case it would be troublesome to justify the loss, by magmatic

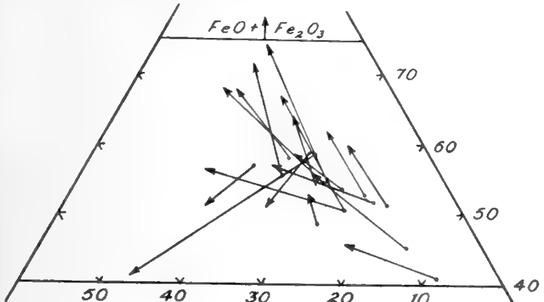

FIG. 7

Three-component diagram illustrating chemical variation between dolerite pegmatite (arrow point) and host dolerite.

processes, of olivine from these rocks which are still in the basaltic stage of differentiation, for Wilkinson (1956) contends that olivine has no reaction relation in alkali basalt magmas. The magnitude of the compositional changes, in comparison with the assumed parent magma, is well within the range which may have been produced solely by metasomatic alteration of a normal, undifferentiated teschenite. It is noteworthy that the change in trace elements as well as major elements (Wilkinson, 1959) of the altered dike rock suggests an advanced stage of differentiation. Rutledge (1952) used chemical analyses of rocks showing different types and degrees of alteration as supporting evidence for the presence of different basalt types in a composite intrusion although it is again possible that metasomatic alteration is largely responsible for the chemical variation. The hesitance shown by Rutledge in comparing altered rocks is shared by others and is, in the author's opinion, well founded. Campbell, Day and Stenhouse (1932, 1934) utilized the normative composition of altered xenolithic rocks as a criterion for establishing the effects of assimilation on dolerite. An analysis of dolerite near quartzose xenoliths shows normative quartz, whereas the chilled margin of the intrusion is undersaturated in the norm. In a previous study of carbonate alteration (Day and Stenhouse, 1930) it was shown that alteration alone produced an identical change in the norm, and it is possible that in this case carbonate alteration rather than assimilation is responsible for the change or at least contributes to it. Because of the extensive deuteric alteration of the Keewenawan lavas, it seems unlikely that Cornwall's (1951*a*) calculations of the composition of successive liquid fractions produced by fractional crystallization directly reflect the liquid chemistry. The same doubts apply to Edward's (1938) calculation of the parental magma composition of the Newer Basalt Series of Victoria because basaltic members of this series are characterized by the occurrence of altered olivine.

Although changes in petrologically important ratios comparable with those produced by magmatic differentiation may result from alteration, there is little in the data presented in the preceding section to suggest that common types of deuteric alteration could change a basic rock to an intermediate or acid one. In carbonate and clay alteration both silica and alkalis are generally leached, although in a few cases these constituents show passive weight percent increases. However, in the presence of alkali-bearing solutions such changes could be effected. This conclusion was reached by Shannon (1924) in respect of quartz-albite rocks which he believed to have formed by deuteric replacement of basic pegmatites. These rocks are the same chemically and mineralogically as others which Shannon considers to be products of magmatic differentiation, and if his conclusions are correct, complete convergence of the processes is implied. Although the composition of the altered rock is such that its normative composition may be plotted on the phase diagram representing the nepheline-kaliophilite-silica system, it does not fall in the low temperature trough. However, other rocks of nearly identical mineralogical composition and which are also thought to have formed by deuteric alteration of basic rocks (Gilluly, 1933) do have normative compositions which plot in the low temperature trough of that system so that this is not, as it is often assumed to be, a reliable criterion for magmatic origin. Much the same conclusions concerning the hydrothermal origin of acid differentiates of diabase sills were reached by Bastin (1935) who, however, appealed to introduction of alkali-bearing solutions from external sources. Fenner (1931) also suggested that hydrothermal processes may produce dike-like bodies of quartzo-feldspathic rocks. Shand (1943, p. 162) stated: "Clearly it is not necessary that hydrothermal alteration should affect all parts of an eruptive mass, or all to the same extent. But if some parts are hydrothermally altered and others are not, the results may be indistinguishable from what has been called 'magmatic differentiation'." A very clear statement that chemical changes due to alteration parallel those of fractional crystallization was given by Neuerburg (1958), and a similar convergence of rocks of originally widely different composition by other types of hydrothermal alteration has been noted by Schwartz (1959) and Macdonald (1944). In alterations of this type it is, of course, no longer a simple matter to designate pairs of rocks as altered and unaltered equivalents because of the great differences in mineralogy. For the most part it would also appear that pronounced changes in fabric must occur, for simple addition of alkalis and silica will produce no change in the Fe/Mg and Fe^3/Fe^2 ratios, and the accompanying leaching of mafic minerals provides space for outgrowths of new minerals. The occurrence of pegmatitic differentiates in flows and intrusions and localization of deuteric alteration in and around these, is generally taken as evidence of pre-consolidation concentration of volatiles so that rapid variations in the original fabric complicates interpretation. In contrast to crystal-liquid processes, the degree of differentiation produced by deuteric alteration is largely dependent upon structural controls which permit concentration and subsequent escape of deuteric fluids carrying dissolved material.

Additional problems in classification arise from assuming that alteration has little or no effect on composition. A number of records (Honess and Graeber, 1926; Fox, 1930; Gee, 1932) of peridotite intrusions utilize composition of carbonated rocks as a criterion for classification as ultrabasic rocks. While the primary minerals of some of these dikes indicate a lamprophyric or more basic composition, leaching of silica from otherwise ordinary basalts by carbonate alteration may produce much the same bulk compositions. Because constituents leached from altered rocks are not in the same proportions as those present in the unaltered rock, it is evident that normative compositions will change. Such observations as Ming-Shan Sun's (1957) that alteration of olivine occurs in rocks in which modal olivine exceeds normative olivine may be the effect rather than cause of alteration. In some pairs of analyses cited in Table III, the C.I.P.W. norm of the fresh rock is high in undersaturated minerals, while that of its altered equivalent has free silica or a high hypersthene/olivine ratio, normative differences which characterize alkali basalt and tholeiitic basalt respectively (Yoder and Tilley, 1956).

Origin and Composition of Deuteric Solutions

Without doubt the dominant constituents of fluids causing deuteric alteration are H_2O and CO_2. However, some mineralogical characteristics of alteration indicate that these fluids carry dissolved material, probably in considerable bulk. In part this additional material is picked up during alteration, but in simple types of alteration such as conversion of magnesian olivine to ferruginous clay and alteration of plagioclase to analcite there is evidence that dissolved material is present at the time alteration commences. In fluids of internal origin, the composition may be controlled by fractional crystallization during which alkalis, silica, and sometimes iron are concentrated simultaneously with volatiles. These constituents may, in the early stages of alteration, exert some control over material going into solution, but additions and subtractions from the fluids will cause continuous compositional changes. These changes may affect not only primary mineral alteration, but also early formed secondary minerals, as is the case in hydrothermal alteration related to ore deposition (Schwartz, 1939, 1959).

Alkali-rich aqueous solutions may also be concentrated independently of crystallization by volatile transfer (Fenner, 1926; Broderick and Hohl, 1935). Kennedy (1955) has pointed out the effects of pressure and temperature on the equilibrium distribution of water and suggested that alkalis may be selectively transported with water. While this may be reflected principally in primary minerals in plutonic rocks, such fluids may cause deuteric alteration in rapidly cooled volcanic rocks. Still another mechanism by which aqueous fluids rich in iron and silica may concentrate independently of crystallization is spontaneous splitting of immiscible liquids (Tomkeieff, 1942). At low temperatures the volatile-rich fractions may then cause hydrothermal alteration of the adjacent wall rock.

In the case of intrusions it is possible that volatile constituents are derived from the wall rock. There is some tendency to regard CO_2 as an externally introduced constituent, especially in respect of " white trap " intrusions in coal seams, but there are many examples of carbonate alteration where no such immediate source is available (Stark and Behrer, 1936; Honess and Graeber, 1926; Wilshire, 1959). It does not seem essential that CO_2 be concentrated solely by crystallization of silicates, and independent concentration may cause simultaneous movement of dissolved constituents such as lime.

Because these fluids constantly change composition by reaction with primary minerals, it is not possible to make direct inferences from the composition of interstitial minerals and vesicle filling as to the composition of liquid residues formed by fractional crystallization. Notwithstanding this possibility, amygdule minerals are sometimes referred to as sublimates of residual, volatile-rich liquids. This view is summed up by Amstutz (1958, p. 4), who states, " The minerals filling amygdules have, for a long time, been recognized to be the hydrothermal rests of the main crystallization ". There are many interpretations opposed to this view (e.g., Fenner, 1910; M'Lintock, 1915; Pecora and Fisher, 1946; Walker, 1951). Amstutz goes on to suggest that rocks composed of many of the common secondary minerals listed above may form by direct crystallization of volatile-rich magmas at low temperatures. While experimental data may be lacking, there are many records of basic pegmatites which have crystallized from volatile enriched liquids. The sequence of events here is much the same as that suggested by Bowen's and Tuttle's (1949) work on the system $MgO-SiO_2-H_2O$: initial crystallization of anhydrous silicates in spite of a high water content. At low temperatures there is commonly a hydrothermal alteration of these rocks where volatiles are retained. Pre-consolidation concentration of volatiles, as it occurs in basic pegmatites, may provide an explanation of localization of deuteric effects which Bowen (1928, p. 72) considers as evidence opposed to the secondary origin of quartz in acid differentiates of diabase sills.

When deuteric processes, if they may be so called, are viewed on a broader scale than the secondary replacements which they may cause, it seems evident that they have other effects of petrogenetic importance. Post-consolidation movement of interstitial residues as envisioned by Bailey *et al.* (1924), Fenner (1926, 1931), Butler and Burbank (1929), Gilluly (1933) and Cornwall (1951*b*) carry the implication that rocks from which these fluids were derived have undergone complementary changes in composition (becoming more basic) by virtue of these losses. That the same thing can occur independently of the crystallization history is evident from Tuttle's and Bowen's (1958) experimental work, and Drever (1952) has suggested that removal of constituents of zeolitic composition from certain lavas may give an ultrabasic product. On the other hand, volatile loss of iron without alteration as proposed by Fenner (1931) and Hotz (1953) provides an alternative explanation of the lack of Fe enrichment in late differentiates to that of Kennedy (1955), who suggests that PO_2 is the dominant control and early separation of iron oxides reduces the iron content of residual liquids. By the same token, relative movements and internal redeposition of material gained by alteration of primary minerals and as well material originally present in deuteric fluids may produce significant composition variations within altered rocks (Campbell, Day, and Stenhouse, 1934; Broderick, 1935; Butler and Burbank, 1929; Schwartz and Sandburg, 1940).

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Journal and Proceedings, Royal Society of New South Wales, Vol. 93, pp. 121–126, 1959–60

Precise Observations of Minor Planets at Sydney Observatory During 1957 and 1958

W. H. Robertson

(*Received* 8 *October*, 1959)

The programme of precise observations of selected minor planets which was begun in 1955 is being continued and the results for 1957 and 1958 are given here. The methods of observation and reduction were described in the previous paper (Robertson, 1958). All the plates were taken with the 9-inch camera by Taylor, Taylor and Hobson (scale 116″ to the millimeter). Four exposures were made on each plate.

In Table I are given the means for all four images for the separate groups of stars at the mean of the times. The differences between the results average $0^s\cdot023 \sec\delta$ in right ascension and $0''\cdot27$ in declination. This corresponds to probable errors for the mean of the two results from one plate of $0^s\cdot010 \sec\delta$ and $0''\cdot11$. The result from the first two exposures was compared with that from the last two by adding the movement computed from the ephemeris.

