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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

$$F(s)=\int K(s,x)f(x)dx \quad \ldots\ldots \quad (2.1)$$

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

$$F(s)=\int_0^\infty xJ_\nu(sx)f(x)dx \quad \ldots \quad (2.2a)$$

and

$$f(x)=\int_0^\infty sJ_\nu(sx)F(s)ds \quad \ldots \quad (2.2b)$$

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

$$\begin{aligned} F(s)&=s^{-\nu}(s^2-a^2)^{\nu-3/2}, \quad s>a \\ &=0, \quad s<a. \end{aligned}$$

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 $g(x)\not\equiv 0$ 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

$$f(x)=-\pi^{-1}\int_{-1}^{+1} \frac{(1-s^2)^{\frac{1}{2}}F(s)}{(1-x^2)^{\frac{1}{2}}(s-x)}ds+C(1-x^2)^{-\frac{1}{2}} \quad \ldots\ldots\ldots \quad (2.3b)$$

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	$\int_0^\pi \cos sxf(x)dx$	$\pi^{-1}F(0)+2\pi^{-1}\sum_{n=1}^{\infty} F(n)\cos nx$	(*e*)
Finite Sine	$\int_0^\pi \sin sxf(x)dx$	$2\pi^{-1}\sum_{n=1}^{\infty} F(n)\sin nx$	(*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	$(4\pi)^{-\frac{1}{2}}\int_{-\infty}^{\infty} e^{-\frac{1}{4}(s-x)^2}f(x)dx$	$\lim_{n\to\infty}(1-D^2/n)^n F(x)$	(*f*)
		$\lim_{n\to\infty}\left(\sum_{p=0}^{n}\frac{(-1)^p D^{2p}}{p!}\right)F(x)$	(*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 *n*th 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

$$F(s)=G(s)/(1-H(s)) \quad ...... \quad (2.9)$$

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.

$$\begin{aligned} \text{In fact } f(x)&=Cx(a^2-x^2)^{2\frac{1}{2}}, \quad |x|<a \\ &=0, \quad |x|>a, \end{aligned}$$

where $C^{-1}=2^{1\frac{1}{2}}\pi a^3\Gamma(3\tfrac{1}{2})$.

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

$$F(s)=(2/\pi)^{\frac{1}{2}}\int_0^\infty (sx)^{\frac{1}{2}}K_\nu(sx)f(x)dx \quad .. \quad (3.1)$$

reduces to the Laplace transform when $m=\frac{1}{2}$.

He later found that (Meijer (1941*a*))

$$F(s)=\int_0^\infty (st)^{-k-\frac{1}{2}}e^{-\frac{1}{2}st}W_{k+\frac{1}{2},m}(st)f(t)dt \quad .... \quad (3.2)$$

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

$$F(s)=\int K(s-x)f(x)dx. \quad .... \quad (3.3)$$

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

$$L_{11}[f(x)]=F(p) = \int_{-\infty}^\infty e^{-px}f(x)dx \quad ...... \quad (3.4)$$

and has the following two properties

$$L_{11}[D^nf(x)]=p^nF(p), \quad D=d/dx \quad .... \quad (3.5)$$

and

$$L_{11}\left[\int_{-\infty}^\infty g(x-t)f(t)dt\right]=G(p)F(p) \quad .. \quad (3.6)$$

(we have used p as a variable to avoid confusion in the next few lines).

The operational form of the Taylor series is

$$e^{aD}f(x)=f(x+a). \quad .... \quad (3.7)$$

These writers now consider the transform

$$\varphi(s)=\int_{-\infty}^\infty g(s-x)f(x)dx \quad .. \quad (3.8)$$

where $g(x)$ has a two-sided Laplace transform $[E(p)]^{-1}$ of the special form

$$E(p)=e^{bp}\prod_{k=0}^{\infty}(1-p/a_k)e^{p/a_k} \quad .. \quad (3.9)$$

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

$$f(x)=e^{bD}\prod_{k=0}^{\infty}(1-D/a_k)e^{D/a_k}\varphi(x) \quad .... \quad (3.11)$$

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

$$\int_0^\infty y^\alpha f(y)J_\nu(xy)dy=g(x),\quad x>1$$

$$\int_0^\infty f(y)J_\nu(xy)dy=k(x),\quad x<1.$$

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

(*Received April* 13, 1959)

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) $$s=r^2/2R \text{ (equation of parabola)},$$

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.

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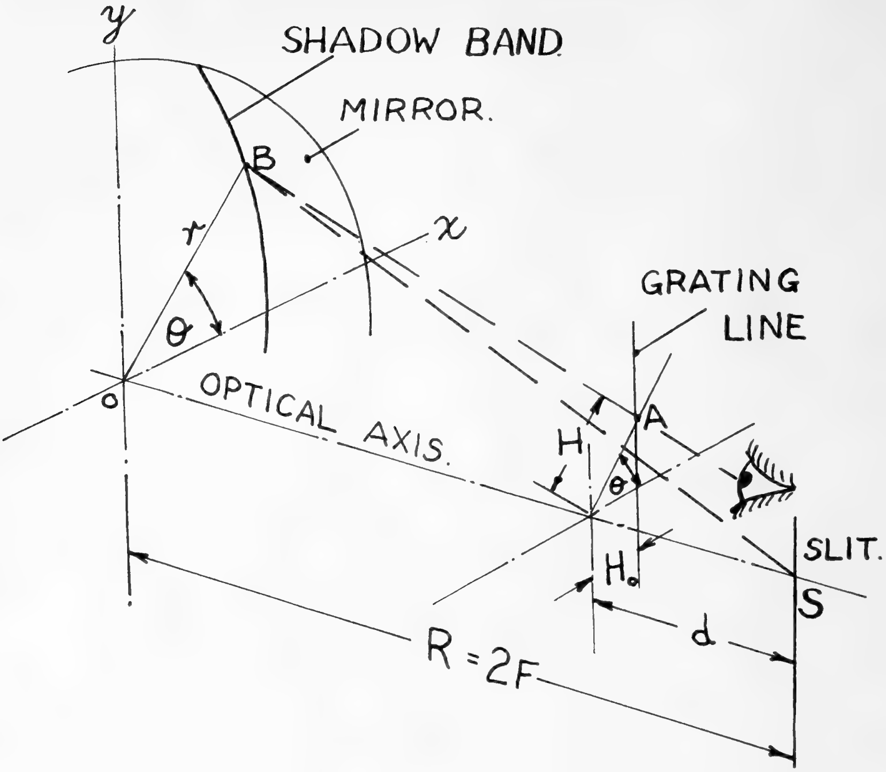

Fig. 1

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.

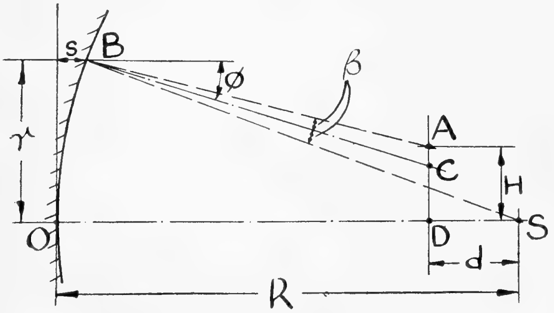

Fig. 2

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

$$d=1\cdot0 \text{ in.}, \quad d=0\cdot5 \text{ in.}, \quad d=0\cdot2 \text{ in.}$$

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.

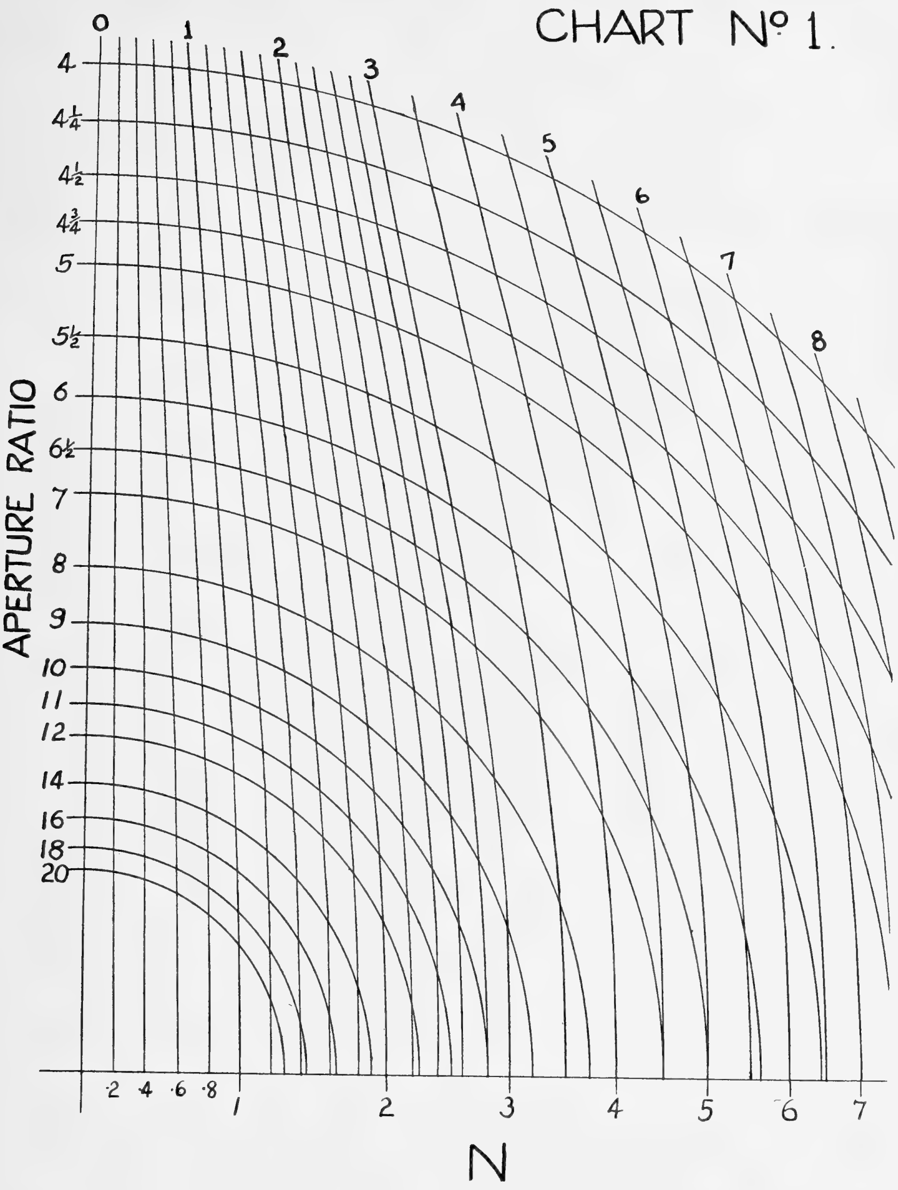

CHART 1

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.

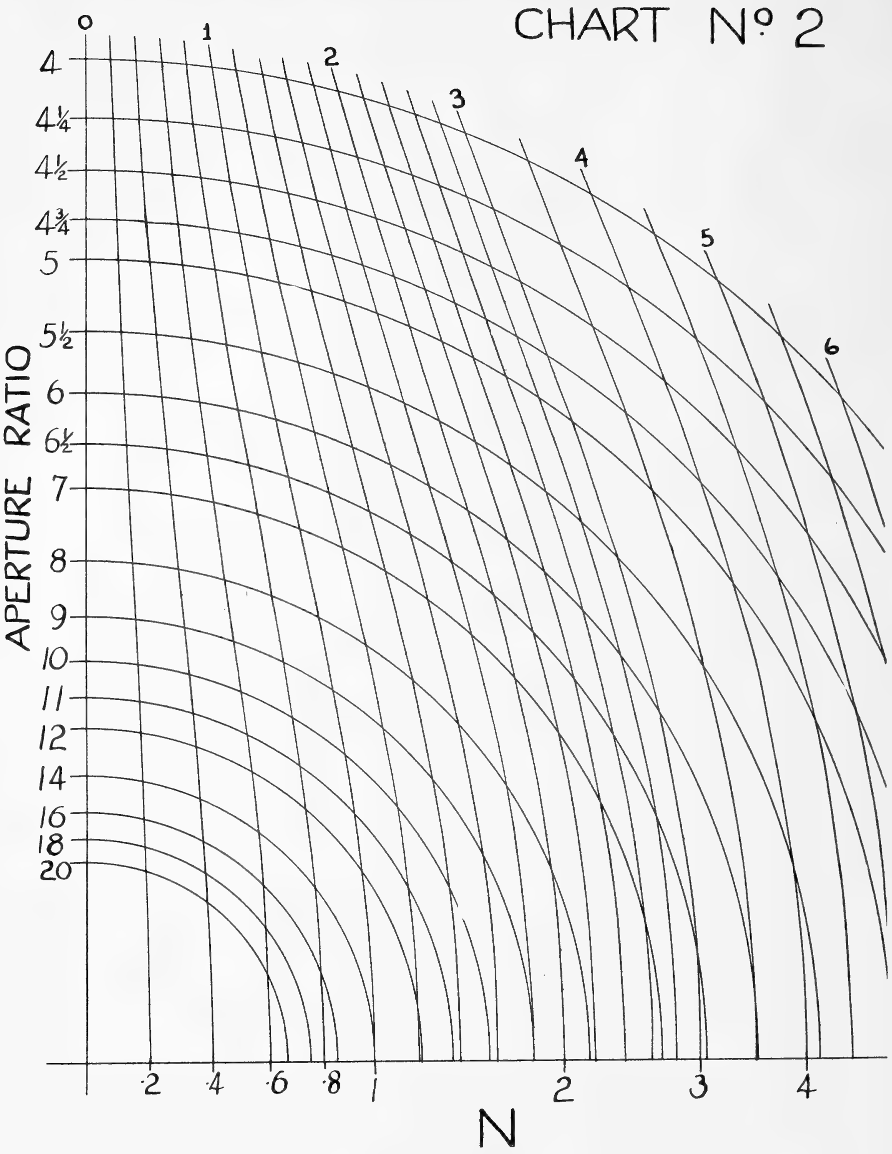

CHART 2

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

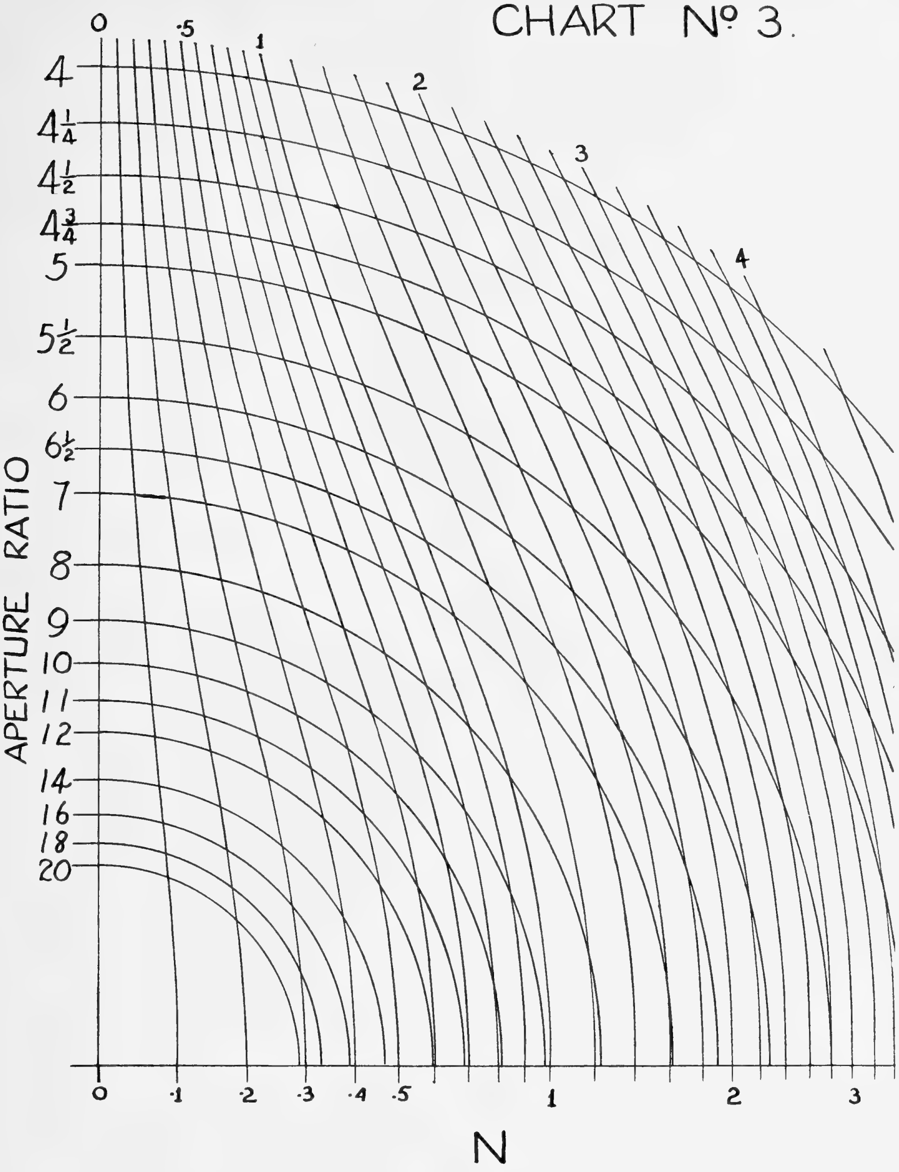

Chart 3

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

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The following observations of occultations were made at Sydney Observatory with the $11\frac{1}{2}$-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 $-0\cdot00152$ hour was applied before entering the ephemeris of the Moon. This corresponds to a correction of $-3''\cdot0$ 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	
										$\Delta\alpha$	$\Delta\delta$
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