Table I

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		2 Pallas 1957 U.T.									
115	Sep.	4·74962	3	02	19·597	— 7	41	47·50	—0·009	—3·86	S
116	Sep.	4·74962	3	02	19·622	— 7	41	47·00			
117	Sep.	12·73266	3	04	55·428	— 9	51	19·48	+0·001	—3·56	W
118	Sep.	12·73266	3	04	55·444	— 9	51	19·44			
119	Sep.	17·71894	3	05	47·046	—11	18	03·20	—0·001	—3·35	R
120	Sep.	17·71894	3	05	47·006	—11	18	03·40			
121	Oct.	1·68390	3	04	49·095	—15	36	28·90	+0·011	—2·73	W
122	Oct.	1·68390	3	04	49·118	—15	36	29·04			
123	Oct.	3·68174	3	04	16·152	—16	14	13·90	+0·023	—2·64	W
124	Oct.	3·68174	3	04	16·119	—16	14	13·46			
125	Oct.	8·65829	3	02	27·978	—17	47	40·54	—0·002	—2·41	R
126	Oct.	8·65829	3	02	27·974	—17	47	40·94			
127	Oct.	16·63572	2	58	21·508	—20	12	25·68	+0·002	—2·05	S
128	Oct.	16·63572	2	58	21·555	—20	12	26·22			
129	Oct.	21·63200	2	55	06·606	—21	37	13·35	+0·042	—1·85	W
130	Oct.	21·63200	2	55	06·620	—21	37	13·49			
131	Oct.	31·59012	2	47	30·568	—24	05	08·07	+0·012	—1·47	R
132	Oct.	31·59012	2	47	30·536	—24	05	07·79			
133	Nov.	11·56018	2	38	23·939	—26	05	32·14	+0·034	—1·17	W
134	Nov.	11·56018	2	38	23·948	—26	05	32·18			
135	Nov.	14·54166	2	35	58·132	—26	29	30·34	+0·004	—1·11	W
136	Nov.	14·54166	2	35	58·130	—26	29	30·33			
137	Nov.	20·52619	2	31	20·396	—27	05	51·61	+0·019	—1·02	R
138	Nov.	20·52619	2	31	20·388	—27	05	51·46			
		6 Hebe 1957 U.T.									
139	June	6·78704	22	09	24·262	— 6	31	12·72	—0·025	—4·01	S
140	June	6·78704	22	09	24·278	— 6	31	12·61			
141	June	25·76693	22	25	45·678	— 6	38	24·62	+0·038	—4·00	S
142	June	25·76693	22	25	45·659	— 6	38	24·45			
143	July	3·74996	22	30	26·896	— 7	05	43·56	+0·043	—3·94	W
144	July	3·74996	22	30	26·902	— 7	05	43·48			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
		6 Hebe 1957 U.T.									
145	July	4·74728	22	30	55·783	— 7	10	19·42	+0·042	—3·93	W
146	July	4·74728	22	30	55·774	— 7	10	19·51			
147	July	10·71980	22	33	17·698	— 7	43	46·99	+0·002	—3·85	R
148	July	10·71980	22	33	17·724	— 7	43	47·32			
149	July	24·69764	22	35	07·290	— 9	43	58·40	+0·049	—3·58	W
150	July	24·69764	22	35	07·340	— 9	43	58·34			
151	Aug.	8·64983	22	31	05·959	—12	55	20·01	+0·036	—3·13	S
152	Aug.	8·64983	22	31	05·892	—12	55	21·06			
153	Aug.	13·61770	22	28	33·174	—14	09	48·94	+0·016	—2·94	W
154	Aug.	13·61770	22	28	33·148	—14	09	48·58			
155	Aug.	20·59405	22	24	12·511	—15	59	04·56	—0·022	—2·68	R
156	Aug.	20·59405	22	24	12·536	—15	59	04·72			
157	Sep.	3·55187	22	14	19·549	—19	33	20·76	—0·013	—2·15	S
158	Sep.	3·55187	22	14	19·534	—19	33	21·05			
159	Sep.	4·56434	22	13	37·554	—19	47	44·08	+0·039	—2·12	S
160	Sep.	4·56434	22	13	37·552	—19	47	44·41			
161	Sep.	12·52888	22	08	36·134	—21	31	43·10	+0·005	—1·85	W
162	Sep.	12·52888	22	08	36·134	—21	31	43·11			
163	Sep.	17·50876	22	06	04·374	—22	27	00·10	—0·010	—1·72	R
164	Sep.	17·50876	22	06	04·373	—22	26	59·08			
165	Sep.	27·47874	22	03	01·018	—23	51	39·35	—0·012	—1·66	R
166	Sep.	27·47874	22	03	00·992	—23	51	39·72			
167	Sep.	30·46855	22	02	42·774	—24	10	01·85	—0·018	—1·46	S
168	Sep.	30·46855	22	02	42·800	—24	10	02·52			
169	Oct.	11·46335	22	04	13·172	—24	50	47·86	+0·062	—1·37	S
170	Oct.	11·46335	22	04	13·150	—24	50	47·67			
171	Oct.	31·40772	22	17	03·670	—24	29	24·06	+0·028	—1·41	W
172	Oct.	31·40772	22	17	03·708	—24	29	23·69			
173	Nov.	1·41251	22	18	01·182	—24	25	30·33	+0·028	—1·42	S
174	Nov.	1·41251	22	18	01·152	—24	25	30·50			
		7 Iris 1957 U.T.									
175	Mar.	26·76714	16	47	26·820	—25	12	45·90	—0·006	—1·30	R
176	Mar.	26·76714	16	47	26·838	—25	12	45·78			
177	Apr.	9·72911	16	48	17·816	—25	10	35·92	—0·012	—1·30	W
178	Apr.	9·72911	16	48	17·786	—25	10	35·56			
179	Apr.	24·70490	16	43	21·688	—24	54	33·93	+0·060	—1·36	S
180	Apr.	24·70490	16	43	21·720	—24	54	34·02			
181	Apr.	29·67279	16	40	24·348	—24	45	35·06	+0·005	—1·36	W
182	Apr.	29·67279	16	40	24·393	—24	45	35·22			
183	May	6·66182	16	35	15·205	—24	29	33·52	+0·045	—1·41	R
184	May	6·66182	16	35	15·247	—24	29	33·82			
185	May	16·62499	16	26	18·032	—23	59	43·20	+0·033	—1·49	S
186	May	16·62499	16	26	17·983	—23	59	43·44			
187	May	23·59842	16	19	17·498	—23	34	20·43	+0·024	—1·55	W
188	May	23·59842	16	19	17·502	—23	34	20·54			
189	May	29·57656	16	13	05·352	—23	10	11·70	+0·020	—1·60	R
190	May	29·57656	16	13	05·432	—23	10	12·36			
191	June	25·48408	15	49	05·691	—21	15	39·82	+0·013	—1·89	W
192	June	25·48408	15	49	05·637	—21	15	39·81			
193	July	3·46770	15	44	42·477	—20	47	23·78	+0·041	—1·97	S
194	July	3·46770	15	44	42·491	—20	47	23·60			
195	July	10·43990	15	42	14·030	—20	27	09·22	+0·019	—2·01	S
196	July	10·43990	15	42	14·071	—20	27	08·62			
197	July	15·41917	15	41	15·430	—20	15	30·68	—0·003	—2·04	R
198	July	15·41917	15	41	15·438	—20	15	30·66			
199	July	26·40052	15	41	23·680	—19	58	27·32	+0·034	—2·08	S
200	July	26·40052	15	41	23·702	—19	58	27·12			
201	Aug.	2·37711	15	43	04·046	—19	53	39·07	+0·016	—2·10	S
202	Aug.	2·37711	15	43	04·028	—19	53	38·89			
203	Aug.	9·35900	15	45	53·432	—19	53	07·92	+0·013	—2·09	R
204	Aug.	9·35900	15	45	53·465	—19	53	07·24			

TABLE I—*continued*

No.			R.A. (1950·0) h	m	s	Dec. (1950·0) °	′	″	Parallax Factors s	″	
	11 Parthenope 1958 U.T.										
205	May	5·80119	20	18	27·408	—16	51	32·42	—0·017	—2·55	S
206	May	5·80119	20	18	27·405	—16	51	32·69			
207	May	19·77354	20	30	17·986	—16	20	08·87	—0·010	—2·63	R
208	May	19·77354	20	30	17·926	—16	20	08·60			
209	May	27·76276	20	34	57·994	—16	10	30·57	+0·015	—2·65	S
210	May	27·76276	20	34	57·964	—16	10	30·48			
211	June	17·70183	20	38	44·706	—16	24	47·20	—0·005	—2·61	R
212	June	17·70183	20	38	44·726	—16	24	47·58			
213	July	2·67101	20	33	23·122	—17	14	50·12	+0·040	—2·50	W
214	July	2·67101	20	33	23·130	—17	14	50·04			
215	July	8·64721	20	29	32·380	—17	43	05·76	+0·025	—2·43	R
216	July	8·64721	20	29	32·399	—17	43	05·90			
217	July	16·63379	20	23	13·570	—18	26	06·56	+0·066	—2·34	S
218	July	16·63379	20	23	13·566	—18	26	06·56			
219	July	21·61367	20	18	49·695	—18	54	43·22	+0·055	—2·26	W
220	July	21·61367	20	18	49·755	—18	54	42·99			
221	July	22·59139	20	17	56·572	—19	00	24·73	—0·006	—2·23	W
222	July	22·59139	20	17	56·534	—19	00	24·72			
223	July	28·57907	20	12	27·568	—19	35	11·30	+0·019	—2·15	R
224	July	28·57907	20	12	27·569	—19	35	11·80			
225	Aug.	7·55815	20	03	44·148	—20	30	18·72	+0·060	—2·02	S
226	Aug.	7·55815	20	03	44·152	—20	30	18·62			
227	Aug.	12·53160	19	59	55·414	—20	55	05·77	+0·027	—1·95	W
228	Aug.	12·53160	19	59	55·350	—20	55	05·04			
229	Aug.	19·50490	19	55	31·966	—21	25	38·11	+0·012	—1·87	R
230	Aug.	19·50490	19	55	31·967	—21	25	37·89			
231	Sep.	1·46866	19	51	10·350	—22	07	24·28	+0·019	—1·77	S
232	Sep.	1·46866	19	51	10·352	—22	07	24·12			
233	Sep.	11·44142	19	51	32·882	—22	25	42·60	+0·019	—1·72	W
234	Sep.	11·44142	19	51	32·897	—22	25	42·76			
235	Sep.	19·42499	19	54	11·740	—22	31	45·98	+0·031	—1·71	R
236	Sep.	19·42499	19	54	11·734	—22	31	46·44			
237	Oct.	1·40525	20	01	45·906	—22	27	03·60	+0·056	—1·73	S
238	Oct.	1·40525	20	01	45·916	—22	27	03·08			
239	Oct.	7·38499	20	06	58·316	—22	18	40·27	+0·032	—1·74	W
240	Oct.	7·38499	20	06	58·266	—22	18	40·22			

TABLE II

No.	Star	Depend.	R.A. s	Dec. ″	No.	Star	Depend.	R.A. s	Dec. ″
115	689	0·357658	42·080	38·99	121	812	0·491168	37·823	18·98
	696	0·381930	55·162	18·92		815	0·287916	07·735	38·85
	710	0·260411	09·331	24·86		834	0·220915	21·624	29·40
116	683	0·336287	47·361	31·03	122	805	0·427824	56·312	25·38
	704	0·291383	01·895	52·61		820	0·301061	44·980	27·32
	706	0·372330	11·303	06·16		843	0·271115	26·141	48·38
117	695	0·245833	21·842	19·36	123	799	0·284473	11·690	07·79
	714	0·420474	07·926	17·92		810	0·395817	26·261	03·02
	704	0·333692	01·895	52·61		838	0·319710	55·587	43·69
118	692	0·192390	59·458	48·26	124	805	0·308296	56·312	25·38
	709	0·429732	51·266	01·96		809	0·390226	12·116	03·63
	712	0·377878	21·566	15·11		831	0·301478	02·667	21·14
119	698	0·295968	46·984	52·13	125	794	0·295657	01·252	39·87
	709	0·341056	51·267	01·96		828	0·247206	48·804	04·78
	717	0·362975	09·963	07·59		854	0·457136	35·051	18·66
120	693	0·245485	07·996	09·07	126	814	0·343803	48·143	46·51
	712	0·461716	52·162	13·77		852	0·344413	14·499	42·97
	714	0·292798	07·927	17·92		810	0·311784	26·261	03·02