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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
A 265	Granite, crushed	42
A 289	Granite	36
A 320	,,	16
A 204	Granodiorite	30
A 673	Crushed Bi. Granite	36
A 674	,, ,, ,,	45
A1141	Granite	22
A 496	Or. Porphyry	22
A 55	Dolerite	23
A 600	Q. Or. Porphyry	14
A 915	Microdiorite	11
A 932	Dolerite	21
A 962	Quartz porphyry	15
A 186	Dolerite	25
A 511	Basalt	17
A 217	,,	10
A 597	Rhyolite	15
A 684	Basalt	15
A 711	Basaltic dolerite	19
A 714	Semi-vesicular basalt	13
A 827	Basalt	11
A 915	,,	10
A 957	,,	12
A 994	,,	11
A 995	,,	17
A 995	,,	13
A1013	,,	14
A1017	,,	16
A1018	,,	20
A1058	,,	13
A1175	,,	21
A1301	Volcanic breccia	13
A 297	Tuff	18
A 687	Quartz	44
A 986	,,	24
A 620	Limestone	20
A 640	,,	26
A 873	,,	24
A 532	,,	18
A 554	Nodular calcareous rock	31
A 268	,, ,, ,,	33
A 709	Indurated siltstone	40
A 828	Silicified mudstone	18
A 915	Indurated shale	14
A 252	,, ,,	17
A 238	,, ,,	16
A 995	Slate	17
A1058	Silicified mudstone	13
A 321	Quartzite	19
A 443	,,	21
A 994	,,	18
A 713	Silicified sandstone	22
A 763	Quartzite	23
A 791	,,	25
A 596	,,	12
A1058	,,	16
A 569	Slag	18
A 296	River gravel	26
A 280	,, ,,	35
A 299	,, ,,	30
A 329	,, ,, crushed	24
A 353	,, ,,	22
A 349	,, ,,	14

TABLE I—*continued*

Sample Number	Rock Type	Los Angeles Test % Loss
A 378	,, ,, ,,	18
A 401	,, ,, ,,	27
A 241	,, ,, ,,	31
A 510	,, ,,	18
A 498	,, ,, ,,	18
A 945	,, ,,	40
A 962	,, ,, ,,	12
A1017	,, ,, ,,	17
A1018	,, ,,	29
A1046	,, ,,	44
A1059	,, ,,	28
A 685	,, ,,	15
A 712	Rounded river gravel	28
A 715	Rounded river gravel	23
A 747	River gravel	36
A 778	,, ,,	22
A 807	,, ,,	14
A 893	,, ,,	18
A 576	,, ,, crushed	22
A 66	,, ,, screened	18
A 622	,, ,,	17
A 414	,, ,,	26
A 482	,, ,, crushed	20
A 363	,, ,, ,,	25
A 269	,, ,,	40
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	4	1	4	1	2
1	4	1	4	1	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	3
—	—	4	1	—	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

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[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	—

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[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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Department of Main Roads, N.S.W.
Central Testing Laboratory
Sydney

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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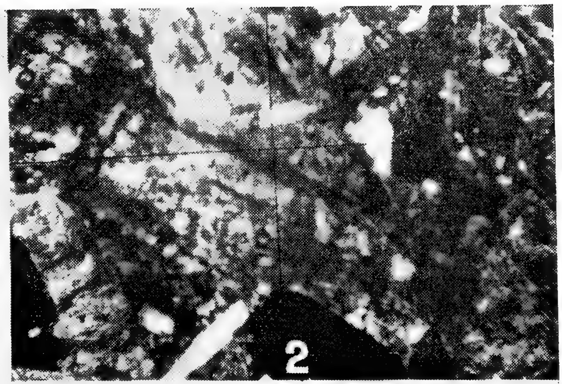
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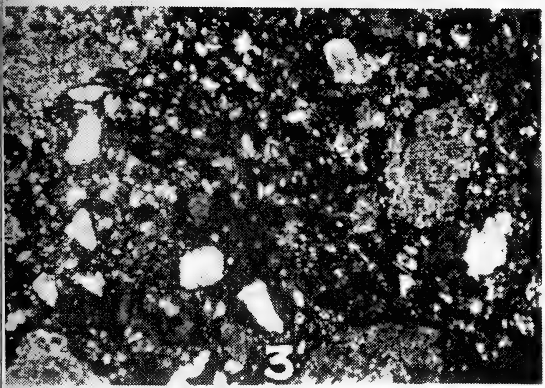
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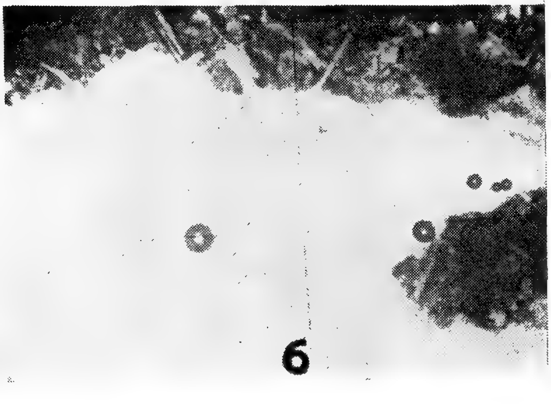
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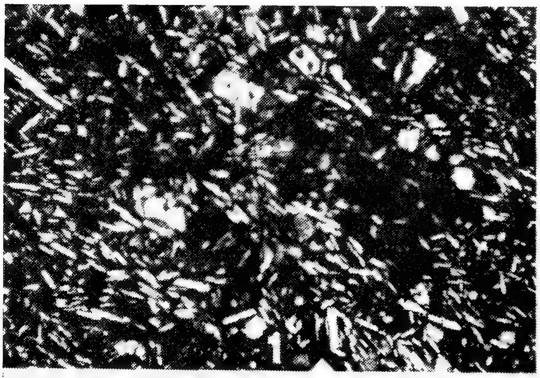
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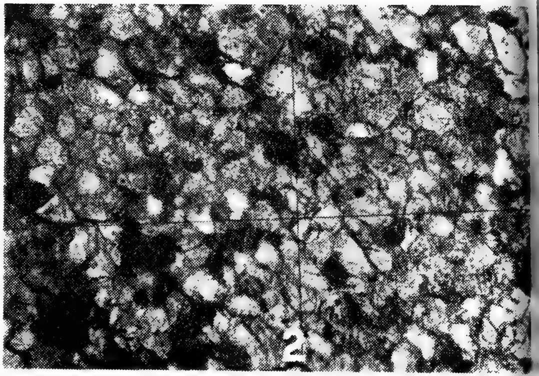
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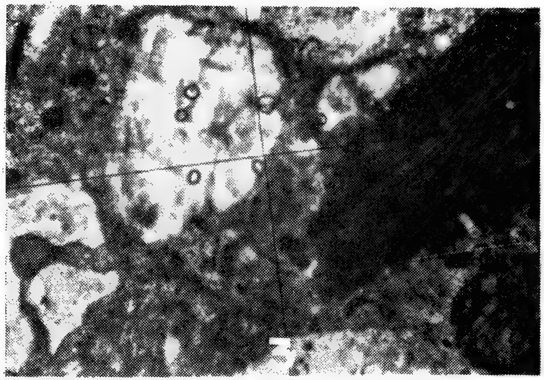
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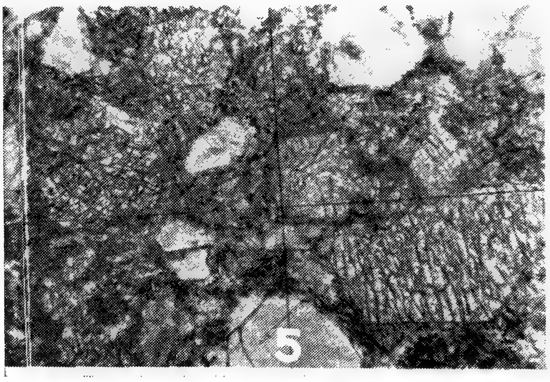
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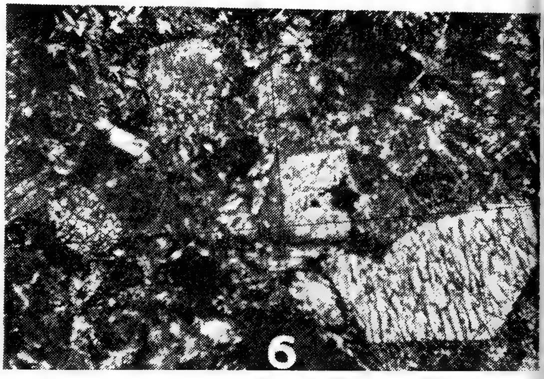
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Explanation of Plates I and II

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

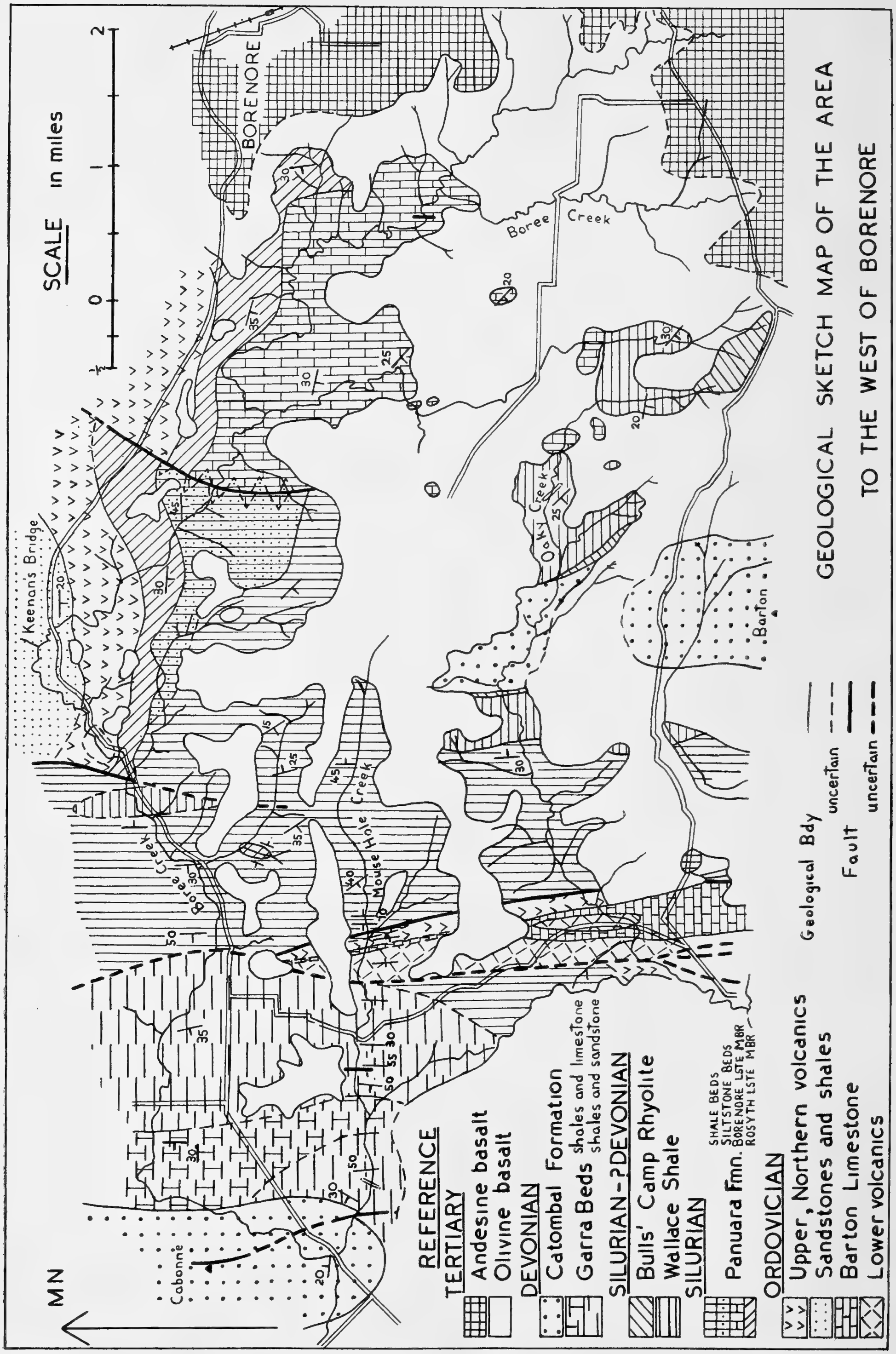

Fig. 1. Geological Sketch Map of the area to the West of Borenore

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,

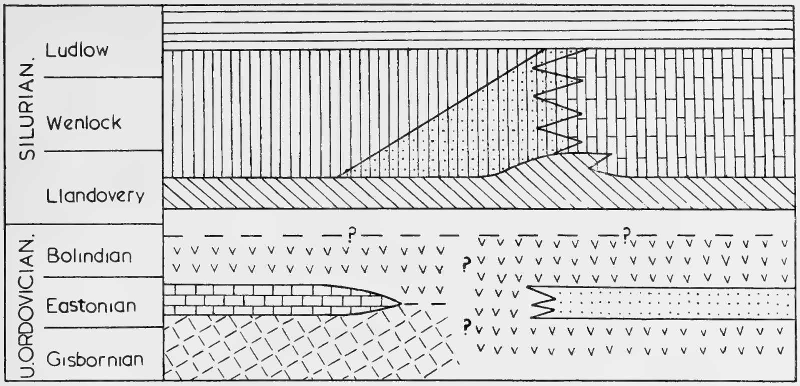

FIG. 2. Diagrammatic section showing the suggested relations of the Ordovician and Silurian rock units in the area to the west of Borenore. Reference as for Fig. 1

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 (1942) 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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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.

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.

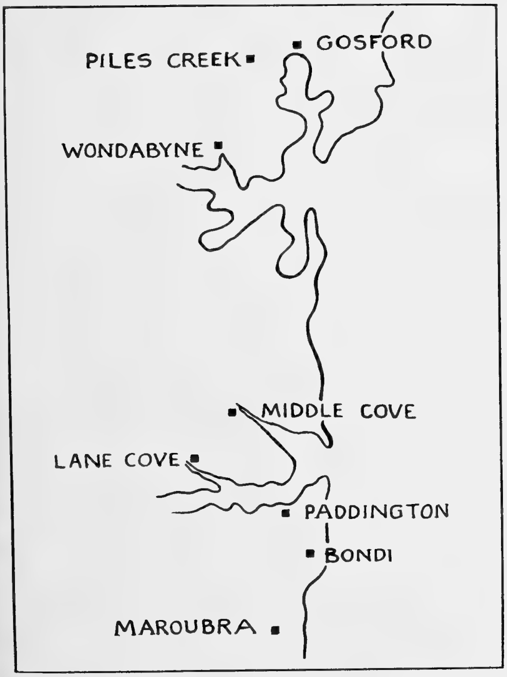

Fig. 1
Sydney-Gosford District, N.S.W.

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.

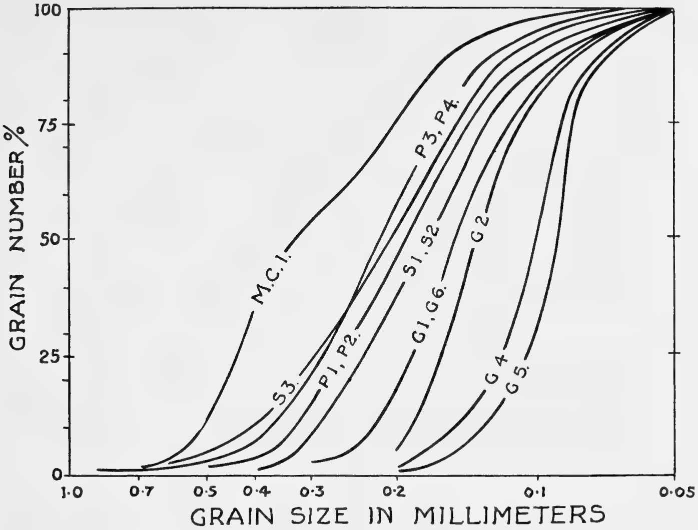

Fig. 2

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 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.

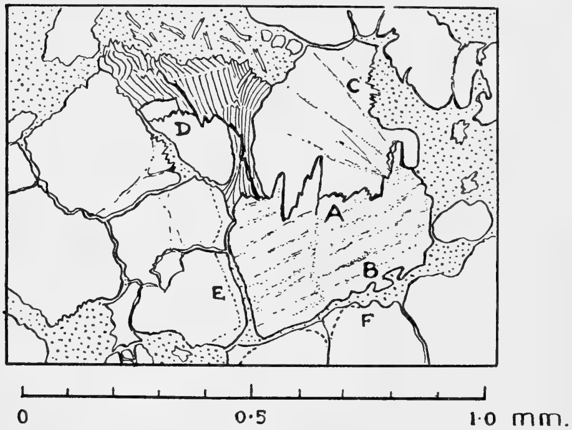

FIG. 3

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.)