TABLE II—*continued*

No.	Star	Depend.	R.A. s	Dec. ″	No.	Star	Depend.	R.A. s	Dec. ″
127	799	0·262296	18·956	30·34	149	8063	0·409242	05·698	29·73
	810	0·408063	54·870	00·19		7974	0·210648	01·012	50·24
	832	0·329640	19·738	43·28		7988	0·380110	50·384	45·47
128	807	0·252115	10·506	08·66	150	7963	0·248982	28·678	00·78
	808	0·567175	40·618	17·27		7986	0·393375	19·543	47·22
	839	0·180710	09·879	50·68		8076	0·357643	20·076	42·99
129	790	0·275155	36·139	33·30	151	7940	0·298256	02·284	40·88
	810	0·344120	54·869	00·19		7985	0·388566	31·341	42·64
	1354	0·380725	22·688	43·17		8403	0·313179	29·611	15·90
130	789	0·323612	32·818	37·08	152	7942	0·305408	06·363	13·87
	807	0·331896	10·506	08·66		7990	0·335032	03·393	10·46
	1371	0·344492	31·573	38·19		8401	0·359560	55·871	10·25
131	1279	0·384208	44·389	26·27	153	7924	0·369976	55·476	57·41
	1282	0·262472	13·830	00·89		8393	0·307160	41·407	25·52
	1316	0·353321	21·990	50·47		8413	0·322864	32·740	43·78
132	1256	0·277898	47·377	06·77	154	8385	0·303214	01·096	24·17
	1301	0·498286	39·165	27·86		8403	0·264167	29·612	15·90
	1309	0·223816	35·335	52·91		8405	0·432618	45·325	34·40
133	1183	0·357327	55·144	58·78	155	8353	0·415240	40·825	15·85
	1231	0·274704	31·249	53·50		8388	0·353836	51·985	54·15
	1235	0·367968	10·886	25·22		8397	0·230924	17·314	25·53
134	1202	0·246742	56·504	50·52	156	8358	0·276522	51·482	09·96
	1203	0·419014	12·741	01·77		8373	0·367856	18·782	22·75
	1234	0·334244	57·839	11·37		8394	0·355622	45·162	14·23
135	998	0·326942	48·560	48·65	157	9452	0·334629	00·736	28·82
	1041	0·202966	09·311	21·25		9463	0·351978	26·728	35·07
	1203	0·470092	12·741	01·77		9482	0·313393	47·250	19·56
136	1004	0·507902	31·531	51·11	158	9447	0·304921	36·134	48·42
	1198	0·289276	35·422	51·33		9468	0·302536	49·233	44·31
	1235	0·202822	10·886	25·22		9478	0·392542	04·058	53·50
137	965	0·202736	15·313	21·06	159	9426	0·232342	30·792	01·84
	982	0·410409	52·849	02·27		9483	0·436164	07·006	10·36
	1178	0·386855	26·236	04·73		9452	0·331494	00·736	28·82
138	973	0·160524	18·322	26·77	160	9447	0·402427	36·093	48·81
	995	0·389796	29·991	51·70		9465	0·395346	33·403	17·73
	1165	0·449680	03·767	37·62		9482	0·202227	47·250	19·56
139	7940	0·316232	34·417	21·13	161	9410	0·324466	52·391	13·78
	7957	0·402090	41·966	43·97		9449	0·389572	42·933	52·20
	7969	0·281678	09·829	04·03		15124	0·285962	36·006	21·10
140	7937	0·245208	49·552	01·16	162	15095	0·294020	04·537	16·59
	7956	0·482918	18·337	53·66		15132	0·310246	07·497	53·45
	7974	0·271874	48·566	37·96		9440	0·395734	01·263	14·44
141	8010	0·454466	44·716	53·02	163	15095	0·360084	04·530	16·53
	8029	0·174638	16·240	35·38		15097	0·356161	13·522	33·98
	8045	0·370896	27·023	54·20		15122	0·283755	24·547	41·17
142	8014	0·288110	05·913	59·76	164	15073	0·403159	06·949	16·56
	8022	0·409778	38·953	51·59		15110	0·262141	05·281	33·84
	8048	0·302112	45·936	40·62		15129	0·334700	01·670	59·28
143	8031	0·274490	48·164	33·09	165	15057	0·306740	27·483	17·87
	8048	0·415684	45·936	40·62		15074	0·254261	21·353	14·09
	8058	0·309825	15·137	56·21		15096	0·439000	11·363	51·36
144	8028	0·166152	23·159	39·07	166	15071	0·379078	01·658	22·13
	8039	0·370076	55·074	38·90		15075	0·388466	31·526	52·35
	8066	0·463772	16·559	45·55		15098	0·232456	27·104	39·51
145	8039	0·247520	55·074	38·91	167	15071	0·484754	01·658	22·13
	8048	0·425922	45·936	40·62		15074	0·311282	21·353	14·09
	8060	0·326558	25·434	06·85		15092	0·203963	53·279	24·98
146	8031	0·252154	48·164	33·08	168	15054	0·302394	24·712	29·92
	8050	0·463806	45·039	06·51		15063	0·206825	01·955	42·91
	8058	0·284040	15·137	56·24		15098	0·490780	27·104	39·51
147	8045	0·457703	27·023	54·21	169	15069	0·239541	55·297	45·79
	8065	0·251828	11·030	59·70		15074	0·418460	21·353	14·10
	8078	0·290470	00·446	25·93		15117	0·341999	06·793	38·97
148	8052	0·278657	04·381	08·85	170	15063	0·430349	01·957	42·92
	8054	0·475086	08·945	26·09		15092	0·351360	53·280	24·98
	8077	0·246257	53·468	55·27		15127	0·218291	26·021	05·88

TABLE II—*continued*

No.	Star	Depend.	R.A. s	Dec. ″
171	15166	0·329404	45·242	29·98
	15187	0·374928	59·831	02·45
	15194	0·295668	27·483	05·09
172	15152	0·128188	31·071	22·71
	15179	0·594178	42·861	49·16
	15200	0·277634	54·223	42·88
173	15179	0·352594	42·861	49·16
	15180	0·371720	53·654	27·58
	15209	0·275686	11·955	32·49
174	15166	0·381772	45·242	29·98
	15187	0·329904	59·831	02·45
	15216	0·288324	22·042	30·29
175	11610	0·220045	31·632	55·83
	11647	0·357503	44·745	39·41
	11655	0·422452	42·588	57·31
176	11608	0·272920	18·983	03·44
	11615	0·302423	11·153	02·53
	11683	0·424656	03·861	27·72
177	11610	0·266289	31·632	55·83
	11655	0·351240	42·588	57·31
	11679	0·382470	32·862	17·26
178	11627	0·405502	22·000	06·27
	11647	0·305920	44·745	39·41
	11691	0·288577	35·956	58·67
179	11571	0·310416	59·929	21·86
	11608	0·490488	18·983	03·44
	11625	0·199095	15·327	18·10
180	11563	0·223474	06·456	29·47
	11585	0·287420	32·570	04·97
	11627	0·489106	22·000	06·27
181	11566	0·446512	30·921	19·49
	11571	0·385698	59·929	21·86
	11604	0·167791	42·812	43·49
182	11555	0·347766	16·805	26·76
	11556	0·225896	16·445	56·85
	11611	0·426339	37·584	27·94
183	11525	0·259098	52·714	52·91
	11528	0·382914	15·925	02·31
	11563	0·357988	06·456	29·47
184	11516	0·172256	09·845	49·45
	11544	0·556158	31·907	59·64
	11555	0·271585	16·805	26·76
185	11462	0·334146	12·919	05·83
	11500	0·397187	30·987	45·41
	11512	0·268666	49·872	19·63
186	11454	0·236876	49·728	46·98
	11492	0·396906	43·467	22·35
	11510	0·366218	02·041	26·29
187	11418	0·359238	47·413	28·13
	11466	0·363886	25·886	24·46
	11470	0·276876	17·744	02·39
188	11423	0·273858	19·703	42·45
	11454	0·222490	49·728	46·98
	11462	0·503652	12·919	05·83
189	11392	0·435562	36·979	23·59
	11396	0·192573	09·274	05·63
	11422	0·371864	17·721	16·66
190	11377	0·379146	56·061	08·11
	11418	0·243362	47·413	28·13
	11421	0·377492	09·732	01·65
191	6534	0·418831	51·220	59·40
	6561	0·340184	25·481	24·31
	6579	0·240984	51·229	56·37
192	6543	0·238212	00·768	22·03
	6555	0·336562	38·839	09·88
	6564	0·425227	37·049	19·34

No.	Star	Depend.	R.A. s	Dec. ″
193	6503	0·202064	24·717	41·15
	6526	0·362360	59·688	53·88
	6540	0·435575	27·220	58·31
194	6496	0·344242	18·108	54·70
	6564	0·240518	37·049	19·34
	6532	0·415240	46·202	42·48
195	6500	0·314532	57·597	15·70
	6503	0·250754	24·717	41·17
	6524	0·434714	55·787	14·55
196	6483	0·202702	28·781	32·57
	6534	0·315568	51·220	59·40
	6508	0·481730	52·239	48·18
197	6498	0·422644	31·011	26·69
	6503	0·335392	24·717	41·17
	6529	0·241964	28·410	33·27
198	6483	0·227702	28·781	32·57
	6523	0·247442	36·017	47·81
	6505	0·524857	19·351	49·20
199	6486	0·375398	56·442	59·16
	6527	0·414402	01·064	10·08
	6503	0·210200	24·717	41·18
200	6483	0·220463	28·781	32·58
	6502	0·439392	12·138	38·33
	6529	0·340145	28·379	31·69
201	6498	0·376945	31·011	26·70
	6533	0·332124	45·323	47·90
	6523	0·290930	36·017	47·81
202	6500	0·253177	57·597	15·70
	6517	0·366027	16·911	39·87
	6524	0·380796	55·769	13·00
203	6517	0·387980	16·911	39·87
	6524	0·345833	55·769	13·00
	6566	0·266187	57·708	02·63
204	6527	0·371112	01·064	10·08
	6529	0·290470	28·379	31·70
	6544	0·338418	12·390	43·70
205	7627	0·319437	08·184	53·07
	7641	0·323630	16·690	19·39
	7678	0·356933	29·563	49·41
206	7634	0·290048	27·156	20·04
	7658	0·268834	32·770	06·49
	7664	0·441118	43·230	54·54
207	7712	0·333558	21·320	04·48
	7734	0·461184	33·241	22·33
	7761	0·205258	30·272	02·26
208	7708	0·358492	14·424	46·48
	7742	0·292004	33·398	32·28
	7755	0·349503	25·473	30·93
209	7740	0·270370	29·893	59·55
	7761	0·346669	30·272	02·26
	7783	0·382960	49·624	53·30
210	7732	0·211504	15·760	49·13
	7773	0·312798	07·568	52·50
	7775	0·475698	17·684	51·02
211	7769	0·368824	56·842	14·47
	7801	0·282902	15·931	08·20
	7802	0·348275	28·809	57·57
212	7771	0·327470	04·582	14·53
	7789	0·403484	27·702	22·23
	7813	0·269047	25·288	07·31
213	7724	0·405917	25·851	39·39
	7775	0·314932	17·684	51·02
	8849	0·279151	51·297	16·87
214	7745	0·408790	44·671	14·36
	7761	0·390642	30·273	02·26
	8837	0·200568	33·334	16·55

TABLE II—*continued*

No.	Star	Depend.	R.A. s	Dec. ″	No.	Star	Depend.	R.A. s	Dec. ″
215	7704	0·302567	33·390	58·06	228	8569	0·306325	36·144	43·65
	7745	0·356184	44·671	14·36		8572	0·344500	12·679	08·64
	8813	0·341248	46·323	03·26		8609	0·349175	39·248	54·17
216	7713	0·256014	34·490	59·82	229	8538	0·288950	34·686	26·61
	7737	0·435256	23·427	15·90		8547	0·259974	04·085	59·90
	8801	0·308730	33·310	07·34		8573	0·451077	16·560	50·61
217	8742	0·359842	20·719	35·95	230	8528	0·246828	11·107	10·22
	8767	0·270846	10·239	18·51		8566	0·325250	50·748	51·66
	8770	0·369312	21·898	49·79		13923	0·427922	02·551	39·64
218	8746	0·231967	39·841	03·25	231	13835	0·285335	23·307	43·74
	8750	0·400744	07·528	38·00		13907	0·266321	36·163	16·22
	8775	0·367289	24·927	55·08		8517	0·448344	40·901	18·92
219	8696	0·345200	52·760	55·50	232	13840	0·440737	41·566	35·81
	8699	0·205396	25·039	52·39		13888	0·254664	43·270	10·64
	8752	0·449404	11·695	51·65		8528	0·304600	11·107	10·23
220	8715	0·335752	57·481	35·52	233	13840	0·358773	41·566	35·81
	8718	0·444686	05·247	14·57		13865	0·216972	54·398	21·17
	8746	0·219561	39·841	03·25		13879	0·424255	55·940	07·30
221	8686	0·210370	26·948	08·84	234	13819	0·304146	52·135	02·95
	8719	0·522189	09·205	58·95		13886	0·363534	40·737	52·55
	8732	0·267441	16·882	22·80		8538	0·332320	34·686	26·62
222	8694	0·261560	41·704	10·01	235	13879	0·374758	55·940	07·30
	8696	0·373704	52·760	55·50		13890	0·320736	52·442	59·25
	8746	0·364736	39·841	03·25		13916	0·304505	05·442	03·35
223	8654	0·380492	57·924	29·39	236	13874	0·350318	16·847	41·44
	8692	0·390597	35·370	49·72		13899	0·272005	42·762	12·34
	8664	0·228911	15·736	33·69		13907	0·377677	36·163	16·22
224	8652	0·375272	53·460	54·31	237	13945	0·325172	53·480	38·04
	8675	0·368400	49·307	51·68		13968	0·273861	03·468	02·63
	8694	0·256328	41·704	10·01		13996	0·400966	34·480	42·47
225	8578	0·324762	17·607	43·21	238	13955	0·304714	21·362	04·07
	8614	0·355030	26·776	05·77		13978	0·269255	55·550	22·60
	8636	0·320207	25·906	15·75		13982	0·426030	40·421	07·32
226	8594	0·140754	50·554	37·83	239	13983	0·245098	40·576	18·97
	8607	0·666234	33·623	12·75		14027	0·537996	02·034	02·98
	8624	0·193012	43·788	55·72		14036	0·216907	11·042	43·09
227	8566	0·395988	50·748	51·66	240	13982	0·252252	40·421	07·32
	8573	0·260460	16·559	50·61		14039	0·398216	41·136	06·05
	8617	0·343552	43·733	43·29		8632	0·349531	58·622	11·51

The means of the differences were $0^s{\cdot}010 \sec \delta$ in right ascension and $0''{\cdot}12$ in declination. No correction has been applied for aberration, light time or parallax but the factors give the parallax correction when divided by the distance.

In accordance with the recommendation of Commission 20 of the International Astronomical Union, Table II gives for each observation the positions of the reference stars and the dependences. The columns headed "R.A." and "Dec." give the seconds of time and arc with proper motion correction applied to bring the catalogue position to the epoch of the plate. The column headed "Star" gives the number from the Yale Catalogue (Vols. **11**, 12 I, 12 II, 13 I, 13 II, 14, 16). A number of the plates were measured by Mrs. M. A. Wilson, who also assisted in the reductions.

Reference

ROBERTSON, W. H., 1958. *J. Proc. Roy. Soc. N.S.W.*, **92**, 18; Sydney Observatory Papers No. **33**.

Sydney Observatory
Sydney

Journal and Proceedings, Royal Society of New South Wales, Vol. 93, pp. 127–136, 1959–60

The Geology of the Parish of Mumbil, near Wellington, N.S.W.

D. L. Strusz

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Abstract—The detailed stratigraphy and structure of an area of some 30 square miles south of Wellington, N.S.W., is described, accompanied by a geological map. In the light of the new information the previous conceptions of the geology of the Wellington district are re-assessed. Joplin's Middle Silurian " Nanima Formation " is shown to consist of two formations, one Ordovician and the other on the Siluro-Devonian boundary, and it is therefore suggested that it be discarded.

Introduction

The area discussed in this paper comprises some 30 square miles in the Parish of Mumbil, County Wellington, and a part of the Parish of Narragal, County Gordon (Fig. 1). It lies east of the Great Western Highway, and for the most part north and east of the Bell River. The town of Wellington, which is 8 miles north-northwest of the area, is 250 miles by road west-northwest of Sydney.

Relatively little geological work has been carried out in this region. Matheson (1930) published a paper on the Wellington district, but his conclusions (particularly about the Lower Palaeozoic) have been considerably altered by later workers. Basnett and Colditz (1945) established a stratigraphic succession, based on work to the north and northeast of Wellington. Knowledge of the regional geology of the Orange-Wellington strip then was very limited. Joplin et al. (1952) published a reconnaissance compilation of this region, relying mainly on previous work, but detail was still lacking. Since 1952, the stratigraphy of the Orange region has become known in considerable detail, especially the relationships of the Ordovician and later rocks. Joplin, following Basnett and Colditz, considered that the large belts of andesitic rocks between Orange and Wellington were Middle Silurian, and called them the Nanima Formation. Work at Orange and to the south (Stevens and Packham, 1952; Packham, in press) showed that the andesitic rocks there were Ordovician, and it was tentatively inferred that the same applied to the north. However, detailed mapping undertaken by the author during 1958, and outlined in this paper, revealed that these rocks fall into two distinct groups—the major one being Ordovician, while the other, whose full extent is as yet unknown, lies on the Silurian-Devonian boundary. For this reason, and to avoid confusion, it is felt advisable to discard the Middle Silurian " Nanima Formation ". This follows also because the work was not done in the type area, north of Wellington.

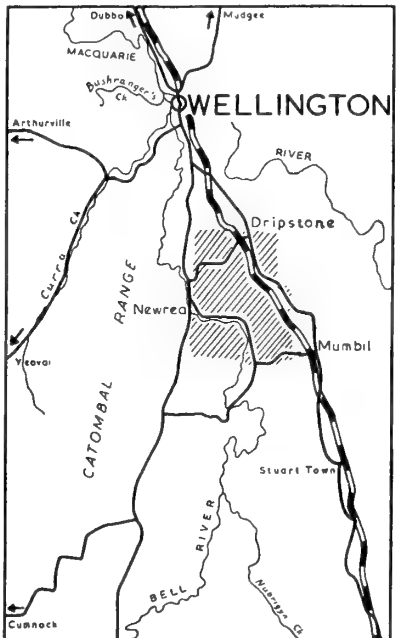

Fig. 1

TABLE I.

Formations, etc.		Thickness	
TOLGA CALCARENITE		700 ft.	Fossiliferous calcarenite, calcilutite
CUGA BURGA VOLCANICS		2100 ft.	Keratophyre & quartz keratophyre lavas, tuffs, & detritus
MUMBIL FORMATION	BARNBY HILLS Shale Member	?	← Horiz. of red shale (300 ft.) ← Horiz. of *M. bohemicus*
	NARRAGAL Limestone Member	up to 500 ft.	Massive & bedded limestone
OAKDALE FORMATION		over 2500 ft.	Spilites to keratophyres, detritus, & limestone lenses

The purpose of this paper, then, is to outline the stratigraphy of the Mumbil area, and to discuss briefly its bearing on the Orange-Wellington region. The rich coral fauna has been described in a separate paper (Strusz, in press).

Acknowledgements

This work forms part of a thesis presented for an honours degree at the University of Sydney. I would like to thank Professor C. E. Marshall for providing facilities within the Geology Department. Dr. G. H. Packham gave much help during the year, including the discovery of the Ordovician and Silurian graptolites. He and Dr. H. G. Wilshire were of great assistance in the preparation of this paper.

Stratigraphy

The rocks in the Mumbil area have been placed in four formations, varying in age from Upper Ordovician to Lower or Middle Devonian. These formations are summarized in Table I; thickness, where given, is approximate.

In the following text, specimen numbers are those of the collections of the Geology Department, University of Sydney—R for rock samples, F for fossils.

Oakdale Formation

The Oakdale Formation outcrops in the core of the Oakdale Anticline (on the properties of "Oakdale" and "Barnby Hills"), in a large area southeast of the Newrea-Dripstone road, and south of the Bell River. The Formation is named after the "Oakdale" property, where there are typical exposures. There are no complete sections of the Formation, nor is its base exposed. It is estimated that the Formation must be at least 2,500 feet thick.

The formation consists of volcanic rocks—ranging from quartz keratophyres to spilites—fine-grained greywackes and tuffaceous sediments, with scattered limestone lenses, all being of limited vertical and horizontal extent. There are in the area no widespread horizons of use in mapping or structural analysis, and the stratigraphic relationships of the various fossil localities are therefore uncertain. The rich shelly fauna from various limestone lenses within the Oakdale Anticline (see faunal lists at end of paper), where only two very poorly preserved diplograptids were found, cannot accurately be correlated with the graptolite fauna near the Dripstone-Newrea road (Fig. 2), which is Upper Ordovician in age.

The top of the Formation in the area is best defined as the base of the Narragal Limestone Member of the Mumbil Formation. The junction between the two is either conformable or more probably disconformable (see below): there is no visible structural discontinuity.

The graptolites found **80** yds. east of the Newrea-Dripstone road (por. **126**, Mumbil parish; **450** yds. north of por. **125**; see faunal lists below) correspond to zone **12**, the zone of *Dicranograptus clingani*, second lowest in the Caradocian, in the British succession (Elles and Wood, **1913**). As this locality is close to the top of the Formation, and as Mr. K. J. Kemezys (personal communication) has found extensive Lower, Middle and Upper Ordovician graptolite faunas in this Formation further south, it seems probable that the Oakdale Formation is confined to the Ordovician. The coral fauna from the Oakdale Anticline is probably also Upper Ordovician in age, although it may extend into the base of the Silurian. The corals are described elsewhere (Strusz, in press); the fauna as known is listed below.

Dr. Packham (personal communication) has found a similar sequence of interbedded lavas, sediments and thin limestone bands about **15** miles to the south, **5** miles northwest of Euchareena (locality "Molong b" in Sherrard **1954**, p. **83**). The fauna is listed below. The graptolites correspond to zone **10**, the zone of *Mesograptus multidens* and *Climacograptus*

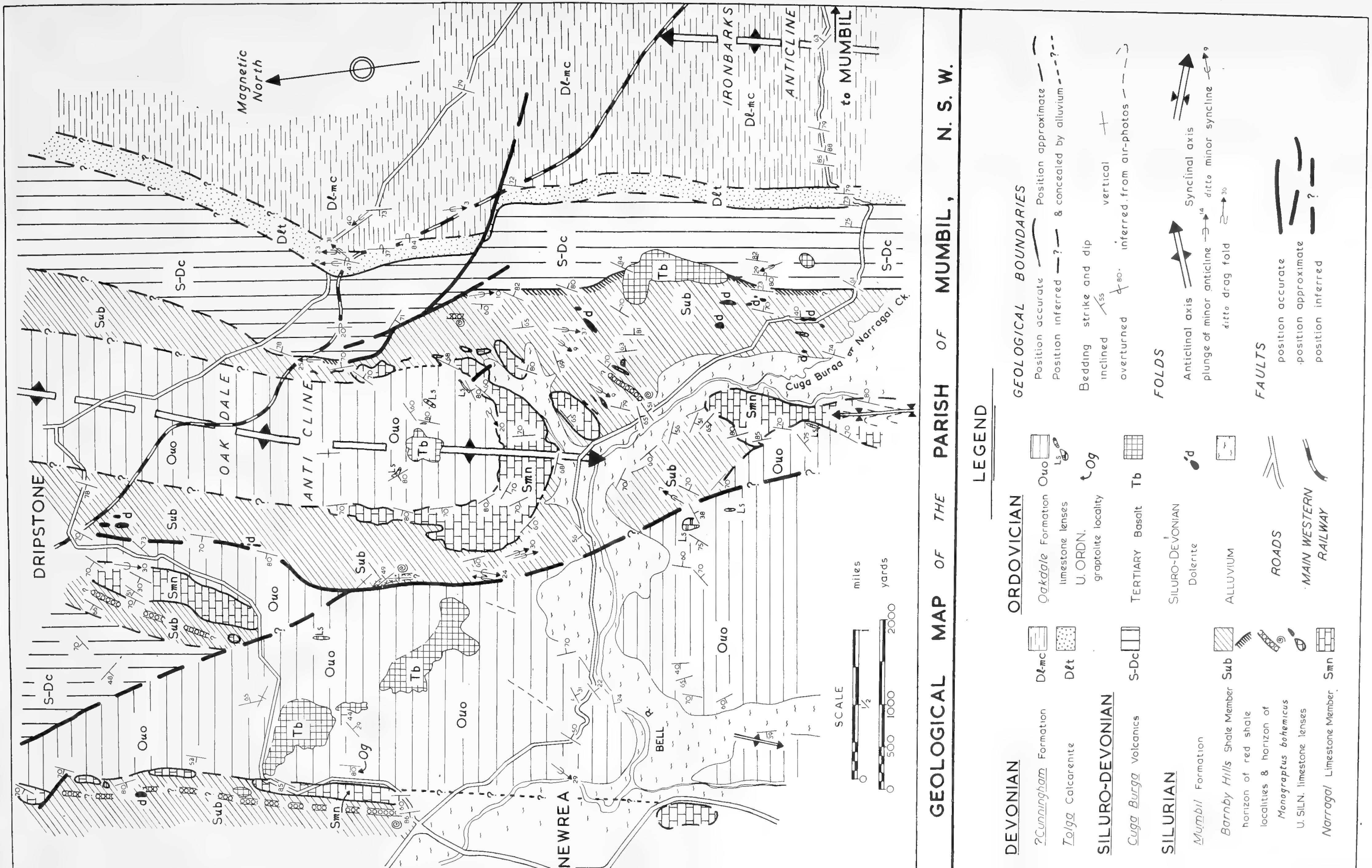
GEOLOGICAL MAP OF THE PARISH OF MUMBIL, N. S. W.
LEGEND
DEVONIAN
?Cunningham Formation Dℓ-mc
Tolga Calcarenite Dℓt
SILURO-DEVONIAN
Cuga Burga Volcanics S-Dc
SILURIAN
Mumbil Formation
Barnby Hills Shale Member Sub
horizon of red shale
localities & horizon of Monograptus bohemicus
U. SILN. limestone lenses
Narragal Limestone Member Smn
ORDOVICIAN
Oakdale Formation Ouo
limestone lenses Ls
U. ORDN. graptolite locality Og
TERTIARY Basalt Tb
SILURO-DEVONIAN Dolerite d
ALLUVIUM
ROADS
MAIN WESTERN RAILWAY
GEOLOGICAL BOUNDARIES
Position accurate
Position inferred
Position approximate
& concealed by alluvium
Bedding strike and dip
inclined
vertical
overturned
inferred from air-photos
FOLDS
Anticlinal axis
Synclinal axis
plunge of minor anticline
ditto minor syncline
ditto drag fold
FAULTS
position accurate
position approximate
position inferred
SCALE
miles
yards
0 500 1000 2000
½ 1
Magnetic North
DRIPSTONE
NEWREA
BELL
OAK DALE ANTI CLINE
IRONBARKS ANTICLINE
to MUMBIL
Cuga Burga or Narragal Ck.

Fig. 2

peltifer (topmost Llandeilo) in the British succession (Elles and Wood, 1913). As the difference in age is small, approximate correlation between the two localities is reasonable, and would indicate that the Oakdale Formation is wholly Ordovician in age, the Lower Silurian being missing.

In the west of the area, between the graptolite locality and the Tertiary basalt cap, there is a large development of coarse conglomerate containing smoothly rounded boulders of lava (identical in composition with those of this Formation) up to 18 inches across, along with large fragments of limestone. These are set in a tuffaceous matrix. These conglomerates are clearly of sedimentary origin, possibly the result of cliff erosion.

It is interesting to note that most of the limestone lenses in the western outcrop of the Formation are only a few yards across, whereas those in the Oakdale Anticline are reasonably well developed—one thin lens extends for over ¼ of a mile. Here they are interbedded with spilitic and keratophyric lavas and tuffs (the latter predominating), and common litho-feldspathic sediments. The lenses are apparently on three horizons, that at the top being only a few feet thick, but relatively persistent, with a slightly richer fauna. There is, however, no significant variation. Halysitids are common in these lenses, and extend only into the very base of the overlying limestone; it is probable that they do not extend above the top of the Llandoverian (see discussion under Mumbil Formation).