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 semicircular 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 microporosity, 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

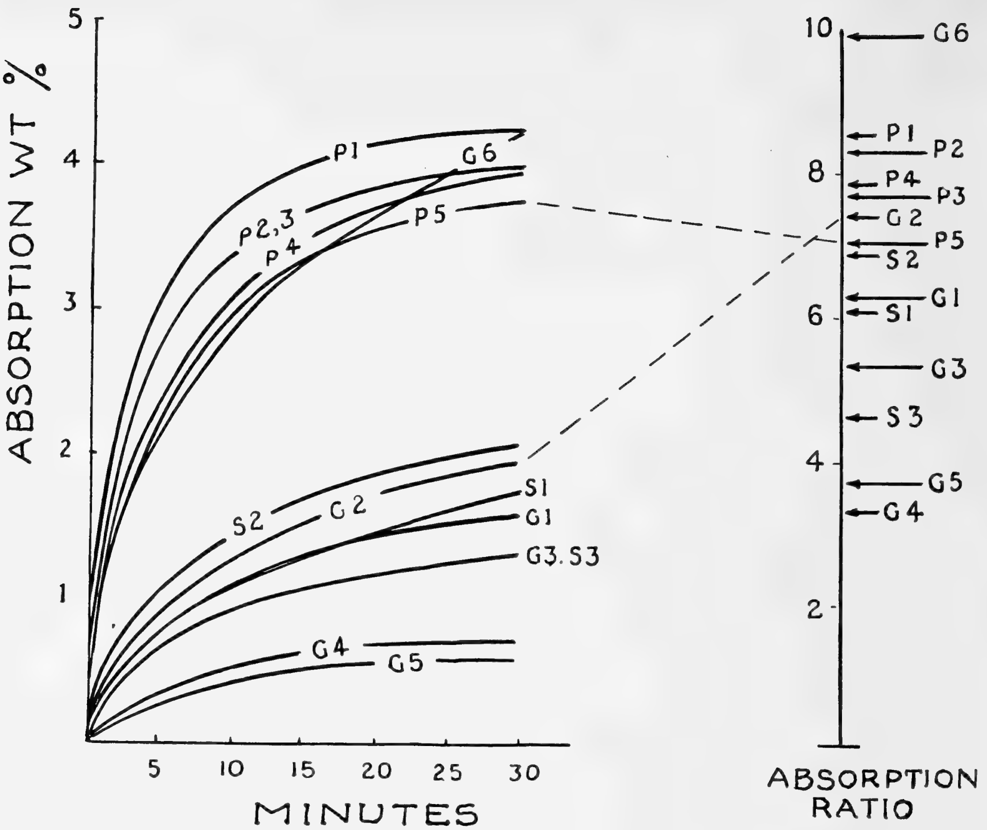

Fig. 4

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 G**6** 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

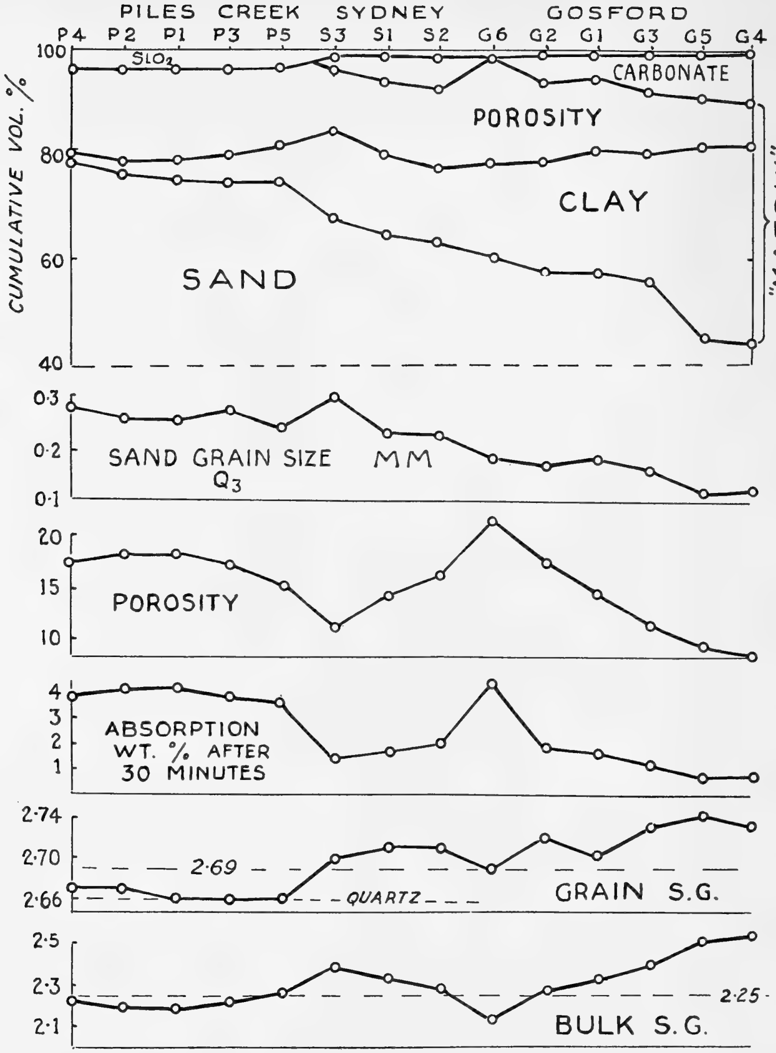

Fig. 5

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.

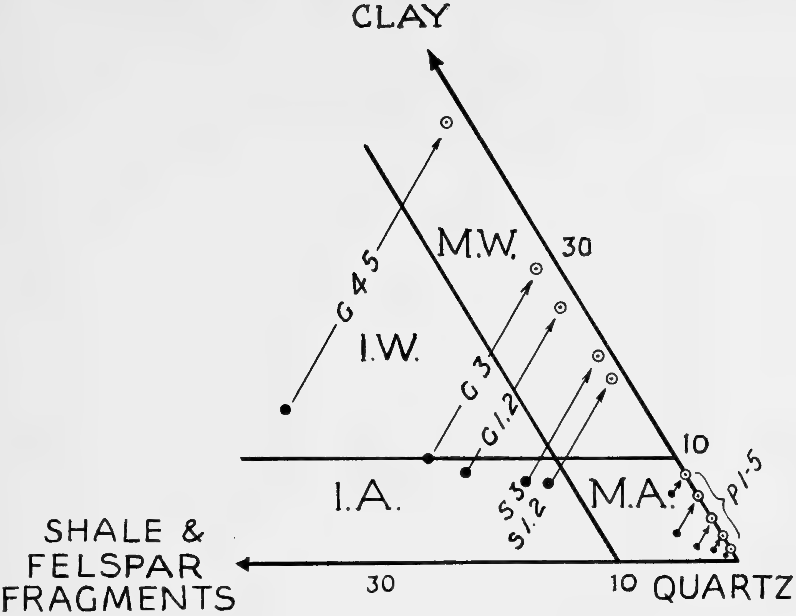

Fig. 6

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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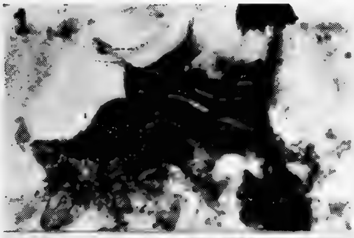
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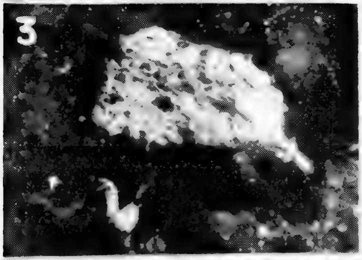
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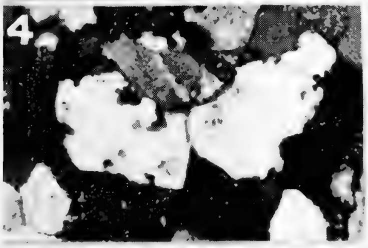
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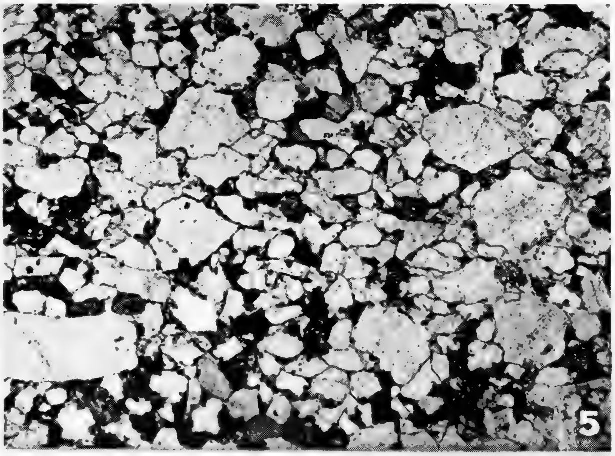
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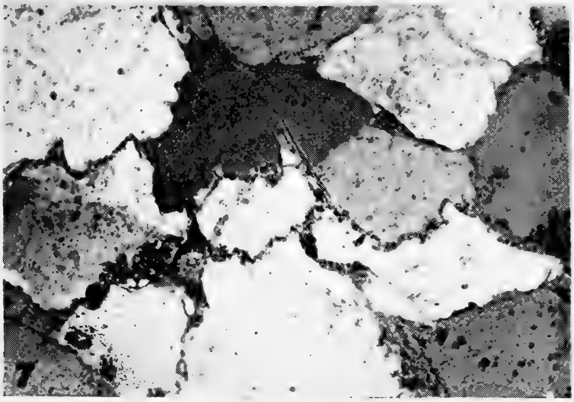
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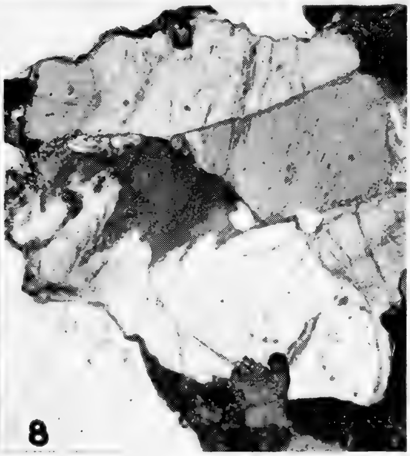
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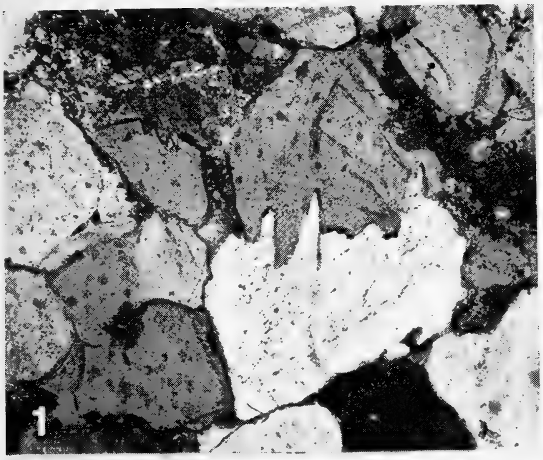
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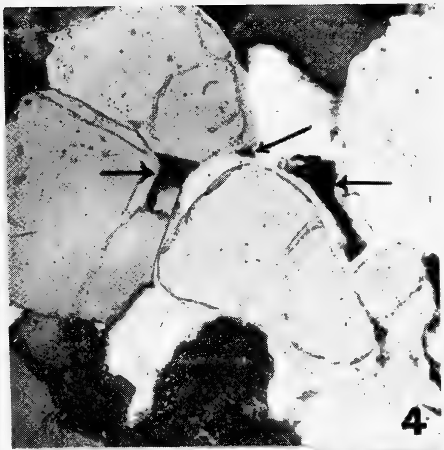
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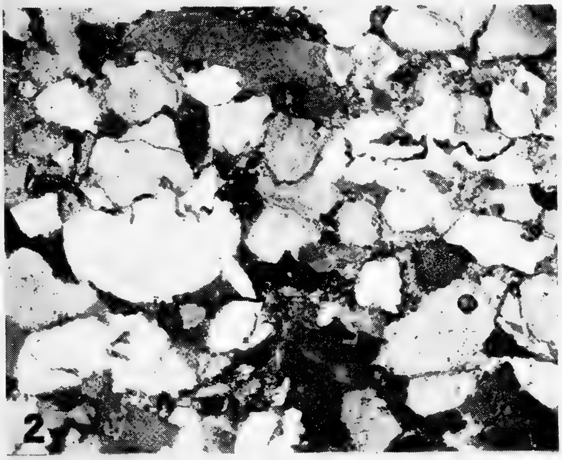
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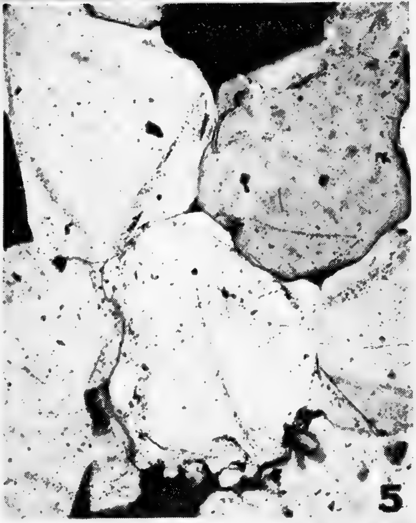
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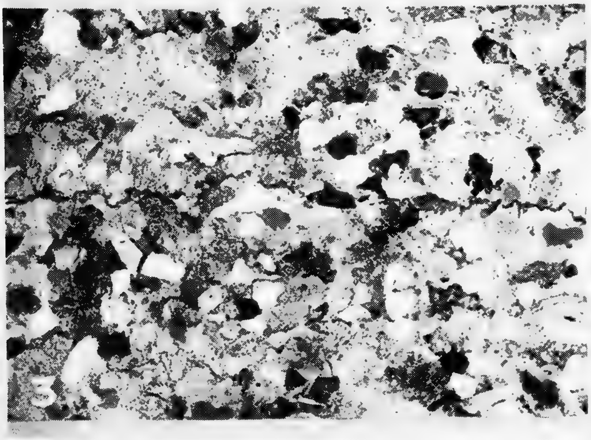
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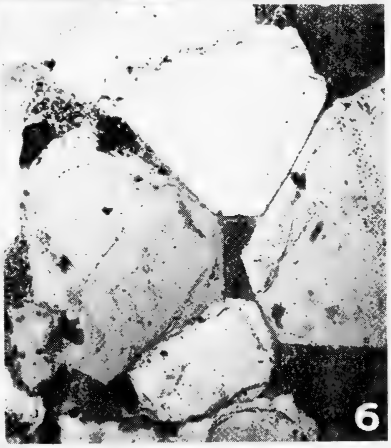
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Explanation of Plates I and II

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 $-1\tfrac{1}{2}\leqslant C<-\tfrac{1}{2}$.
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

$$F(z)=\int_0^\infty xJ_\nu(zx)f(x)dx \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1.1)$$

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

$$f(x)\sim Ax^ce^{-bx},\ b=B+i\beta,\ B\geqslant 0,\ c=C+i\gamma \quad\ldots\ldots\ldots\ldots \quad (1.3)$$

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

$$w=\tfrac{1}{2}\nu\pi+\tfrac{1}{4}\pi \qquad \text{(2.1)}$$

we know that

$$J_\nu(zx)=(\tfrac{1}{2}\pi zx)^{-\frac{1}{2}}\cos(zx-w)[1+0(|zx|^{-1})] \qquad \text{(2.2)}$$

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

$$N\colon\ -\tfrac{1}{2}\pi-\varphi<\arg(z-ib)<-\tfrac{1}{2}\pi+\varphi,\ 0<\varphi<\tfrac{1}{2}\pi,\ 0<|z-ib|<B.$$

Then we may write

$$\begin{aligned} F(z)&=\int_0^X xJ_\nu(zx)f(x)dx+\int_X^\infty xJ_\nu(zx)f(x)dx\\ &=Z_1(z) \qquad\qquad\quad +Z_2(z) \end{aligned} \qquad \text{(2.3)}$$

where X has been chosen so large that

$$f(x)=Ax^c e^{-bx}[1+p(x)] \qquad \text{(2.4)}$$

where $|p(x)|<\varepsilon<1$ for all $x>X$, and

$$J_\nu(zx)=(2\pi zx)^{-\frac{1}{2}}e^{iw}e^{-izx}[1+q(zx)] \qquad \text{(2.5)}$$

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

$$Z_2(z)=(2\pi z)^{-\frac{1}{2}}e^{iw}A[Z_3(z)+Z_4(z)] \qquad \text{(2.6)}$$

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

$$Z_3(z)\sim\Gamma(c+1\tfrac{1}{2})(b+iz)^{-c-1\frac{1}{2}} \qquad \text{(2.7)}$$

provided that $C>-1\frac{1}{2}$.

Writing $z=u+iv$,

$$|Z_4(z)|<3\varepsilon\int_X^\infty e^{-(B-v)x}x^{C+\frac{1}{2}}dx<3\varepsilon\Gamma(C+1\tfrac{1}{2})(B-v)^{-C-1\frac{1}{2}} \qquad \text{(2.8)}$$

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

$$z^{-\nu}F(z)\sim(2\pi)^{-\frac{1}{2}}A\,\Gamma(c+1\tfrac{1}{2})b^{-\nu-\frac{1}{2}}(b+iz)^{-c-1\frac{1}{2}} \qquad \text{(2.9)}$$

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

$$\int_1^\infty e^{-ux}x^{-1}dx\sim-\log u+\Gamma'(1)+0(u) \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.10)$$

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 $c>-1\frac{1}{2}$
$\qquad\sim-(2\pi)^{-\frac{1}{2}}Ab^{-\nu-\frac{1}{2}}\log(b\pm iz)$, 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

$$(-1)^m\left[\frac{d}{zdz}\right]^m z^{-\nu}F(z)=z^{-\nu-m}\int_0^\infty xJ_{\nu+m}(zx)x^mf(x)dx. \qquad \ldots\ldots\ldots\ldots \quad (3.1)$$

Thus $(d/zdz)^m z^{-\nu}F(z)$ 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

$$x^p f(x) \sim A x^{c+p} e^{-bx} \text{ with } C+p > -1\tfrac{1}{2} \quad \ldots\ldots\ldots\ldots \quad (3.2)$$

as $x \to \infty$. Then by Theorem 2

$$\left[\frac{d}{zdz}\right]^p z^{-\nu} F(z) \sim (2\pi)^{\frac{1}{2}} (-1)^p A \Gamma(c+p+1\tfrac{1}{2}) b^{-\nu-p-\frac{1}{2}} (b \pm iz)^{-c-p-1\frac{1}{2}} \quad \ldots\ldots \quad (3.3)$$

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

$$\left[\frac{d}{zdz}\right]^{p-1} z^{-\nu} F(z) \sim (2\pi)^{-\frac{1}{2}} (-1)^p A b^{-\nu-p+\frac{1}{2}} \log (b \pm iz) \quad \ldots\ldots\ldots\ldots \quad (3.4)$$

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 $x\to\infty$, Re $k<-1\frac{1}{2}$.

We will derive some formulae needed later.

From the known formula

$$\int_0^\infty x^{p-1}\cos uxdx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p),\ 0<\text{Re}\, p<1$$

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 $-1<\text{Re}\, p<1$ provided that when $p=0$, we replace the right side by $\Gamma'(1)-\log u$.