Petrologically, the volcanic rocks are highly variable, but fall within the spilite-keratophyre association typical of the earlier phases of geosynclinal development (Turner and Verhoogen, 1951, pp. 201–212; Tyrell, 1955). They range from quartz keratophyres to spilites, with the corresponding tuffs, which grade by reworking into fine-grained sediments. Associated with these sodic lavas are more normal trachytes and andesites, but these are in small quantity. Most of the lavas are porphyritic in plagioclase, grey-green or purplish-brown in colour and probably extensively saussuritized, and often contain numerous vesicles filled with quartz or calcite. Such vughs, up to ½ inch long, are particularly common in lavas from the Oakdale Anticline, R 13836 being typical. This is a striking purplish-brown rock with many large white vughs. The groundmass consists of albite with interstitial iron oxide (probably haematite), surrounding numerous small albite phenocrysts. The vughs are lined with chlorite, and contain also one or more of quartz, chalcedony and calcite. The majority of the lavas are keratophyres and quartz keratophyres, consisting of albite (with associated calcite veins and blebs), magnetite or haematite, and quartz (particularly in vesicles), but lacking ferromagnesian minerals. The iron oxides often make up a considerable proportion of the groundmass. Several thin sections show chlorite pseudomorphs after pyroxene, and where fresh pyroxene remains, it is generally pigeonite. Occasionally, small quantities of hypersthene occur, usually in spilites.

Of the less sodic rocks, two examples are R 13782, an andesite, and 13825, a trachyte. The andesite has phenocrysts of labradorite and pigeonite in a groundmass of plagioclase and magnetite, pigeonite and patches of devitrified siliceous glass. The magnetite content is quite high, mainly as small grains peppering the groundmass, and clearly late-stage magmatic, but it also occurs as skeletal crystals enclosed by labradorite phenocrysts. The trachyte contains scattered phenocrysts of sodic oligoclase and pigeonite in a trachytic groundmass of sanidine, magnetite and chlorite, with numerous small vughs containing either devitrified siliceous glass or chlorite.

Mumbil Formation

As there is no locality where this formation is completely exposed, it takes its name from the Parish of Mumbil. The old "Mumbil" farmhouse is situated on the Narragal Limestone Member, which forms the base of the Formation. The Formation also outcrops along the western side of the two north-south sections of the Newrea-Dripstone road, on the west bank of the Bell River at "Naroogal Park" (the "Narragal Limestone" of Carne and Jones, 1919), and on the western side of the Great Western Highway, opposite "Neurea" farmhouse. The total thickness cannot be ascertained, as the limestones, and more particularly the overlying shales, are highly folded on a small scale.

The Formation has been divided into two Members. The lower, up to 500 feet thick but usually less, is the NARRAGAL LIMESTONE MEMBER. This consists of richly fossiliferous bodies of massive and detrital limestone, which rest, almost certainly disconformably, on the Oakdale Formation. The coral fauna (see faunal lists, below) includes *Phaulactis shearsbyi* and *Entelophyllum latum*, which elsewhere occur in the Wenlockian and Ludlovian (see Hill, 1940, 1942). At the base are halysitids; not far above the limestone is an horizon of grey siliceous shale containing the lower Ludlovian *Monograptus bohemicus*. Other accurately dated N.S.W. limestones with a halysitid fauna are not as yet known above the Llandoverian. The age of the Narragal Limestone Member would therefore appear to extend from the topmost Llandoverian through most or all of the Wenlockian.

The limestone consists of large expanses of more or less well bedded detrital limestone, richly fossiliferous, but without much sign of extensive reworking. There are small areas of shale and chert, and scattered bodies of massive recrystallized limestone. These bodies probably represent small isolated reef knolls in a shoal-reef type of environment. The cherts contain sponge spicules, while the shales are generally siliceous, and similar in composition to many of the overlying sediments.

Above the Narragal Limestone Member are shales and a few small limestone lenses. These make up the BARNBY HILLS SHALE MEMBER, named after the property of " Barnby Hills ", on which typical outcrops are found. The sediments are almost entirely shales and siltstones, usually very quartz-rich, containing also plagioclase, muscovite, and haematite or more commonly limonite. Many of the coarser-grained rocks contain fragments of shale, or volcanic detritus. Several thin sections contained partly altered siderite.

Two useful horizons within this Member are the *Monograptus bohemicus* horizon, a pale grey or fawny-grey siliceous siltstone about 200 feet above the limestone, and a 300 feet thick horizon of red-brown shale at the very top of the Formation. The latter horizon is well developed between the northeast faults and the Tertiary basalt cap (see map), but dies out as it approaches the Newrea-Mumbil road, where it fails to appear. This is probably a lateral facies change rather than a lensing effect. The colour is due to large quantities of haematite.

Where this red shale horizon occurs, the top of the Mumbil Formation is defined as the junction of the horizon with the overlying volcanic sediments. Where it is missing, the top of the Formation must be defined as the base of the first bed of volcanic detritus in the Cuga Burga Volcanics. The junction is conformable.

Cuga Burga Volcanics

The Cuga Burga Volcanics take their name from Cuga Burga (or Narragal) Creek, which cuts through them at the south of the Newrea-Mumbil road. They are typically exposed along both the creek and the road, and also in several railway and road cuttings to the north. The rocks outcrop in a line of hills stretching northward for a considerable distance towards the Macquarie River. On air-photos the formation is clearly visible because of this relief, and because much of the land, being rocky, is uncleared. In the Parish of Ironbarks, south of Mumbil, the strata clearly outline the Ironbarks Anticline, and the considerable dragfolding on its west flank.

The base of the formation is defined as the volcanic rocks and fine-grained greywackes immediately overlying the shales at the top of the Mumbil Formation. The top of the formation on the Newrea-Mumbil road is a massive trachyte (R 13789), which stands out as a wall of rock up to 10 feet high on the hillside to the west of the road, clearly differentiated from the overlying calcarenites. On the railway line to the north, the top is also a lava flow, apparently different from R 13789, however. Between the two are keratophyric tuffs.

The various beds and lava flows within the formation are, on the whole, of small lateral and vertical extent, and so are not stratigraphically useful. There does, however, appear to be a discontinuous string of small limestone lenses, often brecciated and accompanied by volcanic agglomerates (or possibly a flow breccia), lying about $\frac{1}{3}$ of the way up the formation, which is some 2,100 feet thick. The fauna of these limestones is very limited (see faunal lists, below), and of little use for accurate dating. However, the position of these volcanics in the stratigraphic succession, the age of the underlying shales, and the intra-regional correlation of the overlying calcarenites (*q.v.*), suggest that the boundary between the Silurian and Devonian must lie within the Cuga Burga Volcanics.

Petrologically, the volcanic rocks are very similar to the lavas and tuffs of the Oakdale Formation, although no spilites have been found. Keratophyres and quartz keratophyres, both lavas and tuffs, are predominant. Another difference is the greater development of pyroxenes, giving many of the rocks a deep green colour, as opposed to the browns and grey-greens of the Ordovician lavas. The dominant pyroxene is augite, but pigeonite and diopside frequently occur, while orthopyroxenes have been seen. Chlorite is a frequent constituent, derived from the alteration of pyroxenes. As in the Ordovician lavas, magnetite is predominantly a late stage mineral. Ilmenite formed early, skeletal crystals being rather common in the sections prepared.

Less sodic rocks occur also. R 13789, forming the top of the formation on the Newrea-Mumbil road, is a dark green trachyte with phenocrysts up to ½ inch long of orthoclase, with pigeonite and minor enstatite, in a groundmass of albite and chlorite (in about equal amounts), with a small quantity of magnetite. It also contains occasional vughs of calcite. Such dark green lavas, with large pale green feldspar phenocrysts, while not confined to the Cuga Burga Volcanics, are certainly a feature of the formation, although they are less abundant than the tuffs and litho-feldspathic sediments. These have much the same mineralogy as the lavas, with abundant calcite and chlorite, and often a little quartz, iron ore and pyroxene.

Tolga Calcarenite

The Tolga Calcarenite consists of a succession of flaggy beds of calcarenite 3 to 12 inches thick, separated by finely laminated siltstones and calcilutites. The formation is about 700 feet thick, and takes its name from the "Tolga" farmhouse, which is situated on it. It conformably overlies the lavas and tuffs of the Cuga Burga Volcanics, and is overlain by shales and siltstones (possibly the Cunningham Formation: Packham, in press).

The beds are fossiliferous, the dominant elements being fragmental brachiopods and crinoid ossicles (see faunal lists). Some corals have been collected, and there are also fragments of lamellibranchs and polyzoans, while some of the calcilutites contain plant fragments.

The stratigraphic position of the formation and the general nature of the fauna suggest a Lower Devonian age. If this be so, there are two possible correlations. Thus about 10 miles south, near Stuart Town, lies the Nubrigyn Limestone, Lower or Middle Devonian in age. This underlies, and in part is equivalent to, the Cunningham Formation (Packham, in press), and is probably the same age as the Tolga Calcarenite. To the west, in a belt extending from Wellington to Molong, are detrital limestones, calcarenites and shales—the Garra Beds (Joplin and Culey, 1938; Joplin, 1952), which are of the same age. Work done by the author during 1959 on these beds in Curra Ck., 6 miles west of the Mumbil area, has proved interesting. A succession of andesitic tuffs and detrital rocks was found, closely resembling those of the Cuga Burga Volcanics, which passed conformably upwards into the Garra Beds. This strongly suggests that the Tolga Calcarenite can be correlated with the Garra Beds.

The flaggy calcarenites, in thin section, are almost pure calcite, mainly fine-grained recrystallized detritus, with brachiopod shells and other fossil material intermixed. The interbedded shales are often quite different. Typical is R 13811, a coarse grey siltstone containing quartz, biotite and white mica (parallel to the bedding planes), feldspar (probably plagioclase) and blebs of calcite.

Igneous Rocks

Palaeozoic Dolerite—A number of small bodies of dolerite occur in areas occupied by the Mumbil Formation, the majority being on the northeast side of the Newrea-Mumbil road, near Narragal Ck. Some of the outcrops are isolated and irregular, while others are clearly small sills. On the east side of the Mumbil-Newrea road, where it turns north after traversing the Cuga Burga Volcanics, a small intrusion has left the surrounding shales completely undisturbed, and no metamorphic effects could be found.

In hand specimen there is a fair amount of variation, chiefly in the amount of ferro-magnesian minerals present, and also in the grain size—from 1 cm. to less than 1 mm. in average size.

Three thin sections prepared (R 13785, 13816, 13832) contain chlorite-rich devitrified glass (indicating rapid chilling), skeletal ilmenite and augite. The last can often be seen in process of alteration to chlorite and actinolite, these minerals accumulating near the augite crystals. The dolerite resembles the lavas of the Oakdale Formation and Cuga Burga Volcanics in that the plagioclase is usually albite—often with associated ragged patches of calcite, indicating post-magmatic albitization of a more calcic feldspar. In R 13832, the feldspar is oligoclase. This specimen differs from the others also in containing some alkali feldspar (orthoclase?) and a small amount of devitrified quartz glass.

The field relationships of the intrusions, and their petrological affinity with the Palaeozoic lavas, indicate that these dolerites were almost certainly contemporaneous with the lavas and pyroclasts of the Cuga Burga Volcanics, i.e. Upper Silurian to Lower Devonian.

Tertiary Basalt and Alluvium—The Tertiary rocks in the area consist of the remnants of an olivine basalt flow, overlying alluvial deposits. The geological map shows that the flow parallels the Bell River, about a mile to its north.

The alluvial deposits consist of finely laminated white and buff shales, ferruginous sandstone and quartz-rich river gravels. A piece of silicified wood (F 7014) was also found. These indicate that the lava flowed down the old valley of the Bell River. Near the highway, the deposits are quite thick, and during the last century they were worked for gold.

The lava is a typical basalt. Sections show a felted mass of labradorite lathes, of average length 0·4 mm., amounting to about 50% of the rock, with nearly as much interstitial magnetite, and a rather small proportion of interstitial olivine. Very few olivine phenocrysts have been seen.

Geological Structure

The major structure in the area mapped is the Oakdale Anticline. Delineated by the outcrop of the Narragal Limestone Member, this anticline exposes an inlier of Ordovician rocks. The general trend of the fold is a little to the west of south, with a slight " kink " near the railway line; approximately horizontal near Dripstone, it plunges very steeply south at the Bell River. The Cuga Burga Volcanics conform to this structure, dipping eastward. Not visible in the area because of poor outcrops, the Ironbarks Anticline occurs to the southwest of Mumbil. This is clearly seen on air-photos (e.g. Merinda, Run 4, photo CAC 72–5123) to plunge northwards.

The structure of the Oakdale Formation in the west of the area is uncertain, but air-photo interpretation to the south of the Bell River seems to indicate a syncline and anticline plunging gently north.