Thus as $u\to0+$,

$$\int_1^\infty x^{p-1}\cos uxdx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p)-p^{-1}+0(u^2)$$

if $-1<\text{Re}\, p<1$ and $p\neq0$, and

$$\int_1^\infty x^{-1}\cos uxdx=-\log u+\Gamma'(1)+0(u^2).$$

Similarly from

$$\int_0^\infty x^{p-1}\sin uxdx=u^{-p}\Gamma(p)\sin(\tfrac{1}{2}\pi p),\ -1<\text{Re}\, p<1$$

we obtain that as $u\to0+$

$$\int_1^\infty x^{p-1}\sin uxdx=u^{-p}\Gamma(p)\sin(\tfrac{1}{2}\pi p)+0(u)$$

if $-1<\text{Re}\, p<1$ and $p\neq0$, and

$$\int_1^\infty x^{-1}\sin uxdx=\tfrac{1}{2}\pi+0(u).$$

Combining the results, we have as $u\to0+$

$$\int_1^\infty x^{p-1}\cos(ux+\alpha)dx=u^{-p}\Gamma(p)\cos(\tfrac{1}{2}\pi p+\alpha)-p^{-1}\cos\alpha+0(u) \quad \ldots.\ (5.2a)$$

$-1<\text{Re}\, p<1$, $p\neq0$, 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

$$\begin{aligned}Z_2(z)&=\int_X^\infty Ax^{c+1}\cos(\beta x+\zeta)J_\nu(zx)dz+\int_X^\infty xJ_\nu(zx)f_1(x)dx\\ &= \qquad Z_3(z) \qquad\qquad + \qquad Z_4(z) \qquad \ldots\ldots\ (5.3)\end{aligned}$$

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

$$(\tfrac{1}{2}\pi z)^{\frac{1}{2}} Z_3(z) = Z_5(z) + Z_6(z) + Z_7(z) \quad \ldots\ldots \quad (5.4)$$

where

$$Z_5(z) = \tfrac{1}{2}A \int_X^\infty x^{c+\frac{1}{2}} \cos[(\beta - z)x + w + \zeta]\,dx \quad \ldots\ldots \quad (5.5a)$$

$$Z_6(z) = \tfrac{1}{2}A \int_X^\infty x^{c+\frac{1}{2}} \cos[(\beta + z)x + w + \zeta]\,dx \quad \ldots\ldots \quad (5.5b)$$

and

$$Z_7(z) = A \int_X^\infty x^{c+\frac{1}{2}} \cos(\beta x + \zeta) p(xz)\,dx. \quad \ldots\ldots \quad (5.5c)$$

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 $\gamma \neq 0$,

$$Z_5(z) = \tfrac{1}{2}A\Gamma(i\gamma)\cos(w + \zeta \mp \tfrac{1}{2}i\gamma)|z - \beta|^{-i\gamma} - \tfrac{1}{2}A(i\gamma)^{-1}X^{i\gamma}\cos(w + \zeta) + 0(|z - \beta|) \quad .. \quad (5.6)$$

as $z \to \beta \pm$.

when $\gamma = 0$

$$Z_5(z) = -\tfrac{1}{2}A\cos(w + \zeta)[\log|X(z - \beta)| - \Gamma'(1)] \pm \tfrac{1}{4}A\pi\sin(w + \zeta) + 0(|z - \beta|) \quad \ldots\ldots \quad (5.7)$$

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 $\mathrm{Re}\, k < -1\tfrac{1}{2}$,
(*c*) $c = -1\tfrac{1}{2} + i\gamma$

then the only discontinuity of $F(z)$ is at $z = \beta$, and

(i) when $\gamma \neq 0$,

$$F(z) \sim (2\pi\beta)^{-\frac{1}{2}} A\Gamma(i\gamma)\cos(w + \zeta \mp \tfrac{1}{2}i\gamma) + P(\beta) \quad \ldots\ldots \quad (5.8)$$

($P(\beta)$ being independent of z) as $z \to \beta \pm$;

(ii) when $\gamma = 0$ and $\cos(w + \zeta) \neq 0$,

$$F(z) \sim -(2\pi\beta)^{-\frac{1}{2}} A\cos(w + \zeta)\log|z - \beta| \quad \ldots\ldots \quad (5.9)$$

as $z \to \beta \pm$;

(iii) when $\gamma = 0$ and $\cos(w + \zeta) = 0$

$$F(z) \text{ has saltus of } A(\pi/2\beta)^{\frac{1}{2}}\sin(w + \zeta) \text{ at } z = \beta. \quad \ldots\ldots \quad (5.10)$$

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 $-1\tfrac{1}{2}<\operatorname{Re} c<-\tfrac{1}{2}$. The corresponding theorem is

Theorem **6** :—If in the assumptions of Theorem 5, (c) is replaced by $-1\tfrac{1}{2}<\operatorname{Re} c<-\tfrac{1}{2}$, 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 $\cos(\tfrac{1}{2}c\pi+\tfrac{3}{4}\pi\mp w\mp\zeta)$ does not vanish. If both values of $\cos(\tfrac{1}{2}c\pi+\tfrac{3}{4}\pi\mp w\mp\zeta)$ 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

$$\begin{aligned} y&=-\varepsilon x \quad \text{for } -l\leqslant x\leqslant 0 \\ y&=\varepsilon x \quad \text{for } \ \ 0\leqslant x\leqslant l \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

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*).

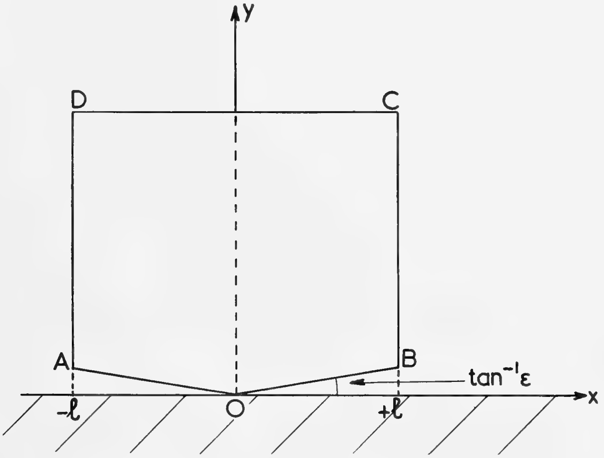

FIG. 1.

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.

$$X_x+Y_y=2[\Phi(z)+\overline{\Phi(z)}] \quad \ldots\ldots\ldots\ldots \quad (2)$$

$$Y_y-X_x+2iX_y=2[\bar{z}\Phi'(z)+\Psi(z)] \quad \ldots\ldots\ldots\ldots \quad (3)$$

$$2\mu(u+iv)=\varkappa\varphi(z)-z\overline{\varphi'(z)}+\overline{\psi(z)} \quad \ldots\ldots\ldots\ldots \quad (4)$$

where $\Phi(z)=\varphi'(z)=\dfrac{d\varphi}{dz}$; $\Psi(z)=\psi'(z)$, 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 $|z|$,

$$\Phi(z)=-\frac{X+iY}{2\pi z}+o\left(\frac{1}{z}\right) \quad \ldots\ldots\ldots\ldots \quad (5)$$

$$\Psi(z)=\frac{X-iY}{2\pi z}+o\left(\frac{1}{z}\right) \quad \ldots\ldots\ldots\ldots \quad (6)$$

By defining $\Phi(z)$ in the upper half-plane as

$$\Phi(z)=-\bar{\Phi}(z)-z\bar{\Phi}'(z)-\Psi(z) \text{ for } z \text{ in } S^+ \quad \ldots\ldots\ldots\ldots \quad (7)$$

(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

$$\Psi(z)=-\Phi(z)-\bar{\Phi}(z)-z\Phi'(z) \text{ for } z \text{ in } S^- \quad \ldots\ldots\ldots\ldots \quad (8)$$

and hence equations (2) and (3) can be rewritten in terms of one arbitrary function $\Phi(z)$ thus:

$$X_x+Y_y=2[\Phi(z)+\bar{\Phi}(\bar{z})] \quad \ldots\ldots\ldots\ldots \quad (9)$$

$$Y_y-X_x+2iX_y=2[(\bar{z}-z)\Phi'(z)-\Phi(z)-\bar{\Phi}(z)] \quad \ldots\ldots\ldots\ldots \quad (10)$$

Adding equations (9) and (10) and taking the complex conjugate, we have

$$Y_y-iX_y=\Phi(z)-\Phi(\bar{z})+(z-\bar{z})\bar{\Phi}'(\bar{z}) \quad \ldots\ldots\ldots\ldots \quad (11)$$

Differentiating equation (4) partially with respect to x and substituting for $\Psi(z)$ given by equation (8) we obtain

$$2\mu(u'+iv')=\varkappa\Phi(z)+\Phi(\bar{z})-(z-\bar{z})\bar{\Phi}'(\bar{z}) \quad \ldots\ldots\ldots\ldots \quad (12)$$

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

$$\overline{\Phi}(z)=-\Phi(z) \qquad (18)$$

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

$$2(u'^- - iv'^-)=\varkappa\overline{\Phi}^+(t)+\overline{\Phi}^-(t) \qquad (20)$$

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

$$\Phi^+(t)+\Phi^-(t)=\frac{4\mu i f'(t)}{\varkappa+1} \text{ on } ab \qquad (21)$$

(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

$$\begin{aligned} v^- &= -\varepsilon t + c \quad \text{for} \quad -l \leqslant t \leqslant 0 \\ \text{and } v^- &= +\varepsilon t + c \quad \text{for} \quad 0 \leqslant t \leqslant l \end{aligned} \qquad \ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

The function $\Phi(z)$ can be determined from equation (22) in which we must put

$$\begin{aligned} f'(t) &= -\varepsilon \quad \text{on} \quad -l \leqslant t < 0 \\ &= +\varepsilon \quad \text{on} \quad 0 < t \leqslant l. \end{aligned}$$

Clearly $f'(t)$ satisfies the Hölder condition on $(-l,l)$ except at the origin.
Therefore

$$\Phi(z) = \frac{2\mu}{\pi(\varkappa+1)(l^2-z^2)^{\frac{1}{2}}} F(z) + \frac{P_0}{2\pi(l^2-z^2)^{\frac{1}{2}}} \qquad \ldots\ldots\ldots\ldots \quad (28)$$

where

$$F(z) = -\varepsilon \int_{-l}^{0} \frac{(l^2-t^2)^{\frac{1}{2}}}{t-z} dt + \varepsilon \int_{0}^{l} \frac{(l^2-t^2)^{\frac{1}{2}}}{t-z} dt \qquad \ldots\ldots\ldots\ldots \quad (29)$$

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

$$\frac{F(z)}{\varepsilon} = \int_0^l \frac{(l^2-t^2)^{\frac{1}{2}} 2t\,dt}{t^2-z^2} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

We let

$$z^2 = l^2 + \zeta^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (31)$$

and we make the change of variable

$$t^2 = l^2 - \zeta^2 u^2 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

to obtain

$$\frac{F(z)}{\varepsilon} = \int_{l/\zeta}^{0} \frac{\zeta u.\, -2\zeta^2 u\,du}{-\zeta^2(1+u^2)} = -2\zeta \int_0^{l/\zeta} \frac{u^2 du}{1+u^2} = -2l + 2\zeta \tan^{-1}(l/\zeta) \qquad \ldots\ldots \quad (33)$$

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

$$F(z) = \varepsilon[-2l + 2(z^2-l^2)^{\frac{1}{2}} \tan^{-1}\{l(z^2-l^2)^{-\frac{1}{2}}\}] \qquad \ldots\ldots\ldots\ldots \quad (34)$$

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

$$F(z) = \varepsilon\left[-2l + 2i(z^2-l^2)^{\frac{1}{2}} \log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} + \pi(z^2-l^2)^{\frac{1}{2}}\right] \qquad \ldots\ldots\ldots\ldots \quad (35)$$

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* 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

$$\begin{aligned} F^+(t)-F^-(t) &= -2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } -l<t<0 \\ &\quad +2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } \quad 0<t<l \end{aligned} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(36)}$$

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

$$\begin{aligned} f(t) &= -2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } -l<t<0 \\ &= +2\pi i\varepsilon(l^2-t^2)^{\frac{1}{2}} \text{ for } \quad 0<t<l. \end{aligned}$$

(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.

$$\begin{aligned} \overline{\int} &= \varepsilon\overline{\int}_{0}^{l}\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2} \\ &= \lim_{\delta\to 0}\ \varepsilon\int_{0}^{t_0-\delta}\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2}+\lim_{\delta\to 0}\ \varepsilon\int_{t_0+\delta}^{l}\frac{(l^2-t^2)^{\frac{1}{2}}2tdt}{t^2-t_0^2} \end{aligned}$$

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

$$\begin{aligned} I &= \int_{l/\zeta}^{(l^2-P^2)^{\frac{1}{2}}/\zeta}\frac{\zeta u.-2\zeta^2udu}{\zeta^2(1-u^2)}+\int_{(l^2-Q^2)^{\frac{1}{2}}/\zeta}^{0}\frac{\zeta u.-2\zeta^2udu}{\zeta^2(1-u^2)} \\ &= 2\zeta\left[-\frac{l}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+l}{\zeta-l}\right] \\ &\qquad -2\zeta\left[-\frac{(l^2-P^2)^{\frac{1}{2}}}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+(l^2-P^2)^{\frac{1}{2}}}{\zeta-(l^2-P^2)^{\frac{1}{2}}}\right] \\ &\qquad +2\zeta\left[-\frac{(l^2-Q^2)^{\frac{1}{2}}}{\zeta}+\tfrac{1}{2}\log\frac{\zeta+(l^2-Q^2)^{\frac{1}{2}}}{\zeta-(l^2-Q^2)^{\frac{1}{2}}}\right]. \end{aligned}$$

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 $\log |t'|$,

$$F^+(t') = \varepsilon[-2l - 2(l^2 - t'^2)^{\frac{1}{2}}\{\log [l - (l^2 - t'^2)^{\frac{1}{2}}[-\log t'\} - i\pi(l^2 - t'^2)^{\frac{1}{2}}] \quad \ldots. \quad (38)$$

The boundary values $F^-(t)$ and $F^-(t')$ may be written down from equation 68.3 (Muskhelishvili, 1953*a*) and the foregoing, thus

$$F^-(t) = \varepsilon[-2l - 2(l^2 - t^2)^{\frac{1}{2}}\{\log [l - (l^2 - t^2)^{\frac{1}{2}}] - \log t\} - i\pi(l^2 - t^2)^{\frac{1}{2}}] \quad \ldots\ldots\ldots \quad (39)$$

$$F^-(t') = \varepsilon[-2l - 2(l^2 - t'^2)^{\frac{1}{2}}\{\log [l - (l^2 - t'^2)^{\frac{1}{2}}] - \log t'\} + i\pi(l^2 - t'^2)^{\frac{1}{2}}] \quad \ldots. \quad (40)$$

In the sequal the boundary values of $(z^2 - l^2)^{\frac{1}{2}}$ are required. We define (see Fig. 2)

$$(z-l)^{\frac{1}{2}} \text{ as } r_1^{\frac{1}{2}} e^{i\alpha/2}$$
$$(z+l)^{\frac{1}{2}} \text{ as } r_2^{\frac{1}{2}} e^{i\beta/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (41)$$

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'^- $(-l < t' < 0)$: $(z^2 - l^2)^{\frac{1}{2}} = (l^2 - t'^2)^{\frac{1}{2}} e^{i3\pi/2}$.

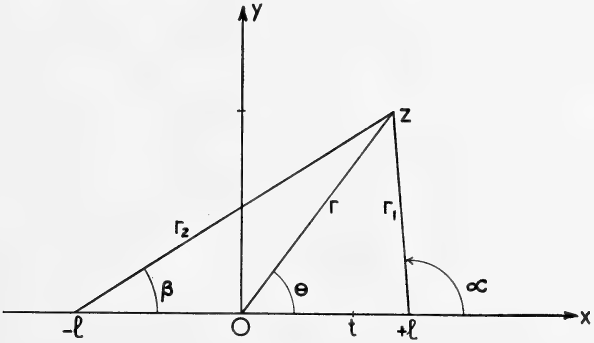

FIG. 2.

Returning now to equation (28), we can write

$$\Phi(z)=\frac{2\mu\varepsilon}{\pi(\varkappa+1)(l^2-z^2)^{\frac{1}{2}}}\left[-2l+2i(z^2-l^2)^{\frac{1}{2}}\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\}+\pi(z^2-l^2)^{\frac{1}{2}}\right]+\frac{P_0}{2\pi(l^2-z^2)^{\frac{1}{2}}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (42)$$

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

$$A=\frac{iP_0}{2\pi}-\frac{4\mu l\varepsilon i}{\pi(\varkappa+1)};\quad B=\frac{2\mu\varepsilon i}{\varkappa+1};\quad C=\frac{4\mu\varepsilon}{\pi(\varkappa+1)}; \quad \ldots\ldots\ldots\ldots\ldots (44)$$

so that

$$\Phi(z)=\frac{A}{(z^2-l^2)^{\frac{1}{2}}}+B-C\log\left\{\frac{l+i(z^2-l^2)^{\frac{1}{2}}}{z}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (45)$$

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 $0<t<l$,

$$\Phi^+(t)=\frac{A}{i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log[l-(l^2-t^2)^{\frac{1}{2}}]-\log t\} \quad \ldots\ldots\ldots\ldots\ldots (46)$$

$$\Phi^-(t)=\frac{A}{-i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log t-\log[l-(l^2-t^2)^{\frac{1}{2}}]\} \quad \ldots\ldots\ldots\ldots (47)$$

so that

$$\Phi^+(t)-\Phi^-(t)=\frac{2A}{i(l^2-t^2)^{\frac{1}{2}}}+2C\log\frac{t}{l-(l^2-t^2)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (48)$$

For $-l<t<0$, if $\log t=\log|t|$,

$$\Phi^+(t)=\frac{A}{i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log[l-(l^2-t^2)^{\frac{1}{2}}]-\log t+i\pi\} \quad \ldots\ldots\ldots\ldots (49)$$

$$\Phi^-(t)=\frac{A}{-i(l^2-t^2)^{\frac{1}{2}}}+B-C\{\log t-\log[l-(l^2-t^2)^{\frac{1}{2}}]+i\pi\} \quad \ldots\ldots\ldots (50)$$

so that

$$\Phi^+(t)-\Phi^-(t)=\frac{2A}{i(l^2-t^2)^{\frac{1}{2}}}+2C\log\frac{t}{l-(l^2-t^2)^{\frac{1}{2}}} \quad \ldots\ldots\ldots\ldots\ldots\ldots (51)$$

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

$$P_0 \geqslant \frac{8\mu l\varepsilon}{\varkappa+1} \quad \dots\dots \quad (53)$$

$P(t)$ 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

$$P_0 = \frac{8\mu l\varepsilon}{\varkappa+1} \quad \dots\dots \quad (54)$$

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

$$P_0 = \frac{8\mu l'\varepsilon}{\varkappa+1} \quad \dots\dots \quad (55)$$

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 $$\bar{\Phi}(z) = \overline{\Phi(\bar{z})} = \frac{\bar{A}}{(z^2-l^2)^{\frac{1}{2}}} + \bar{B} - \bar{C} \log \left\{ \frac{l-i(z^2-l^2)^{\frac{1}{2}}}{z} \right\} \quad \dots\dots \quad (56)$$

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, $$\bar{\Phi}(\bar{z}) = \frac{-A}{(\bar{z}^2-l^2)^{\frac{1}{2}}} - B - C \log \left\{ \frac{l-i(\bar{z}^2-l^2)^{\frac{1}{2}}}{\bar{z}} \right\},$$ 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

$$X_x + Y_y = \frac{4}{r_1^{\frac{1}{2}} r_2^{\frac{1}{2}}} \left[\frac{P_0}{2\pi} - \frac{4\mu l\varepsilon}{\pi(\varkappa+1)} \right] \sin\frac{\alpha+\beta}{2} - \frac{8\mu\varepsilon}{\pi(\varkappa+1)} \left\{ \frac{l^2 - 2r_1^{\frac{1}{2}} r_2^{\frac{1}{2}} \sin\frac{\alpha+\beta}{2} + r_1 r_2}{r^2} \right\} \quad \dots\dots \quad (57)$$

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

$$Y_y - X_x = \frac{-P_0 r^2}{r_1^{3/2} r_2^{3/2}}\left[2 \sin\theta \cos\frac{2\theta - 3(\alpha+\beta)}{2}\right] + \frac{8\mu l^3 \varepsilon}{\pi(\varkappa+1) r_1^{3/2} r_2^{3/2}}\left[2 \sin\theta \cos\frac{2\theta + 3(\alpha+\beta)}{2}\right] \quad \text{.................. (58)}$$

$$X_y = \frac{P_0 r^2}{r_1^{3/2} r_2^{3/2}}\left[\sin\theta \sin\frac{3(\alpha+\beta) - 2\theta}{2}\right] - \frac{8\mu l^3 \varepsilon}{\pi(\varkappa+1) r_1^{3/2} r_2^{3/2}}\left[\sin\theta \sin\frac{3(\alpha+\beta) + 2\theta}{2}\right] \quad \text{.................... (59)}$$

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

$$T_{\max} = \frac{\sin\theta}{\pi r_1^{3/2} r_2^{3/2}}\left[P_0^2 r^4 + \frac{64\mu^2 l^6 \varepsilon^2}{(\varkappa+1)^2} - \frac{16 P_0 r^2 \mu l^3 \varepsilon \cos 2\theta}{\varkappa+1}\right]^{\frac{1}{2}} \quad \text{.............. (61)}$$

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

$$X_x+Y_y=-\frac{8\mu\varepsilon}{\pi(\varkappa+1)}\log\left\{\frac{l'^2-2r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}\sin\dfrac{\alpha+\beta}{2}+r_1r_2}{r^2}\right\} \quad \ldots\ldots\ldots\ldots (64)$$

$$Y_y-X_x=-\frac{8\mu l'\varepsilon}{\pi(\varkappa+1)r_1^{\frac{1}{2}}r_2^{\frac{1}{2}}}\left\{2\sin\theta\cos\frac{\alpha+\beta+2\theta}{2}\right\} \quad \ldots\ldots\ldots\ldots (65)$$

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. 436, 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.

Vice-Presidents: H. A. J. Donegan, M.Sc.; F. N. Hanlon, B.Sc.; A. F. A. Harper, M.Sc.; F. D. McCarthy, Dip.Anthr.

Hon. Secretaries: Ida A. Browne, D.Sc.; H. W. Wood, M.Sc.

Hon. Treasurer: C. L. Adamson, B.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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Notice to Authors

General. Manuscripts should be addressed to the Honorary Secretaries, Royal Society of New South Wales, Science House, 157 Gloucester Street, Sydney. Two copies of each manuscript are required: the original typescript and a carbon copy.

Papers should be prepared according to the general style adopted in this Journal. They should be as concise as possible, consistent with adequate presentation. Particular attention should be given to clarity of expression and good prose style.

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.

Tables. Tabular matter should be typewritten on separate sheets, arranged for the most economical presentation on the printed page. Column lines should *not* be ruled in. Units of measurement should always be indicated in the headings of the columns or rows to which they apply.

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.

Reprints. Authors receive 50 copies of each paper free. Additional copies may be purchased provided they are ordered by the author when returning galley-proofs.

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Royal Society of New South Wales

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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 coalfields, 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.

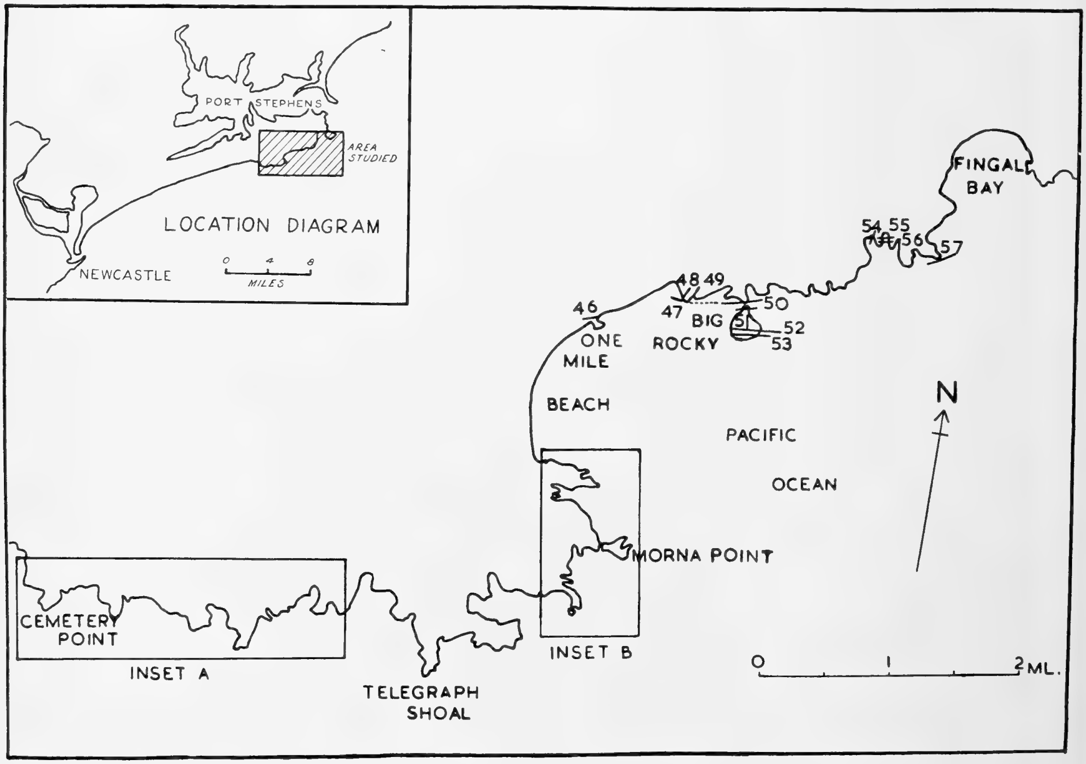

Fig. 1

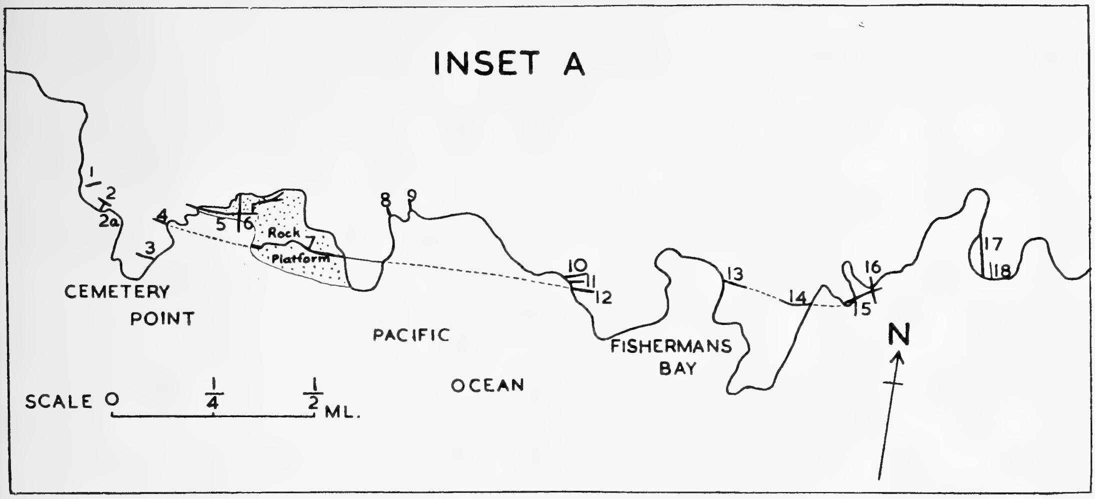

Fig. 1a

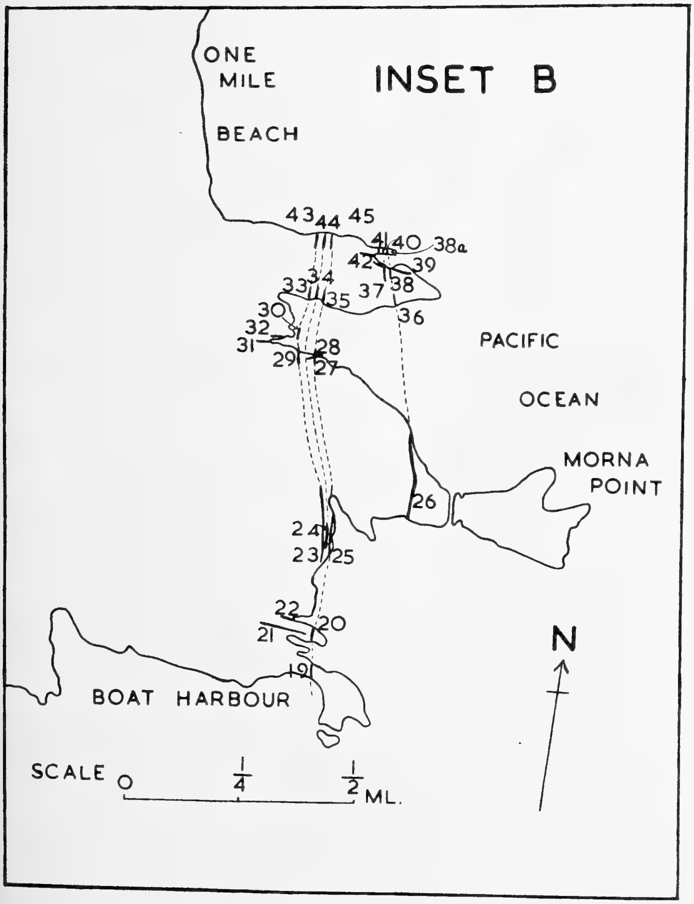

Fig. 1b

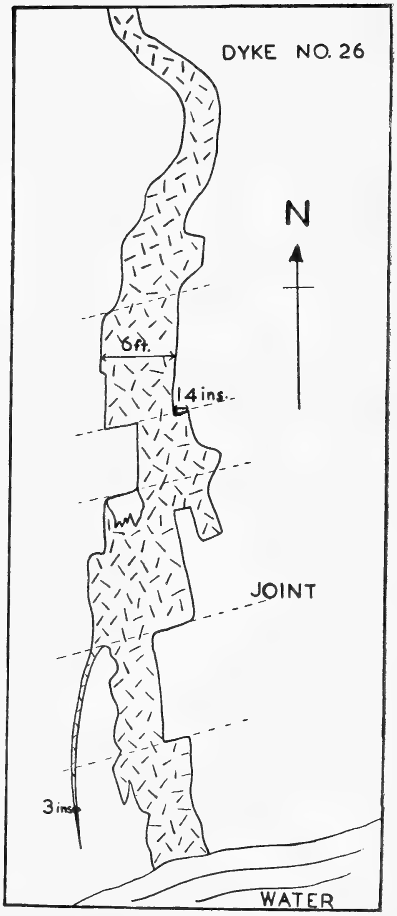

Fig. 2

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

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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).

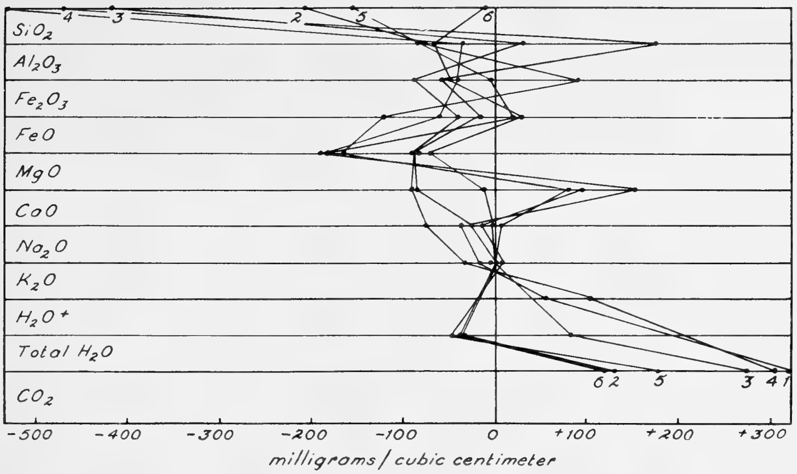

FIG. 1

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

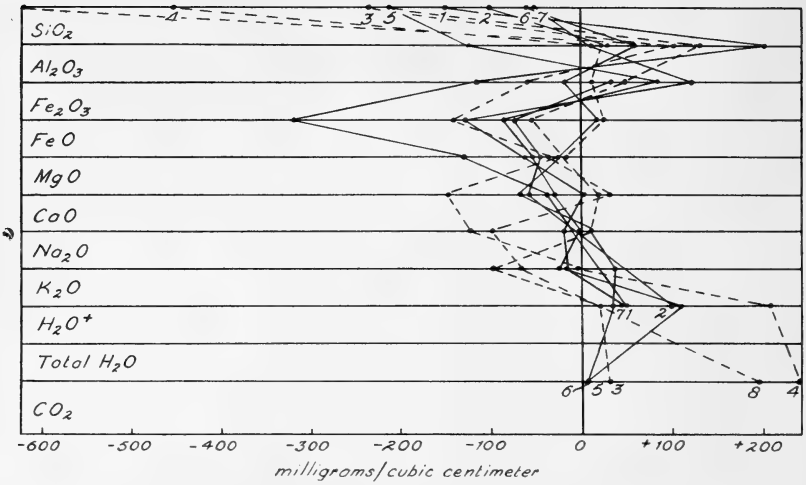

FIG. 2

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 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.

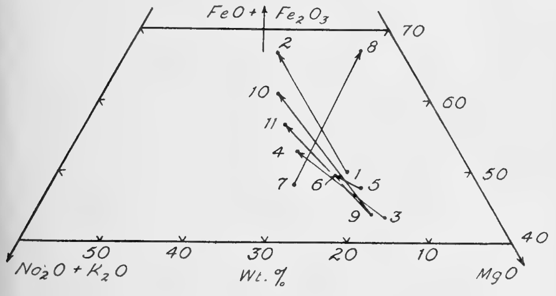

Fig. 3

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.

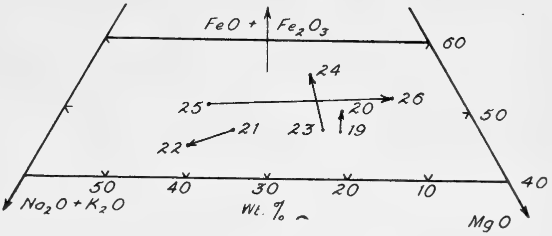

Fig. 4

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.

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-

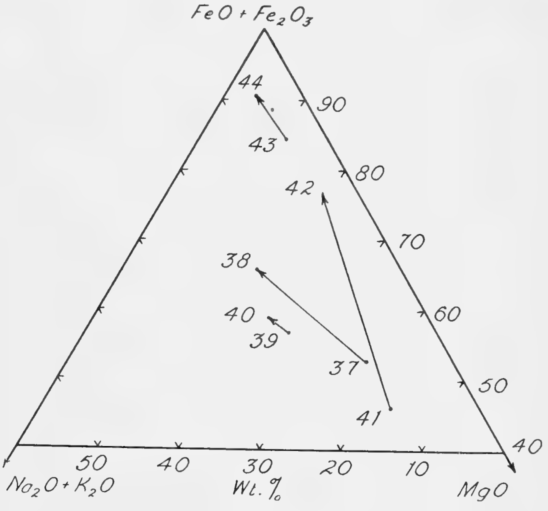

Fig. 5

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.