Associated with the folding are numerous small dragfolds—visible in air-photos in the Narragal Limestone, and on the western limb of the Ironbarks Anticline. These have made estimation of the thickness of the Mumbil Formation impossible.

The major fault in the area is that passing approximately north-south, through Dripstone and west of the " Oakdale " farmhouse. This has apparently moved the Oakdale Formation on its west side upwards through an unknown but probably considerable distance; whether it is normal or reverse is unknown. It is joined by a second fault trending to the northwest. This forms a wedge of Silurian and Siluro-Devonian strata southwest of Dripstone. A number of quartz pods along the line of the second fault west of Dripstone have been excavated by gold fossickers.

Two intersecting faults have cut the Cuga Burga Volcanics, shifting the outcrop by ⅓ mile, and overturning the strata in the northern block. These faults, and some minor ones cutting the Narragal Limestone Member, appear to be of a peri-anticlinal nature (de Sitter, 1956, p. 207), intimately associated with the folding.

Discussion

Joplin (1952), following Basnett and Colditz (1945), considered that the Silurian was deposited unconformably around islands of folded Ordovician rocks. The succession was of limestones and shales, with lavas and tuffs in the Middle Silurian. It was thought that, following folding at the end of the Silurian, Lower and Middle Devonian limestones were formed, while Upper Devonian deltaic sandstones were laid down after further folding at the end of the Middle Devonian. The final fold movements were placed at the end of the Devonian.

It is now clear that, in the Mumbil area at least, and probably over much of the Wellington district, there was no significant folding before the end of the Middle Devonian, as the succession is structurally conformable from the Upper Ordovician to the Lower or Middle Devonian.

Joplin and Culey (1938) found no angular unconformity beneath the Upper Devonian near Molong, nor did Basnett and Colditz (1945) in the Wellington district. Joplin (1952) considered that there is a regional overlap; moreover, her sections do not show this to be an angular unconformity. Mr. J. Connolly (personal communication) has found a completely conformable passage from Middle Devonian Garra Beds to Upper Devonian Catombal Group in Bushranger's Creek, west of Wellington. It seems probable, therefore, that the regional overlap of Upper on Middle Devonian is a reflection of continuous sedimentation during slow, mild folding, with a shift of the axis of deposition.

Folding in the Upper Devonian Catombal Group is just as severe as in the Lower Palaeozoic, vertical and overturned strata being far from rare. From this, and the evidence presented in this paper, it seems that on the Molong Geanticline (Packham, in press), in the north at least, folding movements began slowly somewhere about the beginning of the Devonian, but did not become intense until the Carboniferous. The gap in the succession corresponding to the Lower Silurian is probably a faint reflection of the Benambran Orogeny (David, 1950), but the Bowning Orogeny cannot be recognized in the area.

Faunal Lists

The coral faunas from the area are described elsewhere (Strusz, in press). The graptolites were identified with the help of Dr. G. H. Packham, while Dr. P. J. Coleman assisted in the tentative identification of the brachiopods. Trilobite remains consist of pygidia and one librigena, from two species. Insufficient work has been done on Australian lower Palaeozoic Polyzoa and Nautiloidea for these to be identified from the material available.

A. FAUNAL LISTS, MUMBIL AREA

1. Oakdale Formation

RUGOSA: *Palaeophyllum rugosum* Billings; *Tryplasma lonsdalei* Etheridge, *T. derrengullenense?* Eth.; *Nipponophyllum* sp. aff. *giganteum* Sugiyama.

TABULATA: *Heliolites daintreei* Nicholson and Eth. (group 4, Jones and Hill); *Propora conferta* Edwards and Haime; *Favosites gothlandicus* Lamarck; *Multisolenia tortuosa* Fritz; *Striatopora* sp. Hill and Jones; *Acanthohalysites australis* (Eth.), *Schedohalysites orthopteroides* (Eth.), *Halysites lithostrotonoides* Eth., *H.* sp., *Falsicatenipora chillagoensis* (Eth.), *Quepora bellensis* Strusz; *Syringopora* sp.

STROMATOPOROIDEA: *Clathrodictyon* sp., et altera.

TRILOBITA: *Encrinurus* sp.

GRAPTOLITHINA: *Climacograptus scharenbergi* Lapworth; *Dicellograptus* sp. cf. *elegans* var. *rigens* Lapw.; *Orthograptus truncatus* var. *intermedius* Elles and Wood; unidentifiable diplograptids.

Also brachiopods, including a minute Orthid, cryptostome polyzoans and several nautiloids.

2. Narragal Limestone Member

Found only in base of member—

RUGOSA: *Palaeophyllum* sp., sp. nov.?

TABULATA: *Multisolenia tortuosa* Fritz; *Acanthohalysites australis* (Eth.).

TRILOBITA: *Encrinurus* spp.

Found throughout—

RUGOSA: *Phaulactis shearsbyi* (Süssmilch); *Entelophyllum latum* Hill; *Tryplasma lonsdalei* Eth., *T. wellingtonense* Eth., *T? columnare?* Eth.; *Nipponophyllum multiseptatum* Strusz; *Coronoruga dripstonense* Strusz.

TABULATA: *Heliolites daintreei* Nicholson and Eth. (groups 1 and 4, Jones and Hill); *Propora conferta* Edwards and H.; *Favosites allani* Jones, *F. gothlandicus* Lamarck; *Striatopora* sp. Hill and Jones; *Syringopora* spp.

Also brachiopods, including large pentamerids, cryptostome and trepostome polyzoans and stromatoporoids.

3. Barnby Hills Shale Member

RUGOSA: *Disphyllum* sp. aff. *floydense* (Belanski); *Tryplasma lonsdalei* Eth.

TABULATA: *Heliolites daintreei* Nicholson and Eth. (group 3, Jones and Hill); *Favosites gothlandicus?* Lamarck, *F.* sp.; *Striatopora* sp. Hill and Jones.

STROMATOPOROIDEA: *Clathrodictyon* sp.

GRAPTOLITHINA: *Monograptus bohemicus* (Barrande).

4. Cuga Burga Volcanics

RUGOSA: *Tryplasma derrengullenense?* Eth., *T.?* sp.; *Fletcheria?* sp.

TABULATA: *Favosites* spp.; *Striatopora* sp. Hill and Jones.

BRACHIOPODA: *Atrypa* sp. cf. *? reticularis* Linné.

POLYZOA: Unidentifiable Trepostomata.

5. Tolga Calcarenite

RUGOSA: *Tryplasma derrengullenense?* Eth.

TABULATA: *Heliolites daintreei* Nicholson and Eth. (group 3, Jones and Hill); *Favosites gothlandicus?* Lamarck, *F.* sp.

Also fragments of brachiopods, crinoids, polyzoans and a few plant remains.

6. Marl just above the Tolga Calcarenite (=Cunningham Formation ?)

RUGOSA: *Tryplasma derrengullenense?* Eth.

TABULATA: *Favosites* spp.

BRACHIOPODA (tentative): cf. *Schizophoria* sp.; *Rhynchotreta* sp. cf. *americana* Hall; cf. *Acrospirifer* sp.; plus numerous unidentifiable casts and fragments. There are also lamellibranchs, polyzoans and crinoids.

B. FAUNAL LIST, LOCALITY "MOLONG B" OF SHERRARD (1954)

(corals by personal communication, G. H. Packham)

TABULATA: Species of *Halysites*, *Heliolites*, *Syringopora* and *Multisolenia* or *Desmidopora*.

GRAPTOLITHINA : *Climacograptus bicornis* Hall, *C. scharenbergi* Lapworth ; *Orthograptus* sp. cf. *apiculatus* (Elles and Wood), *Lasiograptus harknessi* (Nicholson).

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The Structure of the Earth*

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I have been asked to speak on the general structure of the Earth. We cannot take samples of the material more than a few miles down, but nevertheless we can get relevant information from many sources. Petrology helps us to some extent, at least in suggesting ideas, some of which stand further test and some do not. Below the sedimentary rocks, which probably averaged 1 or 2 km in thickness, our most detailed information comes from seismology, which gives us the velocities of elastic waves all the way to the centre. In addition we have a great deal of information about the Earth's gravitational field, which determines both gravity over the surface and the motion of the Moon. This gives most valuable information, and the two together enables us to fix the distribution of density within rather narrow limits.

The commonest rocks at the Earth's surface are silicates; if we compare the number of metallic valencies with the number of silicon atoms they fall into an order as follows.

	Typical Mineral	Metal/ Silicon
Silica	SiO_2	0 : 1
Trisilicates (felspars)	$KAlSi_3O_8$	4 : 3
Metasilicates ..	$MgSiO_3$	2 : 1
Orthosilicates ..	Mg_2SiO_4	4 : 1

Granites are mostly silica and trisilicates, with a mean density about 2·7; basalts (including dolerite, diabase and gabbro) a mixture of trisilicates, metasilicates and orthosilicates, with a mean density about 3·0; and dunite, consisting mostly of olivine $(Mg,Fe)_2SiO_4$, has a mean density about 3·3. Olivine is a usual constituent of basalts but in the fairly pure form of dunite it is rare at the surface.

In the Earth as a whole we should expect some stratification according to density. The mean density is about 5·5, and far more than that of any common surface rock. The first question is whether this is a matter of a surface skin of light materials or whether it implies an increase of density continuing to great depths. This is settled by considerations from the theory of the Figure of the Earth.

Let M denote the mass, a the mean radius, C the moment of inertia about the polar axis, and A the mean moment of inertia about two perpendicular axes in the equator. The precession of the equinoxes, a very accurately determined astronomical motion, gives the ratio $\frac{C-A}{A}$. But the gravitational potential due to the Earth is

$$U=f\frac{M}{a}\left\{\frac{a}{r}+J\frac{a^3}{r^3}(\tfrac{1}{3}-\cos^2\varphi)+\ldots\right\}$$

where f is the constant of gravitation, φ is the latitude, and $J=\frac{3}{2}\frac{C-A}{Ma^2}$. The J term is a consequence of the fact that the Earth is not quite a sphere.

If we write $\omega^2 a/g_e=m$, where ω is the rate of rotation and g_e is gravity at the equator, the fact that the ocean surface is one of constant pressure leads to the equation (to the first order in e and m)

$$J=\frac{3}{2}\frac{C-A}{Ma^2}=e-\tfrac{1}{2}m,$$

where e is the ellipticity. Also gravity satisfies

$$\frac{g}{g_e}=1+\left(\frac{5}{2}m-e\right)\sin^2\varphi,$$

where φ is the latitude. Up till last year the most probable value of e seemed to be $1/297\cdot1$, but the latest determinations from artificial satellites, which determine J directly, indicate that $e=1/(298\cdot1\pm0\cdot1)$. Then comparison of J with $(C-A)/C$ gives

$$\frac{C}{Ma^2}=0\cdot330\pm0\cdot001.$$

For a homogeneous sphere the ratio would be 0·4. Further, if the differences of density were confined to a surface skin the ratio would hardly be affected. Therefore the density must go on increasing to a great depth.

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We should expect some increase of density anyhow. Even if the material was the same everywhere, the deeper parts would be compressed by those above. But there might also be a concentration of denser materials towards the centre. Wiechert first worked out the consequences of the increase being entirely due to difference of material. He assumed a uniform shell of density ρ_0, surrounding a core of radius $a\alpha$ with density ρ_1. The mean density gives the relation

$$\bar{\rho}=\rho_0+(\rho_1-\rho_0)\alpha^3,$$

and the ratio C/Ma^2 gives a determination of

$$\{\rho_0+(\rho_1-\rho_0)\alpha^5\}/\bar{\rho}.$$

(Wiechert's actual method was more complicated but is equivalent to this.) One extra datum would suffice to determine ρ_0, ρ_1, and α. His favoured solution took ρ_0 as the density of a dense surface rock, 3.2, and led to $\alpha=0{\cdot}78$, $\rho_1=8{\cdot}2$. This looked plausible because the densities would agree with those of stony and iron meteorites.

Seismology goes into much more detail. An internal shock sends out both longitudinal and transverse elastic waves. The velocities of longitudinal (P) and transverse (S) elastic waves are α, β, related to the elastic constants λ, μ, k and the density ρ by

$$\alpha^2=(\lambda+2\mu)/\rho\,;\quad \beta^2=\mu/\rho\,;\quad k=\lambda+\tfrac{2}{3}\mu.$$

Then $\alpha^2-\frac{4}{3}\beta^2=k/\rho$.

So if we can time elastic waves we should get a lot of information about elasticity. Early recording was poor, and it was not till **1900** that the phases were satisfactorily separated, by R. D. Oldham, of the Geological Survey of India. We measure distance by the angle Δ at the centre of the Earth subtended by the path. The linear distance would be proportional to $\sin\frac{1}{2}\Delta$. Oldham found that the times did not increase as fast as $\sin\frac{1}{2}\Delta$, which was evidence that the velocities increased with depth. The waves *P* and *S* could be traced to about $\Delta=100°$, taking about 14 and 25 minutes, and then disappeared. In **1906** Oldham discussed observations near the antipodes ($\Delta=180°$) and found that *P* emerged again about 140° and was traceable to the antipodes, but it took about 20 minutes. If the velocity at the deepest point reached by a ray emerging at 100° was continued all the way to the centre, the time would be 18 minutes. To reconcile the data there must be a drop of velocity. The *S* wave does not reappear at all.