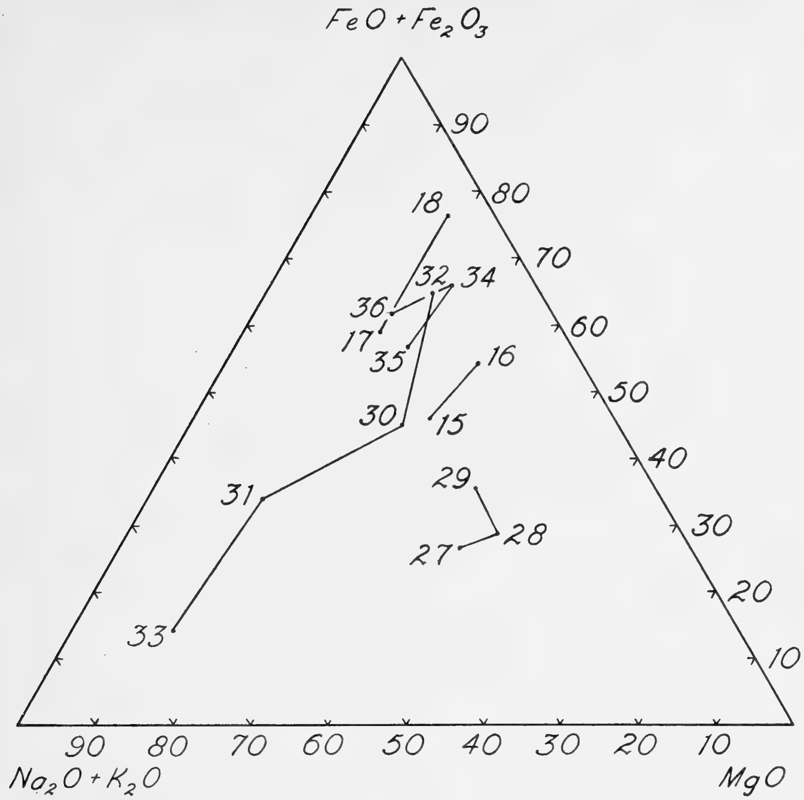

FIG. 6

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

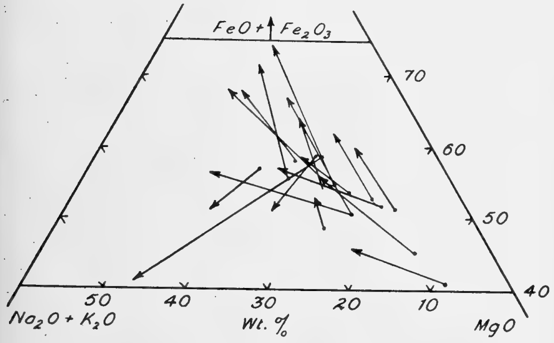

FIG. 7

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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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 0s·023 sec δ in right ascension and 0″·27 in declination. This corresponds to probable errors for the mean of the two results from one plate of 0s·010 sec δ and 0″·11. 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. ″
127	799	0·262296	18·956	30·34
	810	0·408063	54·870	00·19
	832	0·329640	19·738	43·28
128	807	0·252115	10·506	08·66
	808	0·567175	40·618	17·27
	839	0·180710	09·879	50·68
129	790	0·275155	36·139	33·30
	810	0·344120	54·869	00·19
	1354	0·380725	22·688	43·17
130	789	0·323612	32·818	37·08
	807	0·331896	10·506	08·66
	1371	0·344492	31·573	38·19
131	1279	0·384208	44·389	26·27
	1282	0·262472	13·830	00·89
	1316	0·353321	21·990	50·47
132	1256	0·277898	47·377	06·77
	1301	0·498286	39·165	27·86
	1309	0·223816	35·335	52·91
133	1183	0·357327	55·144	58·78
	1231	0·274704	31·249	53·50
	1235	0·367968	10·886	25·22
134	1202	0·246742	56·504	50·52
	1203	0·419014	12·741	01·77
	1234	0·334244	57·839	11·37
135	998	0·326942	48·560	48·65
	1041	0·202966	09·311	21·25
	1203	0·470092	12·741	01·77
136	1004	0·507902	31·531	51·11
	1198	0·289276	35·422	51·33
	1235	0·202822	10·886	25·22
137	965	0·202736	15·313	21·06
	982	0·410409	52·849	02·27
	1178	0·386855	26·236	04·73
138	973	0·160524	18·322	26·77
	995	0·389796	29·991	51·70
	1165	0·449680	03·767	37·62
139	7940	0·316232	34·417	21·13
	7957	0·402090	41·966	43·97
	7969	0·281678	09·829	04·03
140	7937	0·245208	49·552	01·16
	7956	0·482918	18·337	53·66
	7974	0·271874	48·566	37·96
141	8010	0·454466	44·716	53·02
	8029	0·174638	16·240	35·38
	8045	0·370896	27·023	54·20
142	8014	0·288110	05·913	59·76
	8022	0·409778	38·953	51·59
	8048	0·302112	45·936	40·62
143	8031	0·274490	48·164	33·09
	8048	0·415684	45·936	40·62
	8058	0·309825	15·137	56·21
144	8028	0·166152	23·159	39·07
	8039	0·370076	55·074	38·90
	8066	0·463772	16·559	45·55
145	8039	0·247520	55·074	38·91
	8048	0·425922	45·936	40·62
	8060	0·326558	25·434	06·85
146	8031	0·252154	48·164	33·08
	8050	0·463806	45·039	06·51
	8058	0·284040	15·137	56·24
147	8045	0·457703	27·023	54·21
	8065	0·251828	11·030	59·70
	8078	0·290470	00·446	25·93
148	8052	0·278657	04·381	08·85
	8054	0·475086	08·945	26·09
	8077	0·246257	53·468	55·27
149	8063	0·409242	05·698	29·73
	7974	0·210648	01·012	50·24
	7988	0·380110	50·384	45·47
150	7963	0·248982	28·678	00·78
	7986	0·393375	19·543	47·22
	8076	0·357643	20·076	42·99
151	7940	0·298256	02·284	40·88
	7985	0·388566	31·341	42·64
	8403	0·313179	29·611	15·90
152	7942	0·305408	06·363	13·87
	7990	0·335032	03·393	10·46
	8401	0·359560	55·871	10·25
153	7924	0·369976	55·476	57·41
	8393	0·307160	41·407	25·52
	8413	0·322864	32·740	43·78
154	8385	0·303214	01·096	24·17
	8403	0·264167	29·612	15·90
	8405	0·432618	45·325	34·40
155	8353	0·415240	40·825	15·85
	8388	0·353836	51·985	54·15
	8397	0·230924	17·314	25·53
156	8358	0·276522	51·482	09·96
	8373	0·367856	18·782	22·75
	8394	0·355622	45·162	14·23
157	9452	0·334629	00·736	28·82
	9463	0·351978	26·728	35·07
	9482	0·313393	47·250	19·56
158	9447	0·304921	36·134	48·42
	9468	0·302536	49·233	44·31
	9478	0·392542	04·058	53·50
159	9426	0·232342	30·792	01·84
	9483	0·436164	07·006	10·36
	9452	0·331494	00·736	28·82
160	9447	0·402427	36·093	48·81
	9465	0·395346	33·403	17·73
	9482	0·202227	47·250	19·56
161	9410	0·324466	52·391	13·78
	9449	0·389572	42·933	52·20
	15124	0·285962	36·006	21·10
162	15095	0·294020	04·537	16·59
	15132	0·310246	07·497	53·45
	9440	0·395734	01·263	14·44
163	15095	0·360084	04·530	16·53
	15097	0·356161	13·522	33·98
	15122	0·283755	24·547	41·17
164	15073	0·403159	06·949	16·56
	15110	0·262141	05·281	33·84
	15129	0·334700	01·670	59·28
165	15057	0·306740	27·483	17·87
	15074	0·254261	21·353	14·09
	15096	0·439000	11·363	51·36
166	15071	0·379078	01·658	22·13
	15075	0·388466	31·526	52·35
	15098	0·232456	27·104	39·51
167	15071	0·484754	01·658	22·13
	15074	0·311282	21·353	14·09
	15092	0·203963	53·279	24·98
168	15054	0·302394	24·712	29·92
	15063	0·206825	01·955	42·91
	15098	0·490780	27·104	39·51
169	15069	0·239541	55·297	45·79
	15074	0·418460	21·353	14·10
	15117	0·341999	06·793	38·97
170	15063	0·430349	01·957	42·92
	15092	0·351360	53·280	24·98
	15127	0·218291	26·021	05·88

Table II—*continued*

No.	Star	Depend.	R.A.	Dec.	No.	Star	Depend.	R.A.	Dec.
			s	″				s	″
171	15166	0·329404	45·242	29·98	193	6503	0·202064	24·717	41·15
	15187	0·374928	59·831	02·45		6526	0·362360	59·688	53·88
	15194	0·295668	27·483	05·09		6540	0·435575	27·220	58·31
172	15152	0·128188	31·071	22·71	194	6496	0·344242	18·108	54·70
	15179	0·594178	42·861	49·16		6564	0·240518	37·049	19·34
	15200	0·277634	54·223	42·88		6532	0·415240	46·202	42·48
173	15179	0·352594	42·861	49·16	195	6500	0·314532	57·597	15·70
	15180	0·371720	53·654	27·58		6503	0·250754	24·717	41·17
	15209	0·275686	11·955	32·49		6524	0·434714	55·787	14·55
174	15166	0·381772	45·242	29·98	196	6483	0·202702	28·781	32·57
	15187	0·329904	59·831	02·45		6534	0·315568	51·220	59·40
	15216	0·288324	22·042	30·29		6508	0·481730	52·239	48·18
175	11610	0·220045	31·632	55·83	197	6498	0·422644	31·011	26·69
	11647	0·357503	44·745	39·41		6503	0·335392	24·717	41·17
	11655	0·422452	42·588	57·31		6529	0·241964	28·410	33·27
176	11608	0·272920	18·983	03·44	198	6483	0·227702	28·781	32·57
	11615	0·302423	11·153	02·53		6523	0·247442	36·017	47·81
	11683	0·424656	03·861	27·72		6505	0·524857	19·351	49·20
177	11610	0·266289	31·632	55·83	199	6486	0·375398	56·442	59·16
	11655	0·351240	42·588	57·31		6527	0·414402	01·064	10·08
	11679	0·382470	32·862	17·26		6503	0·210200	24·717	41·18
178	11627	0·405502	22·000	06·27	200	6483	0·220463	28·781	32·58
	11647	0·305920	44·745	39·41		6502	0·439392	12·138	38·33
	11691	0·288577	35·956	58·67		6529	0·340145	28·379	31·69
179	11571	0·310416	59·929	21·86	201	6498	0·376945	31·011	26·70
	11608	0·490488	18·983	03·44		6533	0·332124	45·323	47·90
	11625	0·199095	15·327	18·10		6523	0·290930	36·017	47·81
180	11563	0·223474	06·456	29·47	202	6500	0·253177	57·597	15·70
	11585	0·287420	32·570	04·97		6517	0·366027	16·911	39·87
	11627	0·489106	22·000	06·27		6524	0·380796	55·769	13·00
181	11566	0·446512	30·921	19·49	203	6517	0·387980	16·911	39·87
	11571	0·385698	59·929	21·86		6524	0·345833	55·769	13·00
	11604	0·167791	42·812	43·49		6566	0·266187	57·708	02·63
182	11555	0·347766	16·805	26·76	204	6527	0·371112	01·064	10·08
	11556	0·225896	16·445	56·85		6529	0·290470	28·379	31·70
	11611	0·426339	37·584	27·94		6544	0·338418	12·390	43·70
183	11525	0·259098	52·714	52·91	205	7627	0·319437	08·184	53·07
	11528	0·382914	15·925	02·31		7641	0·323630	16·690	19·39
	11563	0·357988	06·456	29·47		7678	0·356933	29·563	49·41
184	11516	0·172256	09·845	49·45	206	7634	0·290048	27·156	20·04
	11544	0·556158	31·907	59·64		7658	0·268834	32·770	06·49
	11555	0·271585	16·805	26·76		7664	0·441118	43·230	54·54
185	11462	0·334146	12·919	05·83	207	7712	0·333558	21·320	04·48
	11500	0·397187	30·987	45·41		7734	0·461184	33·241	22·33
	11512	0·268666	49·872	19·63		7761	0·205258	30·272	02·26
186	11454	0·236876	49·728	46·98	208	7708	0·358492	14·424	46·48
	11492	0·396906	43·467	22·35		7742	0·292004	33·398	32·28
	11510	0·366218	02·041	26·29		7755	0·349503	25·473	30·93
187	11418	0·359238	47·413	28·13	209	7740	0·270370	29·893	59·55
	11466	0·363886	25·886	24·46		7761	0·346669	30·272	02·26
	11470	0·276876	17·744	02·39		7783	0·382960	49·624	53·30
188	11423	0·273858	19·703	42·45	210	7732	0·211504	15·760	49·13
	11454	0·222490	49·728	46·98		7773	0·312798	07·568	52·50
	11462	0·503652	12·919	05·83		7775	0·475698	17·684	51·02
189	11392	0·435562	36·979	23·59	211	7769	0·368824	56·842	14·47
	11396	0·192573	09·274	05·63		7801	0·282902	15·931	08·20
	11422	0·371864	17·721	16·66		7802	0·348275	28·809	57·57
190	11377	0·379146	56·061	08·11	212	7771	0·327470	04·582	14·53
	11418	0·243362	47·413	28·13		7789	0·403484	27·702	22·23
	11421	0·377492	09·732	01·65		7813	0·269047	25·288	07·31
191	6534	0·418831	51·220	59·40	213	7724	0·405917	25·851	39·39
	6561	0·340184	25·481	24·31		7775	0·314932	17·684	51·02
	6579	0·240984	51·229	56·37		8849	0·279151	51·297	16·87
192	6543	0·238212	00·768	22·03	214	7745	0·408790	44·671	14·36
	6555	0·336562	38·839	09·88		7761	0·390642	30·273	02·26
	6564	0·425227	37·049	19·34		8837	0·200568	33·334	16·55

TABLE II—*continued*

No.	Star	Depend.	R.A. s	Dec. ″
215	7704	0·302567	33·390	58·06
	7745	0·356184	44·671	14·36
	8813	0·341248	46·323	03·26
216	7713	0·256014	34·490	59·82
	7737	0·435256	23·427	15·90
	8801	0·308730	33·310	07·34
217	8742	0·359842	20·719	35·95
	8767	0·270846	10·239	18·51
	8770	0·369312	21·898	49·79
218	8746	0·231967	39·841	03·25
	8750	0·400744	07·528	38·00
	8775	0·367289	24·927	55·08
219	8696	0·345200	52·760	55·50
	8699	0·205396	25·039	52·39
	8752	0·449404	11·695	51·65
220	8715	0·335752	57·481	35·52
	8718	0·444686	05·247	14·57
	8746	0·219561	39·841	03·25
221	8686	0·210370	26·948	08·84
	8719	0·522189	09·205	58·95
	8732	0·267441	16·882	22·80
222	8694	0·261560	41·704	10·01
	8696	0·373704	52·760	55·50
	8746	0·364736	39·841	03·25
223	8654	0·380492	57·924	29·39
	8692	0·390597	35·370	49·72
	8664	0·228911	15·736	33·69
224	8652	0·375272	53·460	54·31
	8675	0·368400	49·307	51·68
	8694	0·256328	41·704	10·01
225	8578	0·324762	17·607	43·21
	8614	0·355030	26·776	05·77
	8636	0·320207	25·906	15·75
226	8594	0·140754	50·554	37·83
	8607	0·666234	33·623	12·75
	8624	0·193012	43·788	55·72
227	8566	0·395988	50·748	51·66
	8573	0·260460	16·559	50·61
	8617	0·343552	43·733	43·29
228	8569	0·306325	36·144	43·65
	8572	0·344500	12·679	08·64
	8609	0·349175	39·248	54·17
229	8538	0·288950	34·686	26·61
	8547	0·259974	04·085	59·90
	8573	0·451077	16·560	50·61
230	8528	0·246828	11·107	10·22
	8566	0·325250	50·748	51·66
	13923	0·427922	02·551	39·64
231	13835	0·285335	23·307	43·74
	13907	0·266321	36·163	16·22
	8517	0·448344	40·901	18·92
232	13840	0·440737	41·566	35·81
	13888	0·254664	43·270	10·64
	8528	0·304600	11·107	10·23
233	13840	0·358773	41·566	35·81
	13865	0·216972	54·398	21·17
	13879	0·424255	55·940	07·30
234	13819	0·304146	52·135	02·95
	13886	0·363534	40·737	52·55
	8538	0·332320	34·686	26·62
235	13879	0·374758	55·940	07·30
	13890	0·320736	52·442	59·25
	13916	0·304505	05·442	03·35
236	13874	0·350318	16·847	41·44
	13899	0·272005	42·762	12·34
	13907	0·377677	36·163	16·22
237	13945	0·325172	53·480	38·04
	13968	0·273861	03·468	02·63
	13996	0·400966	34·480	42·47
238	13955	0·304714	21·362	04·07
	13978	0·269255	55·550	22·60
	13982	0·426030	40·421	07·32
239	13983	0·245098	40·576	18·97
	14027	0·537996	02·034	02·98
	14036	0·216907	11·042	43·09
240	13982	0·252252	40·421	07·32
	14039	0·398216	41·136	06·05
	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 reassessed. 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.