The consequences were followed up by Gutenberg and compared with observation. There are many other pulses derived by reflexion and refraction at the core boundary, and theoretical times for these were computed; and where comparison was possible they were found on actual seismograms. Of particular importance are the reflexions at the outer surface of the core, which both show that there is a core with a sufficiently sharp boundary to give clear reflexions and enable us to determine its depth. Its radius is close to $0{\cdot}55a$, disagreeing greatly with Wiechert's estimate.

In European earthquakes observed at short distances some additional movements are found, which appear to be pulses that have travelled in various superficial layers. Comparison of the seismological values of $\alpha^2-\frac{4}{3}\beta^2$ with laboratory determinations of k/ρ indicated that there was an upper layer that might be obsidian (the glassy form of granite), possibly resting on an intermediate one that might be tachylyte (the glassy form of basalt). Below that is the Mohorovičić discontinuity; the properties below it correspond to dunite. In North America and South Africa, however, the upper layers agree better with ordinary granite and basalt. The total thickness of these layers in the continents is on an average about **35** km. Under the oceans the granitic layer is mostly absent and the deep-seated material is at a depth of 5 to 10 km.

L. H. Adams and E. D. Williamson completed the proof that there must be a change of material at great depths. If p is the pressure and $M(r)$ the mass within distance r of the centre, the condition for equilibrium gives

$$\frac{dp}{dr}=-f\frac{M(r)\rho}{r^2}$$

and by definition of the bulk-modulus

$$\frac{dp}{k}=\frac{d\rho}{\rho}.$$

Then it follows that

$$\frac{d\rho}{dr}=-f\frac{M(r)}{r^2}\,\frac{\rho^2}{k}.$$

Also
$$\frac{dM(r)}{dr}=-4\pi f\rho r^2.$$

The total mass is $M(a)$. Starting with $M(a)$ and a reasonable density near the surface, and knowing k/ρ as a function of r, Adams and

Williamson integrated the differential equations for ρ and M step by step as if all changes of density were due to compression. The result was that a large point mass was left over at the centre—the known materials would not account for the mass of the Earth even when compression was taken into account.

Seismology had shown no sharp change of properties at the Wiechert core radius, but did show one at the Oldham-Gutenberg core. So this was the natural place to assume a change of material. If we go back to the equations for C and Ma^2 it is found that with the assumption that $\alpha=0{\cdot}55$ they lead to $\rho_0=4{\cdot}6$, ρ_1 about 12. But compression gives a variation of density from 3·3 to 5·5 in the shell and 4·6 is a reasonable mean. Wiechert had got a wrong radius through neglecting compression. This was not his fault, as there were no data at that time to estimate it.

There is no evidence of transverse waves through the core, so it is probably liquid. If the pressure was taken off the density would be between 6 and 7, so it looks as if the supposition that it was iron was not far wrong after all. The wave velocities have a rather sharp increase at a depth of 200 km, probably spread over another 200 km. This is known as the 20° discontinuity, from the strong curvature shown by the time-distance curves at that distance.

Bullen repeated the work of Adams and Williamson with more accurate data. Finding the densities of successive layers, he was left with values for the mass and moment of inertia of the core. These gave C/Ma^2 for the core greater than 0·4—the density would have to decrease inwards ! So there must be some other change in the shell, and it was natural to put it at the 20° discontinuity, where the velocities had already shown an anomalous variation. If this is done there must be a jump of density of about 0·5 not accounted for by the model used. No suitable change of material seemed likely, and Bernal suggested that there might be a transition of olivine at high pressure from a rhombic to a cubic form as in spinel and magnetite. Spinel is $Mg(AlO_2)_2$; in comparison with olivine, Mg_2SiO_4, the silicon is replaced by magnesium and the magnesium by aluminium. Magnetite is $Fe(FeO_2)_2$. This is checked by the Moon. The pressure at 400 km depth in the Earth is not reached in the Moon, and the density of the Moon, if its materials are also abundant in the Earth, should agree with ordinary olivine ; and it does. But if the change was due to a new material we should expect a good deal of it in the Moon, and the Moon's density would be higher. Laboratory work has not yet reached the pressures needed to convert pure olivine from the rhombic to the cubic form. But germanium, the next element below silicon in the periodic table, forms a compound Ni_2GeO_4, and this does take a cubic form under pressure. A. E. Ringwood has studied the transition in mixtures or nickel germanate and olivine and infers that for pure olivine it would take place at about the right pressure.

There is a further change of properties far within the core ; this inner core has about one-third of the radius of the main core. The velocity of longitudinal waves rises and Bullen suggests that the inner core may be solid. If so, it may give us some information about temperature. But just outside this inner core there seems to be a region where the velocity decreases as we go deeper, and no explanation of this seems available.

W. H. Ramsey has argued that the core is not iron but a further pressure modification of olivine, which may pass into an ionized state like a metal. Present data do not permit a proper check on this idea, but the corresponding transition for hydrogen has been worked out theoretically and has led for the first time to an explanation of the densities of Jupiter and Saturn ; these planets must be about 90% hydrogen by mass to account for their low densities. This is most important. For one thing, it is the first explanation of how Saturn could have the low density of 0·7, though the range of pressure is about the same as in the Earth. For another, it confirms an opinion reached by astrophysicists after long discussion, that the stars and especially the Sun are nearly all hydrogen.

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The Measurement of Time in Special Relativity

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Abstract—Einstein's definition for measuring an observer's time of a distant event is examined in terms of its physical significance. The case of two receding observers at A and B, with similar clocks previously synchronized, is investigated. It is shown that A's time (according to Einstein's definition) of an event at B and B's clock reading coincident with it, are related according to the relevant Lorentz transformation, only if the two separated clocks have remained synchronous. The corresponding case of two approaching observers is also considered. It is suggested that the proposed interpretation of Einstein's definition is fully consistent with the principle of relativity and makes all inertial systems equivalent with regard to time, thus rendering unnecessary the concept of time dilatation.

1. Introduction

In developing his concepts of Relativity, Einstein encountered the problem of measuring the co-ordinates of a body moving relatively to the observer. There are in fact two problems involved in such a measurement. The first concerns the synchronization of similar clocks separated by a displacement which may be varying. Einstein outlined a light-signal method for synchronizing clocks which were stationary in the same inertial reference frame. He also considered that relatively moving clocks could only be synchronized if and when they were coincident in space, but not otherwise.

The second problem concerns the determination of a moving body's co-ordinates relative to the observer's reference frame. Here Einstein (1905) proposed a convention based again on a light-signal method and he showed that this measurement convention leads to and is consistent with the Lorentz transformations linking the co-ordinates as measured by any observer with those relative to another observer stationary in a different inertial frame.

The Lorentz transformations embody in mathematical form the principles of relativity and of light velocity constancy. They have also proved invaluable in the development of mathematical physics. So perhaps it is not surprising that many scientists have ignored the conventional nature of the underlying method of measurement and have attributed to it instead a universal significance which they take for granted.

It is proposed to examine Einstein's measurement convention and to show that the difference in measures of the " time " of an event, obtained by observers in relative motion, has a simple physical interpretation fully consistent with the principle of relativity.

2. Assumptions and Postulates

We will assume as basic* Einstein's principles of Relativity, viz.,

I. The laws of nature are the same for all inertial systems ;

II. The velocity of light is invariant for all inertial systems ; more exactly, the measure of this velocity is a constant c for all observers.

We now define the co-ordinates and relative velocities involved in the Lorentz transformation as those obtained according to Einstein's conventions postulated as follows :

(i) Synchronization of relatively stationary clocks : Consider two relatively stationary clocks A and B. Let a ray of light start at the " A time " t_A^1 from A towards B, let it at the " B time " t_B be reflected at B in the direction of A, and arrive again at A at the " A time " t_A^3 ; then the two clocks synchronize if

$$t_B=\tfrac{1}{2}(t_A^1+t_A^3).$$

This definition does not apply to relatively moving clocks ; the latter can be synchronized if and when they are coincident in space.

(ii) " The ' time ' of an event is that which is given simultaneously with the event by a stationary clock located at the place of the event, this clock being synchronized for all time determinations, with a specified stationary clock." (Einstein, 1905.)

* These are considered by most physicists as fundamental physical laws conforming with the experimental evidence to date. However, even if they are weaker than this, we are interested in deriving the consequences which are fully consistent with these assumptions.

Since, by (i), the stationary clock is reflected by a light-signal from the observer, midway between his times, t_A^1, of sending the signal, and t_A^3, of receiving its reflection, his "time", t_A^m, of the event must be given by

$$t_A^m=\tfrac{1}{2}(t_A^1+t_A^3)$$

where t_A^m may be considered as the "arithmetic mean time" of the light-signalling process. This interpretation of the "time" of an event is the one applied by Einstein (1905) in his derivation of the Lorentz transformations.

(iii) The measure of the space interval, s_A, separating an event from an observer A follows from (ii) and II in terms of his clock readings.

Thus $s_A=c(t_A^m-t_A^1)=\frac{c}{2}(t_A^3-t_A^1)$.

This definition is used by Synge (1956) and others, and it is consistent with the usual one involving a rigid rod stationary in A's inertial system.

(iv) The measure of the velocity, v_A, of the location of an event relative to an observer A is given by

$$v_A=\frac{ds_A}{dt_A^m}.$$

If v_A is constant, then

$$s_A=v(t_A^m+\varepsilon),$$

where ε is a constant and ε is zero if A measures his time from the instant when s_A was zero. In general the relative velocity is uniform if the ratio

$$\frac{s_A}{t_A^m+\varepsilon}$$

is constant for all t_A^m and a given ε.

We will now adduce one more assumption followed by a definition. These were not made by Einstein and are in fact contrary to what is assumed by most physicists.

III. The time taken by a light-signal to travel, in vacuo, between two points A and B (in relative motion or not) is related in some consistent fashion to the distance between its source and destination; and this relation is the same whether the path of the signal is from A to B or vice-versa.

This assumption will be referred to as the "light-signal hypothesis".* It implies that no special status should be assigned to either A or B, and that the velocity of light is the same in both directions. Thus the "hypothesis" can be considered as a consequence of I and II.

(v) We define a relatively moving clock at B to be synchronous with the clock A of an observer A if the reading, t_B^r, of clock B reflected by a light-signal from A agrees with the time, t_A^r, of the light-signal's reflection, as calculated by applying the light-signal hypothesis to A's clock readings of the signal's departure and return.

It will be shown that if, according to (v), clock B is synchronous with clock A relative to the observer A, then clock A is also synchronous with clock B relative to an observer at B.

We note that for the case when A and B are relatively stationary (v) reduces to (i).

In the interests of conciseness and provided the context is clear, we will refer to an observer at a point, A say, as the "observer A" or even occasionally as "A"; and to his clock as the "clock A".

3. Calculation of the Reflection Time t_A^r

Consider two observers A and B receding from one another with relative velocity v and carrying similar clocks which were synchronized at $t_A=t_B=0$ during their spatial coincidence. The observer A transmits a light-signal at time t_A^1 which reflects an event on B, the reading t_B^r of B's clock and returns to A at time t_A^3.

Then according to (ii), A's time of the event is

$$t_A^m=\tfrac{1}{2}(t_A^1+t_A^3) \qquad (1),$$

or applying Einstein's definition literally, t_A^m is the reading of a synchronous stationary clock located at B and therefore at a distance vt_A^m from A. Hence also

$$c(t_A^m-t_A^1)=c(t_A^3-t_A^m)=vt_A^m. \qquad (2)$$

Now let the time of reflection, according to A's time-scale, be denoted by t_A^r, which is to be calculated on the basis of the light-signal hypothesis.

* The hypothesis as stated may appear self-evident and perhaps even trivial, yet the implications which flow from its quantitative expression, given in equations (3) to (7) below, contradict the generally accepted assumptions regarding reflected light-rays.

The distance between A and B is vt_A^1 at the departure of the signal and vt_A^r at its arrival at B. Hence the distance, d_{AB}, travelled by the signal on its outward journey cannot be less than vt_A^1, nor greater than vt_A^r, though it may have some intermediate value between these two bounds. We may write therefore

$$d_{AB}=vt_A^1+k_{AB}(vt_A^r-vt_A^1) \qquad (3)$$

where k_{AB} is a constant depending on v and $0\leqslant k_{AB}\leqslant 1$, and also $d_{AB}=c(t_A^r-t_A^1)$ since the signal travels with velocity c in the interval t_A^1 to t_A^r.

The light-signal is reflected at B at t_A^r and returns to A at t_A^3; hence, by the same reasoning as before, the distance d_{BA} travelled by the reflected signal on its return journey is

$$d_{BA}=vt_A^r+k_{BA}(vt_A^3-vt_A^r)=c(t_A^3-t_A^r) \qquad (4)$$

where k_{BA} depends only on v and $0\leqslant k_{BA}\leqslant 1$. Then, since A and B have the same status* relative to one another,

$$k_{AB}=k_{BA}=k \text{ (say)}.$$

It is this equality which is proposed by the light-signal hypothesis in contradistinction to the orthodox assumption that the out and return paths are of equal length entailing that $k_{AB}=1$ and $k_{BA}=0$.

The constancy of k for a given system is the only assumption required to develop the rest of the argument. Thus using (3) for the outward journey we obtain

$$t_A^r-t_A^1=\frac{v(t_A^1+kt_A^r-kt_A^1)}{c}$$

therefore

$$\frac{t_A^r}{t_A^1}=\frac{1+\frac{v}{c}-\frac{v}{c}k}{1-\frac{v}{c}k} \qquad (5)$$

And using (4) for the return journey,

$$t_A^3-t_A^r=\frac{v(t_A^r+kt_A^3-kt_A^r)}{c}.$$

Therefore

$$\frac{t_A^3}{t_A^r}=\frac{1+\frac{v}{c}-\frac{v}{c}k}{1-\frac{v}{c}k} \qquad (6).$$

* More exactly, the relative status of A and B during the transmission of a light ray from A to B is exactly reversed during its reflection from B to A.

From (5) and (6) we obtain

$$(t_A^r)^2=t_A^1t_A^3 \qquad (7).$$

Thus t_A^r can be considered as the "geometric mean time" of the light-signalling operation.

To relate t_A^r to t_A^m we have from (2),

$$t_A^1=\left(1-\frac{v}{c}\right)t_A^m \qquad (8)$$

and

$$t_A^3=\left(1+\frac{v}{c}\right)t_A^m \qquad (9),$$

therefore in (7)

$$t_A^r=t_A^m\sqrt{1-\frac{v^2}{c^2}} \qquad (10).$$

Thus if B's time, t_B^r, of the event reflected by his clock is given by

$$t_B^r=t_A^m\sqrt{1-\frac{v^2}{c^2}} \qquad (11)$$

as predicted by the relevant Lorentz formula and where t_A^m has been obtained conventionally, then $t_A^r=t_B^r$ and clocks A and B are synchronous according to (v); in fact (11) can only be satisfied if the clocks have remained synchronous.

Combining (10) with (8) and (9) in turn, we obtain

$$t_A^r=t_A^1\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}t_A^1 \qquad (12)$$

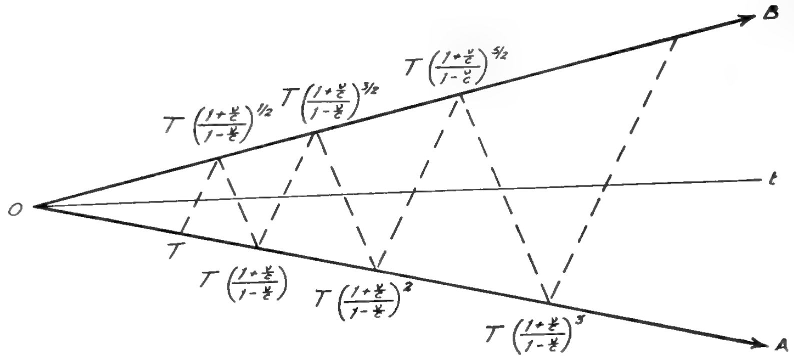
and

$$t_A^3=t_A^r\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}t_A^r \qquad (13)$$

These relationships enable us to demonstrate graphically the consequences of our assumptions.

Thus consider a light-signal reflected to and fro between our two receding observers A and B as described above. If the signal is initially transmitted by A at time T, then the subsequent times of reflection, on A's time scale, are given according to our calculations above, in the Figure, representing the diverging "world paths" of A and B.

If clock B is synchronous with clock A, according to (v), then the times of reflection at B



(according to observer A) are also B's clock readings. From the latter we can determine the times of reflection at A according to B's time-scale. Thus it is seen that if B is synchronous with A, according to (v), then A is also synchronous with B, for the times of reflection are equally consistent with regard to B's time scale as with regard to A's. Each observer will find that for any particular to-and-fro journey the time of reflection, t^r, is related to the arithmetic mean time, t^m, by

$$t^r=\sqrt{1-\frac{v^2}{c^2}}t^m.$$

Both observers will obtain the same measure for their relative velocity according to (iv).

We can consider therefore that they share a common time scale, " t ", represented by the horizontal line commencing at 0 where A and B were spatially coincident.

It may be noted that the reciprocity exhibited in the Figure is incompatible with the assumption that the out and return paths of a light-signal are of equal duration when it is reflected from a relatively moving object.

Case of mutually approaching observers—By extrapolating clock readings backwards from zero time we can obtain also the solution for the corresponding system of mutually approaching observers A and B, again timing an event on B with similar clocks. Since these clocks can, in fact, not be synchronized according to (i) until A and B are spatially coincident, we will assume that their clock readings are negative until such coincidence when each clock will read zero. The negative clock readings are then proportional to the contracting distance between A and B, leading to a calculation similar to that for the receding observers.

Let the velocity of B relative to A be $-v$, and consider, as before, a light-signal sent by A at time t^1_A, reflecting an event on B (a clock reading t^r_B) and returning to A at t^3_A. Then if t^m_A is A's " time " of the event we have

$$t^m_A-t^1_A=\frac{-vt^m_A}{c}=t^3_A-t^m_A,$$

remembering that

$$t^1_A<t^m_A<t^3_A<0.$$

Therefore

$$t^1_A=\left(1+\frac{v}{c}\right)t^m_A$$

and
$$t^3_A=\left(1-\frac{v}{c}\right)t^m_A.$$

It is easily shown that

$$t^r_A=\sqrt{t^1_At^3_A}$$

is valid here also. Hence the time of reflection of the event is given by

$$t^r_A=t^m_A\sqrt{1-\frac{v^2}{c^2}} \qquad (14)$$

In this case, however, t^r_A and t^m_A are negative and therefore $t^r_A>t^m_A$. Hence if the clocks A and B are synchronous such that t^r_A agrees with t^r_B, then the conventional measurement t^m_A makes clock B's reading, t^r_B, appear fast relative to observer A. From (14) we also obtain

$$\frac{dt^r_A}{dt^m_A}=\frac{dt^r_B}{dt^m_A}=\sqrt{1-\frac{v^2}{c^2}}. \qquad (15).$$

4. Conclusions

The Equivalence of Inertial Systems with respect to Time

We have seen that Einstein's definition for measuring the observer's " time " of a distant event makes receding clocks appear slow and approaching clocks fast ; and in both cases the clocks appear to be losing time. The defined measure of a space interval, according to (iii), has the same relation to the corresponding interval at the time of reflection as has t_A^m to t_A^r. Thus a measuring rod moving relatively to an observer appears contracted. These apparent contractions are therefore both due to the disparity (in the case of moving events) between the time of reflection of the event and the observer's conventionally measured time. In two simple but crucial applications this turns out to be a difference between a " geometric mean time " and an " arithmetic mean time ".

The relation between these two times is given unequivocally by the relevant Lorentz formula. This is not surprising since Einstein deduced the Lorentz transformations from his definitions. What is surprising is that he (and most other physicists) then interpreted the transformations as above convention. Contrary, therefore, to the usual interpretation we have shown that the time dilatation formula is obeyed in the case of receding or approaching clocks only if they are synchronous with that of an observer. The Lorentz transformations relate measurements, they do not demonstrate a slowing down of moving clocks. Hence no suggestion of clock paradoxes can arise since time does in fact flow at the same rate in all inertial systems.

It is claimed that " time dilatation " has been experimentally verified in two ways. Thus Møller (1952) states that " the transverse Doppler effect " (observed by Ives (1938) in canal rays) " is a direct expression for the retardation of moving clocks ".

Further, Crawford (1957), following on the work of Rossi (1940) and co-workers, claims to have verified that high-energy μ-mesons with velocities approaching c, have extended half-lives due to their movement.

However, neither of these phenomena is necessarily a consequence of " time dilatation ". Provided that observers use Einstein's convention for measuring their time of an event,* then the apparent slowing down of relatively fast-moving phenomena is inevitable, even though they obey the same laws as when relatively stationary. It should be noted that the " correction " of an observer's measurement of moving events is available precisely in the form of the Lorentz transformation.

The equivalence of all inertial systems with regard to time would appear to be a natural corollary of the principle of relativity. We have attempted to show that such equivalence can be deduced from the principle of relativity and is consistent with the formulae expressing this principle.

Acknowledgements

The author wishes to record his thanks to Professor C. S. Davis and Mr. J. L. Griffith for their stimulating criticisms, which resulted in a strengthening and generalization of the argument ; also for the suggestion by Mr. Griffith of a figure similar to the one included in the text.

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* Or, equivalently, assume that the out and return times are equal when a light signal is reflected by an object moving relatively to the observer. In the case of light signals received from a radiating moving object, the equivalent assumption is that the time taken for the signal to reach the observer is the same as if the object had been relatively stationary at the instant when it radiated the signal.

Discussion

N. W. Taylor

The theory developed in the above paper is an alternative to the conventional Special Theory of Relativity. Therefore, it would appear to be superfluous, since the conventional theory is not in any serious doubt. However, it must be accepted for consideration for the following reason. It is based on a set of self-consistent and simple postulates, and after the advent of the Special Theory of Relativity, simplicity has been a major consideration in the development of physical theories. It is almost a physical principle. (Schilpp, **1959**.)

The main difference between this theory and conventional relativity is embodied in Assumption III, the " light signal hypothesis ". This assumption leads to a result which appears strange to the usual way of thinking. From the point of view of the observer A, the out and return journeys of a ray of light reflected at B are of different lengths (given by equations (3) and (4), respectively). Now, it is customary to let A suppose that the event of reflection involves only a single instant and a single point, and this point cannot have two different distances from A no matter how the reflector moves. The measurement convention of Special Relativity (described by equation (1)), which Assumption III replaces, seems to be the more logical hypothesis.

It might be possible to avoid something which looks like a paradox by saying that the distances of the out and return journeys are the respective estimates of two *different* observers, the point of view shifting from that of A to that of B when the light signal is reversed. If this were done, another conflict with orthodox theory would occur. Measurements made by two different observers would be used in a statement of a physical law.

From another aspect, the light signal hypothesis would, for an observer A, seem to give special significance to some framework not directly attached to A. It is as if the whole process were being described from the point of view of some imaginary outsider who can claim to have a more fundamental place in the universe than the given observer. This is directly opposed to the principles of relativity theory.

A significant result of the theory under discussion is the reinstatement of a universal time, as implied by the equation $t_A = t_B$. This would be an attractive feature to some philosophers and physicists. However, as it has just been shown, this feature entails results which do not accord with our conception of the physical universe at the present time. In any case, it has been amply demonstrated in a number of ways (e.g., by Builder, **1957** ; Møller, **1952** ; Schild, **1959**) that the usual relativistic interpretation of time leads to no *real* difficulties at present.

The experimental verification of time dilatation mentioned in Section IV is very convincing evidence in favour of the usual interpretation of Special Relativity. It seems that a more detailed analysis than that given by the author would be necessary to show that the results of these experiments do not conflict with his theory.

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Author's Reply

S. J. Prokhovnik

The continuing controversy (cf. Cullwick, 1959) around Special Relativity is clear indication that the conventional approach, with its built-in " clock paradox ", is not beyond criticism. Even the adherents of time-dilatation are unable to agree on its interpretation. Thus Builder and Møller are widely divergent both in approach to the resolution of the paradox and, particularly, in their interpretation of the physical significance of time-dilatation. In fact, Builder (1958a, 1958b) has, with a certain logic, retreated from Relativity to a neo-Lorentzian view.

It is agreed that the " light signal hypothesis " leads to a result which appears strange to the usual way of thinking. This is because we are intuitively accustomed to thinking in terms of absolute concepts, viz.: " We are stationary, the observed body is moving." However, for the purposes of physical observation and measurement, such notions are untenable; only the relative motion between observer and observed has relevance to their mutual relations.

Thus consider a light signal despatched from A to a receding body B at t_A^1 and reflected at B at t_A^r. Clearly any other signal sent from A to B at a time subsequent to t_A^1, say at t_A^r, would have a longer path than its predecessor since A and B are receding. This must apply equally to a signal reflected at (or transmitted from) B at t_A^r back to A. This seems to be a natural consequence of the principle of relativity unless one could argue that a signal transmitted from B to A would travel differently to one reflected (say from A) at B at the same instant.

Seen in this light, the non-coincidence of t_A^r with the conventionally-measured time, t_A^m, is consistent with the viewpoints of observers on either A or B or even elsewhere. In fact the figure presented in the article shows that this is the only approach which gives a consistent sequence of reflection times from either viewpoint; and which renders intelligible the reciprocity of the Lorentz transformations.

It should be emphasised that Einstein's procedure (ii) for measuring the " time " of an event was never considered by him as anything but a convenient definition. Yet this " time " has been given a preconceived meaning, without justification in the light of the principles of relativity I and II. The article is an attempt to correct this anomaly.

The Lorentz transformations are relations between measurements. The transverse Doppler effect is then also a measurement relationship which has been verified by Ives. It is his identification of time with measurements of time which we question. The meson-life evidence is of a different nature and certainly demands a careful and unprejudiced analysis. Suffice it to say here that examination of Rossi's relevant publications (1940, 1941) reveals that, far from verifying, he assumed the existence of time-dilatation to develop certain conclusions. However, this assumption is at variance with one set of his experimental findings and, at best, the support for it is not conclusive.

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