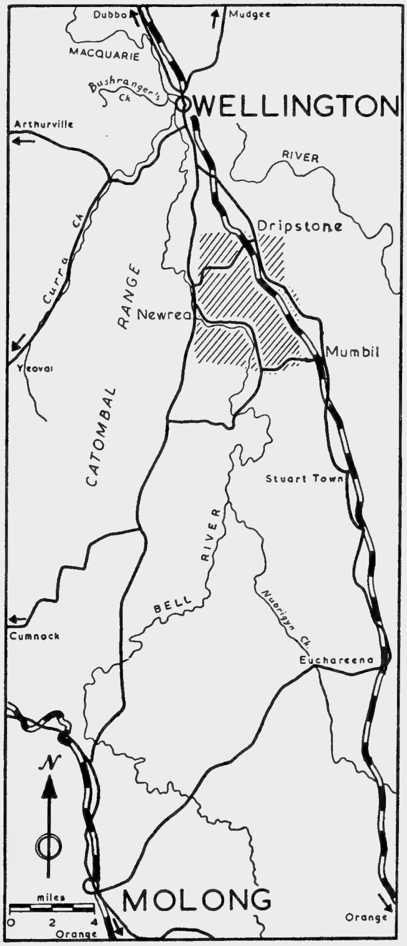


Fig. 1

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*

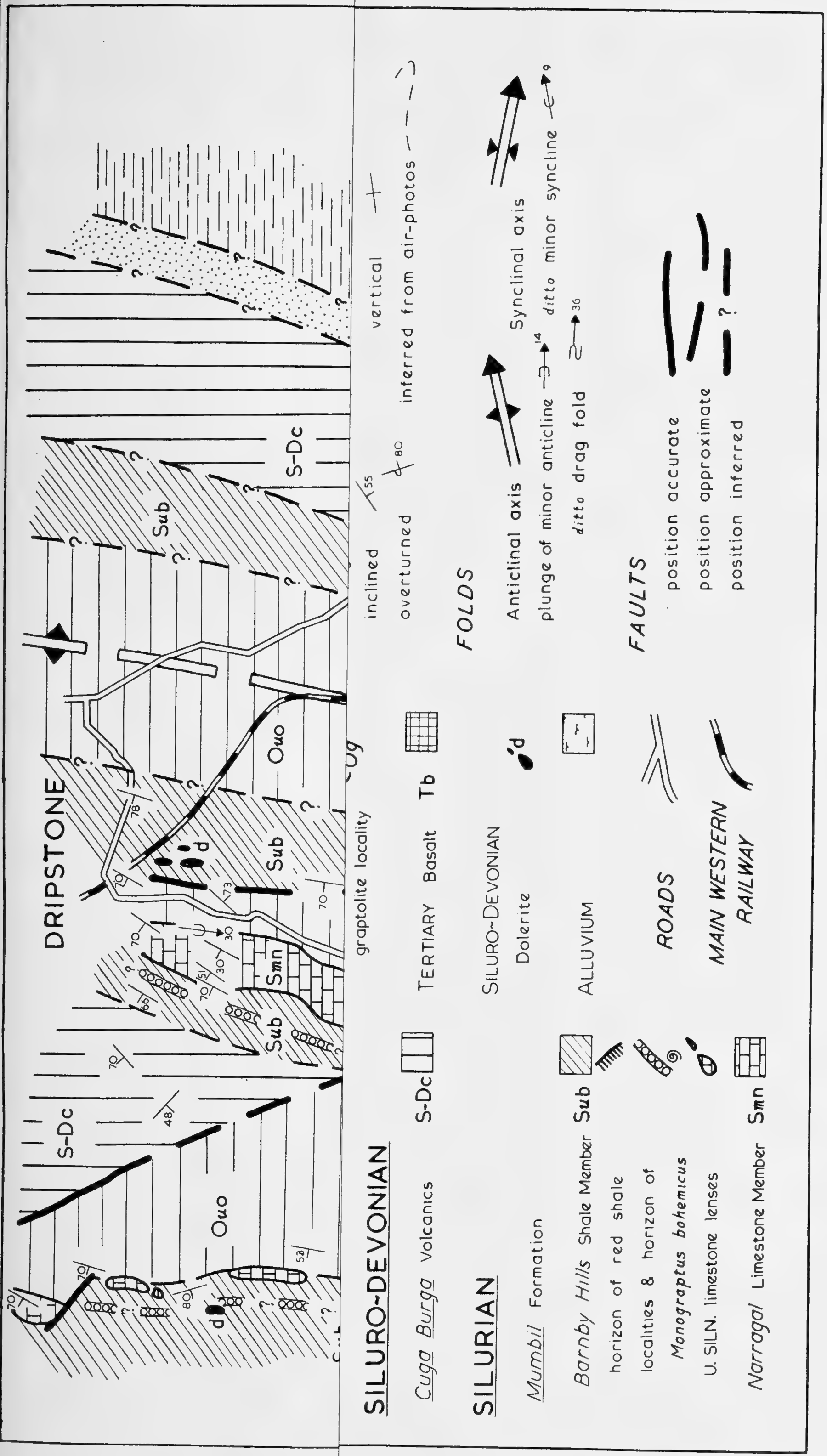
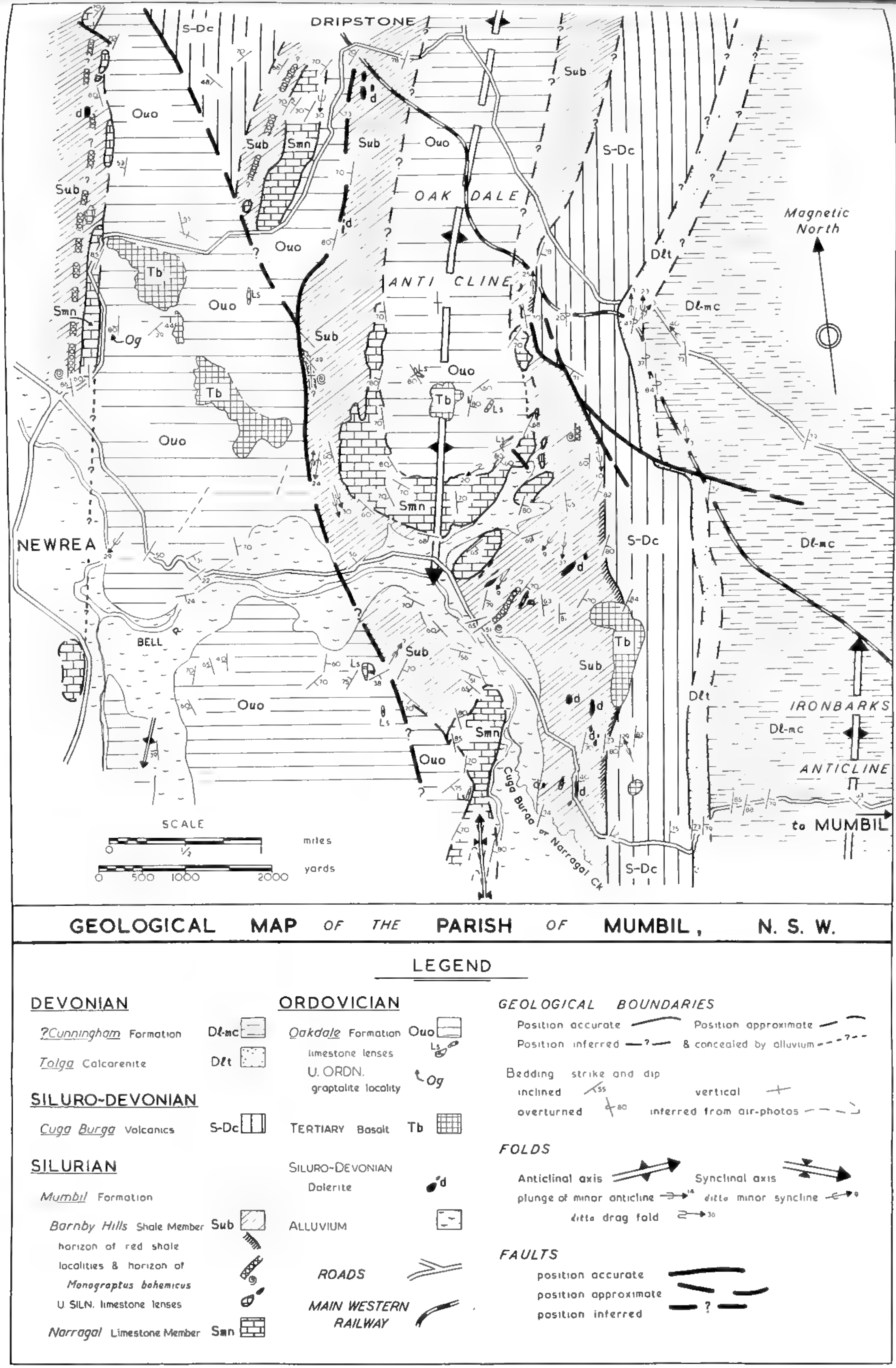

DRIPSTONE
S-Dc
Sub
Ouo
Smn
d
Og
SILURO-DEVONIAN
Cuga Burga Volcanics S-Dc
SILURIAN
Mumbil Formation
Barnby Hills Shale Member Sub
horizon of red shale
localities & horizon of Monograptus bohemicus
U. SILN. limestone lenses
Narragal Limestone Member Smn
graptolite locality
TERTIARY Basalt Tb
SILURO-DEVONIAN Dolerite d
ALLUVIUM
ROADS
MAIN WESTERN RAILWAY
inclined 55
overturned 80
vertical
inferred from air-photos
FOLDS
Anticlinal axis
Synclinal axis
plunge of minor anticline 14
ditto minor syncline 9
ditto drag fold 36
FAULTS
position accurate
position approximate
position inferred ?

Fig. 2



GEOLOGICAL MAP OF THE PARISH OF MUMBIL, N. S. W.

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 drag-folding 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 ferromagnesian 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 $\frac{1}{3}$ 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

$$U=f\frac{M}{a}\left\{\frac{a}{r}+J\frac{a^3}{r^3}(\tfrac{1}{3}-\cos^2\varphi)+\dots\right\}$$

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 $\omega^2a/g_e=m$, 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 1/297·1, but the latest determinations from artificial satellites, which determine J directly, indicate that $e=1/(298{\cdot}1\pm0{\cdot}1)$. Then comparison of J with $(C-A)/C$ gives

$$\frac{C}{Ma^2}=0{\cdot}330\pm0{\cdot}001.$$

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 $\alpha=0\cdot78$, $\rho_1=8\cdot2$. 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 $\alpha^2-\dfrac{4}{3}\beta^2=k/\rho$.

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 $0\cdot55a$, 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 $\alpha^2-\dfrac{4}{3}\beta^2$ 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 $\alpha=0\cdot55$ they lead to $\rho_0=4\cdot6$, 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.)

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* 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 $s_A=c(t_A^m-t_A^1)=\dfrac{c}{2}(t_A^3-t_A^1)$.

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.

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* 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

$$\frac{t_A^3}{t_A^r}=\frac{1+\frac{v}{c}-\frac{v}{c}k}{1-\frac{v}{c}k} \qquad (6).$$

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

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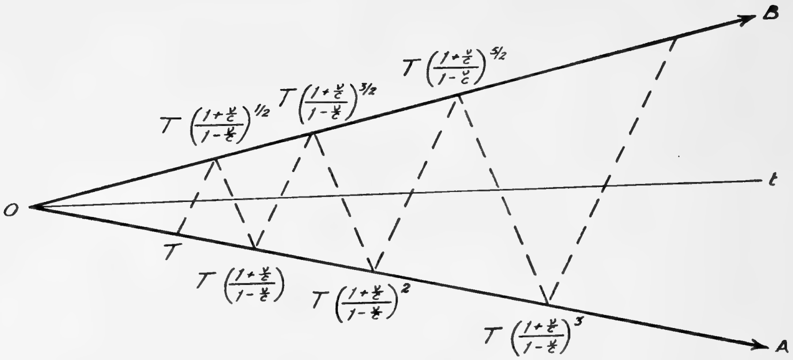
[*] More exactly, the relative status of A and B during the transmission of a light ray from A to B is exactly reversed during its reflection from B to A.



(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

$$t^r_A = \sqrt{t^1_A t^3_A}$$

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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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. 94, pp. 1–58, 1960

The Zonal Distribution of Australian Graptolites*

D. E. THOMAS

Introduction

I am indeed sensible of the honour paid me in being invited to give the Clarke Memorial Lecture for 1959, but I have some misgivings as to whether the subject that I have selected is worthy of the Rev. W. B. Clarke, who pioneered geological investigations in New South Wales and laboured mostly on his own, and under great difficulties, to establish the succession of the sedimentary rocks of New South Wales. Our later work owes much to this great pioneer, and it is a reflection of his remarkable ability and his scientific approach that the results of his work have stood the test of time so well.

To honour this occasion, therefore, I have chosen to summarize the present state of our knowledge of those remarkable early Palaeozoic fossils known as graptolites and, in particular, the sequence of graptolite faunas in the Lower Palaeozoic rocks of Australia. This also provides the opportunity to point out the contributions that workers in this country have made in this field and to pay tribute to those workers without whose guidance I would not have been able to present this paper; I refer in particular to the late Dr. W. J. Harris, whose untimely death cut short the work upon which we have been engaged during the past quarter century, and to R. A. Keble.

What Are Graptolites?

The graptolites, which are placed in the Class Graptolithina, are found only in Palaeozoic rocks, and most of the forms are restricted to the Lower Palaeozoic. The Class Graptolithina consists of two principal orders: the Graptoloidea, or true graptolites, which are restricted to the Ordovician and Silurian, and the Dendroidea, which range from the Cambrian into the Carboniferous. The zoological affinities of the graptolites are still much in dispute and they have been assigned by various workers to the Hydroidea, Polyzoa or the Pterobranchia; recent opinion places them with the Stomochorda (Pterobranchia) because of the stolon system which is present in the Dendroidea, and the histological features of the periderm (Bulman, 1955; Kozlowski, 1948). The true relationship of certain middle Cambrian forms that resemble graptolites in some respects, such as *Archaeocryptolaria* and *Archaeolafoeia*, is still in doubt, but they have been regarded in Australia by some as belonging to the Hydroidea and distinct from true graptolites.

As pointed out by James Hall as early as 1865, and elaborated later by others (e.g. Ruedemann, 1925; Bulman, 1928, 1957), the Dendroidea must have been sessile forms. Actual instances of attachment are very rare while siculate Dictyonemas are abundant. The association of the Dendroidea with organisms usually considered to be of shallow marine benthonic habitat, and the presence of creeping stolons and of worm tubes found rarely in the basal parts of the rhabdosomes of some Dendroidea, suggest that these colonial organisms were sessile and benthonic, and that they lived in a shallow marine environment.

The Graptoloidea, however, appear to have been planktonic or epi-planktonic forms. Although Scharenberg (1851), Richter (1871) and Jaekel (1889) regarded them as bottom-living, other contemporaries (Hall, 1865; Nicholson, 1872) considered them to be free-floating forms, and Lapworth (1897) showed beyond reasonable doubt that they had an epi-planktonic mode of life. Lapworth pictured the graptolites as being attached by their nemae to masses of floating algae such as are found in the present Sargasso Sea. Ruedemann's original discovery (1895) of numerous rhabdosomes (synrhabdosomes) grouped around what appears to be a central float, since verified by many others, shows that at least many of the biserial graptolites were truly planktonic.

Mode of Occurrence of Graptolites

If graptolites were actually planktonic organisms their remains would not be expected to be associated with any particular type of sediment, and they are in fact found in av ariety of sedimentary rocks such as sandstones, cherts,

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shales and limestones. They are most abundantly found, however, in black shales that are generally almost devoid of any other types of fossils ; the black colour of such shales is doubtless due to the presence of carbon, which can comprise up to 13 per cent of the rock, and such rocks also invariably contain sulphur (up to 7 per cent) in the form of pyrite (Marr, 1925 ; Twenhofel, 1932). Some analyses of black shales from Victoria show 3·92 per cent of carbon (Baragwanath, 1923) but Joplin (1946), from her study of Ordovician slates from New South Wales, has suggested that these shales are derived from volcanic ash.

It is generally agreed that black shales are deposited under anaerobic conditions where there is a lack of circulation of bottom water so that the oxygen supply cannot be replenished ; under these circumstances organic matter from the upper aerated layers sinks down and accumulates on the sea bottom. Sediments of this type are being deposited at the present day for example in the Black Sea, in narrow silled embayments such as the Norwegian fiords, and even in some coastal lagoons ; it is therefore highly probable that the graptolites drifted over or lived in similar areas in Palaeozoic time and accumulated in great numbers in this type of bottom sediment.

Much has been also written concerning the parallel grouping and orientation of graptolites, presumably due to the effects of bottom currents (Hundt, 1933–1938), and ripple marks, rain prints and sun cracks have also been recorded from beds containing graptolites (e.g. Öpik, 1929).

Although graptolites are found most abundantly in black shales, their presence in other types of sediments, such as the greenish shales and silts of the Silurian of central Victoria and New South Wales in which they are often associated with abundant shelly fossils, should not be overlooked. At some places in these areas the graptolites do not lie in single bedding planes as they generally do in the black shales, but they are oriented in various directions obliquely to the bedding planes ; Hills and Thomas (1954) have suggested that turbidity currents may have been responsible not only for this unusual orientation, but that such currents may also have influenced the mortality rate of the graptolites. It has also been shown recently (Smith, 1957) that mud-laden currents were apparently strong enough to drag graptolites along the sea bottom, where the sediments were sufficiently viscous to preserve the gouge marks caused by the dragging of the graptolites, and scratch marks on the surfaces of the graptolites were also apparently caused by the dragging movement along the sea floor.

The graptolites in black shales are usually rather poorly preserved and more or less strongly compressed, but the well-preserved and uncompressed forms that are often found in limestones and cherts interbedded with the black shales in some sequences are particularly suitable for detailed morphological studies. Much detailed work has been carried out on pyritised specimens from black shales.

In sequences of black shales deposited continuously during a comparatively long time span the assemblages of graptolites change gradually in character throughout the sequence and the resulting admixture of forms makes it difficult to define clearly the exact boundaries of biostratigraphic zones within such sequences, particularly when they are condensed. However, in Victoria, and particularly in the Lower Ordovician sequence, the graptolite-bearing beds are separated by appreciable thicknesses of unfossiliferous rocks, so that typical distinct assemblages can be readily recognized and it is possible to trace and map individual fossiliferous bands and correlate them on the basis of the well-defined assemblages contained in them. In these circumstances the horizons of the first appearance and the disappearance of particular forms of graptolites, particularly the former, have proved of great stratigraphic value in defining zones that can be satisfactorily correlated in widely separated regions.

Evolution of the Graptolites

In Australia no graptolites have yet been found sufficiently well preserved to enable detailed study of their morphology to be undertaken and most emphasis has consequently been placed on the study of the general characters of assemblages and the times of their appearance in the Lower Palaeozoic succession, rather than on determining relative position within the sequence on the basis of stages in the evolutionary development of lineages. Because of the generally sharp and close folding of the Lower Palaeozoic rocks in Australia, as exemplified so well in our goldfields, the graptolites are usually strongly compressed and distorted so that minute differences in relative proportions of morphologic features, so often used to distinguish and separate species, cannot always be applied. Nevertheless it is very evident from our studies that there is a considerable degree of variation in the morphologic features of individual species and that these variations are of such a nature that they were clearly not caused by distortion or compression. Apart from the difficulty of identifying compressed specimens with forms of the same species preserved in the uncompressed state, the distortion suffered by specimens in sharply folded rocks makes comparison between such forms on the basis of detailed measurements quite unreliable.

In the early days of the study of graptolites the genera were established on the basis of their broad morphologic features and while this tended to keep within reasonable limits the number of genera erected, most of these old genera have since been shown to be polyphyletic. The recognition of the evolutionary trends in graptolites and their application in defining and determining biostratigraphical zones is to a large extent due to the work of Elles (1922), who maintained that the early graptolites developed according to the *Dichograptus* plan and that the direction of their evolution is expressed by the following general trends: (1) Change in direction of growth from pendent to scandent forms; (2) simplification in branching; (3) elaboration of thecal type; (4) localization of thickening in the periderm walls.

In recent years it has become evident that, although generally correct, this scheme is an oversimplification; for example, the early forms of *Dictyonema*, the Bryograpti and many of the dichograptids were pendent, while the later Diplograpti and Monograpti were scandent.

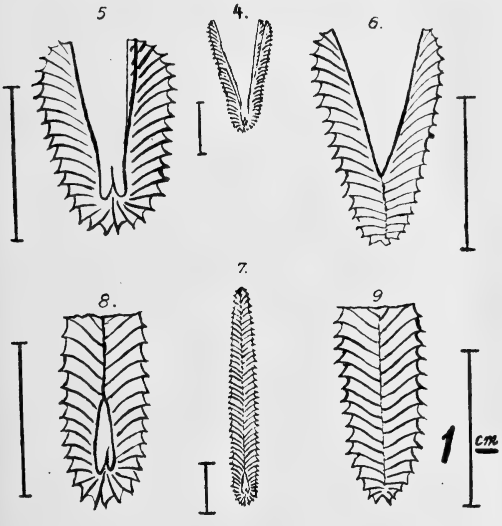

Fig. 1

Development of *Phyllograptus cor* (Nos. 7, 8 and 9) from *Tetragraptus phyllograptoides* (Nos. 4, 5 and 6). A scale of 1 cm. is shown against each diagram.

Even in Tremadocian times most of the Clonograpti, Staurograpti and Anisograpti were horizontal. Horizontal Didymograpti and declined Tetragrapti are very abundant at the base of the Bendigonian stage, but reclined forms such as *Didymograptus hemicyclus* are also present; at a slightly lower horizon in Scandinavia the presence of *Tetragraptus phyllograptoides* in which the secondary stipes are partly concrescent, and of *Phyllograptus cor*, is even more difficult to reconcile with the above scheme. The same can be said of the "burst" of pendent Tetragrapti (*T. fruticosus*, *T. pendens*) which is accompanied by that of the reclined Tetragrapti (*T. similis*, etc.) and by the scandent Phyllograpti.

Bulman (1955) has pointed out that Nicholson and Marr (1895), as a result of their work on certain dichograptids, showed that graptolite genera are probably polyphyletic and they introduced the idea of an evolutionary trend toward stipe reduction which was then extended to include *Clonograptus* and *Loganograptus*. This so-called evolutionary trend from the many-branched forms to the two-branched Didymograpti and single stipe of *Azygograptus* may be expressed schematically as follows:

Genus	Number of Branches	Number of Dichotomies
Clonograptus	32+	5+ (8–9)
Loganograptus	16	4
Dichograptus	8	3
Tetragraptus	4	2
Didymograptus	2	1
Azygograptus	1	0

This mathematical concept of an evolutionary trend of progressive reduction in number of branches by failure of dichotomous branching is not supported by stratigraphic evidence, and it has already been pointed out (Harris and Thomas, 1940*a*) that the appearance in time of these forms does not support such an evolutionary trend and that the failure of dichotomy at any time can give rise to the simpler branched forms. Although an overall progressive reduction of branching did take place in a general way during the time span of the graptolites as a whole, the process was by no means a regular evolutionary trend as is well shown by the fact that *Didymograptus*, *Tetragraptus* and *Phyllograptus* appeared in time before *Dichograptus* and *Loganograptus* had evolved. The same tendency has been described for *T. fruticosus* and *T. harti*.

The establishment of the Anisograptidae by Bulman (1950) has added to the problem

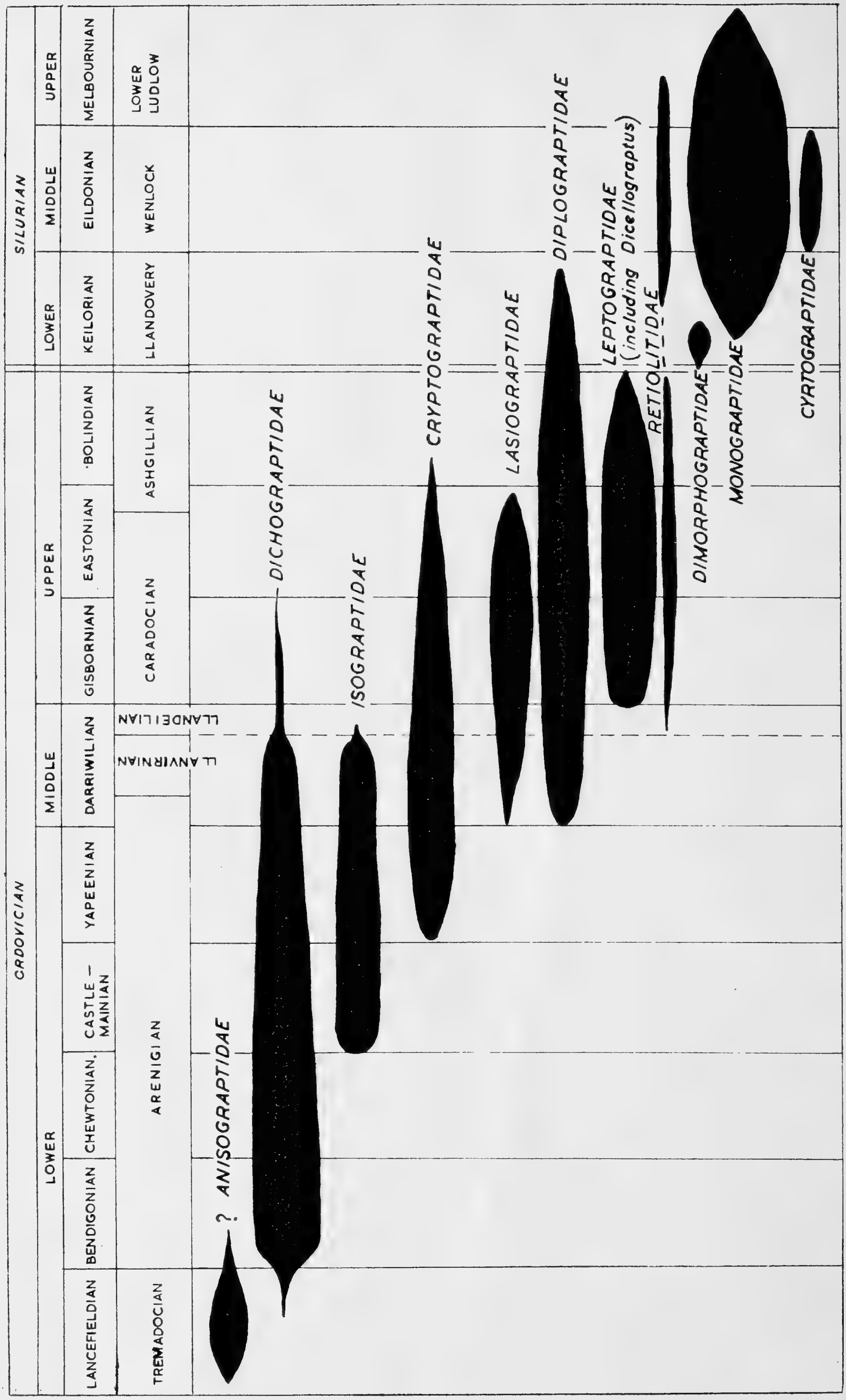

Fig. 2

Simplified diagram showing succession of graptolite faunas in Australia.

of the early appearance of Didymograpti and Tetragrapti because until specimens have been found preserved in such a way as to establish that they possess bithecae, these forms must be considered as normal Didymograpti and Tetragrapti. It has yet to be proved that the forms placed in this group all possess bithecae and some of the Bryograpti and many of the later Clonograpti also may not possess bithecae. In Victoria *Dichograptus* first appears in the Bendigonian stage.

The existence of " bursts " of many-branched forms that are found at various horizons has generally been ignored and this phenomenon certainly complicates the concept of an evolutionary trend of simplification of branching; the " burst " of dichograptids, for example, is contemporaneous with that of the horizontal Didymograpti and the declined and reclined Tetragrapti. Although *Loganograptus* appears sparingly with *Dichograptus*, the typical *Loganograptus* burst occurs in the Castlemainian stage, much later. In the Middle Ordovician of Victoria there is a burst of *Pterograptus* and *Brachiograptus*, while near the base of the Upper Ordovician is the burst of *Nemagraptus* and, higher in the sequence, that of *Pleurograptus*. Although the growth pattern of graptolites is different in the Middle Silurian (by cladial development and not by dichotomy) there is a " burst " at this horizon of the Cyrtograpti and in the Upper Silurian branched forms such as *Linograptus*, *Abiesgraptus*, *Barrandeograptus* and *Diversograptus* appear.

The elaboration of thecal type (Elles, 1922) reaches its acme in the Monograpti ; some of the later Didymograpti, however, also show this (e.g. *Didymograptus nodosus*, *D. spinosus*, *D. cognatus*, *D. dubitatus*, *D. callotheca*). In the last thirty years it has become increasingly evident that a trend of elaboration of thecal type is present even in the dichograptids, and Mu (1958) has created a new family Sinograptidae for many of these forms. It is also somewhat anomalous that the " burst " of Dicellograpti and Dicranograpti is characterized by the abundance of those forms with complex thecal types (e.g. *Dicellograptus sextans*, *Dicranograptus ramosus*) while the later forms seem to revert to simpler thecal types. The Lasiograptidae are scandent biserial forms with attenuated periderm and a clathria, well developed thecal and septal spines, and lacinia ; these forms do not appear until high up in the sequence, after the burst of type B of the Isograptidae. Bulman (1958) has summarized most of the above problems and has recast the faunal sequence ; this dispenses with many of the anomalies but it is still not entirely acceptable to Australian workers.

Harris and Thomas (1938) stressed the incoming in force of the Diplograpti in Britain long before the appearance of the Leptograpti.* Bulman (1958, p. 160) states " Harris and Thomas (1956) have remarked that to put the Leptograptid Fauna stratigraphically below the Diplograptid Fauna 'is not warranted by observed facts', and in effect, that we in Britain seem to have got the Leptograptid and Diplograptid Faunas inverted ". The stress laid by Harris and Thomas is upon the incoming in force of new forms and, in Victoria, four diplograptid zones are present before the appearance of *Leptograptus*, *Dicranograptus*, *Dicellograptus* or *Nemagraptus*. As is shown in the accompanying plate (Pl. 6) the Diplograpti keep on developing and increasing numerically and the development and acme of the Orthograpti is higher, in the Leptograptid Fauna.

To omit the Leptograptid Fauna as a major unit and reduce it to a subfauna does not help the field geologist as the association of diplograptids and leptograptids is utilized in the subdivisions of our " Upper Ordovician " (Caradocian and Ashgillian of Britain). To state (Bulman, 1958, p. 160) that " the Leptograptid Fauna can hardly now be claimed to correspond to any precise stratigraphical unit " certainly does not apply in Australia. The Upper Ordovician in Australia is essentially the range of *Dicellograptus* from its entry to its disappearance.

Bulman introduced into the Anisograptidae those forms that have the typical " triad " development of the Dendroidea, which he considers to be the forerunner of the Dichograptidae, but many forms cannot yet be definitely assigned to either of these groups. The " burst " of the true " dichograptids " in the basal part of the Bendigonian stage may in fact point to the stabilization of the dichograptid plan of development.

While Bulman (1938, p. 161) maintains " that there is stratigraphic support for the morphological evidence linking leptograptids and dicellograptids to *Dichograptus* and *Anisograptus* in a continuous evolutionary series ", he points out that the origin of scandent forms is obscure and that they appear quite abruptly ; he accepts the incoming of the Diplograptidae

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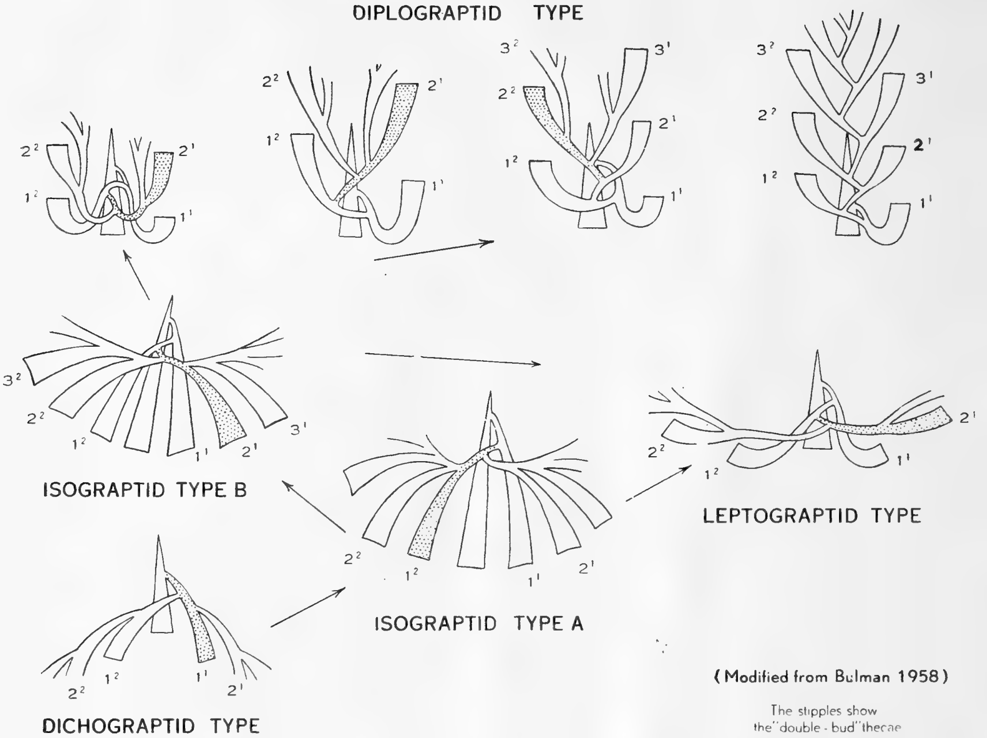
* In this paper Diplograpti is used to include *Diplograptus* (=*Mesograptus*), *Glyptograptus* and *Orthograptus*.



(Modified from Bulman 1958)

The stipples show the "double - bud" thecae

FIG. 3

Thecal diagram of terminal ends to show progressive changes.

as of much greater stratigraphical importance than that of the tuning-fork graptolites and extends the Diplograptid Fauna and " docks the tail of the Dichograptid Fauna ".

The formulation of the family Isograptidae by Harris is a very significant contribution and one which graptolithologists will increasingly utilize. Bulman neglects the possibility that the Isograptidae form a connecting link between the Dichograptidae and the diplograptid and leptograptid faunas, but the late Dr. Harris and myself maintain that the Isograptidae are one of the links connecting the Dichograptid with the Diplograptid and Leptograptid faunas. Isograptus marks a stage in which the theca carrying the " double bud " is now Th1^2. In the Castlemainian stage, *Isograptus* tends to increase in size upward through the sequence but it still preserves this fundamental pattern. However, at the base of the Yapeenian stage (and uppermost part of the Castlemainian) many variants of *Isograptus* appear ; while it is not yet proved beyond all doubt, some of these forms have three crossing canals, and therefore follow the " leptograptid " type of development. Two lines of development then become apparent : (*a*) There is the concentration of the crossing canals near the upper part of the sicula in such forms as *Isograptus hastatus* and *I. manubriatus* ; (*b*) in other forms the crossing canals are relatively closer to the mouth of the sicula as in *Meandrograptus tau* and *M. aggestus*. The former development is suggested as one possible line of ascent leading to the scandent forms and the latter to the leptograptids. Not only is the scandent form of the diplograptids foreshadowed in these new developments, but also the leptograptid type of thecae.

Oncograptus and *Cardiograptus* are considered to be a side branch which, perhaps by retrogressive development, soon became extinct (cf. the Tremadocian *Tetragraptus phyllograptoides* and *Phyllograptus cor!*). The stratigraphical position of these forms, however, draws attention to the need for further work on their development.

There is fairly general agreement regarding the stratigraphic position of the Diplograptid fauna but, in eastern Australia, the Leptograptid Fauna is retained as a biostratigraphical unit because the " burst " of this fauna in the zone of *Nemagraptus gracilis* marks the base of the Upper Ordovician, and it disappears just below the base of the Silurian. The second burst of the multi-branched forms, in this case *Pleurograptus,* takes place after the disappearance of *Dicranograptus* and this burst marks the base of the Bolindian stage. For these reasons the Leptograptid Fauna is of great stratigraphic significance in the Lower Palaeozoic sequence in Australia. Work in Australia has thrown no additional light on the Monograptid Fauna, which will not be dealt with at length here.

History of Zoning of Victorian Graptolite-bearing Beds

The graptolites found about a century ago by the Geological Survey of Victoria were identified by Sir Frederick McCoy, and his early identifications are printed on the various Quarter Sheets (1856, 1865, 1868, etc.). These were only broadly correlated but it is interesting to note the similarity of these forms with those elsewhere in the world. In 1862 McCoy published a faunal list in the *Annals and Magazine of Natural History,* and in 1867 he stated that " all the slates containing gold-bearing veins in Victoria were identical in age and character with those in North Wales, in which the Romans worked the gold mines of Gogofau ".

Between 1892 and 1932 the zoning of the Australian sequence was firmly established by T. S. Hall; in 1899 he amplified his earlier work and recognized four main divisions of the Lower Ordovician in descending sequence, the Darriwil, Castlemaine, Bendigo and Lancefield. In 1912 Hall extended these observations by recording *Tetragraptus approximatus* in the upper part of the Lancefield and lower part of the Bendigo Beds.

W. J. Harris (1916) proved the existence of beds between the Castlemaine and the typical Darriwil, but his suggested name of Yapeen for these beds was not adopted at that time.

The detailed work on the zoning of the Bendigo goldfield, carried out by R. A. Keble on the basis of the graptolites, has never been described except in its broader outlines, but the distribution of the major zones is shown on the maps accompanying a report by H. Herman (1923); the only indication of the detailed subdivisions Keble had worked out is contained in a short paper (1920), but the basis of this zoning has never been published.

Harris and Crawford (1921) made a tentative attempt at zoning the upper Ordovician rocks and, in 1932, Harris and Keble published their zoning of the Victorian graptolite sequence where five zones were recognized in each of the four main stages.

Thomas and Keble (1933) described the Ordovician and Silurian rocks of the Sunbury district and proposed serial subdivisions of the Upper Ordovician, namely the Gisbornian, Eastonian and Bolindian, which are still in use although in a slightly emended form; at that time the Yeringian stage of the Silurian was considered to be of Wenlock age but subsequently, largely as the result of this paper, it was accepted as being younger. The Keilorian stage was recognized as the lowest division of the Silurian and the Melbournian as the highest, but the term Yarravian has been discarded and the name Eildonian can be utilized for the intermediate division (Thomas, 1947). Work by Harris and Thomas (1933 to 1957 in collaboration or separately) has led to the re-evaluation of the subdivision of the sequence and of the many factors involved in correlation with sequences overseas.

In New South Wales the pioneering work of Mrs. Sherrard in that state cannot be too highly praised, and the broad outline she has established can be correlated with subdivisions elsewhere in the world. Let us not forget the work now being undertaken by the younger generation, by Drs. Packham and Stevens in New South Wales, by Mr. G. Bell and Mr. P. Kenley in Victoria, and by Mr. M. Banks in Tasmania.

The Sequence of Graptolite Assemblages

The succession of graptolite assemblages throughout the world in its broad outline is everywhere essentially the same, but when individual species and/or their minute differences are used in zoning, discrepancies become evident. This is undoubtedly due to the varying lithology and thickness of the various zones in the sedimentary sequence and the response of the fossils to slightly different environmental conditions. No doubt many species that have been created are unnecessary and are merely local geographical variants of more widely distributed forms, and it is becoming increasingly evident that many stratigraphic units are of limited geographical extent. It is hoped that the recent work begun by Margaret Sudbury (1958) will lead to an increase in this type of investigation which combines our increased knowledge with further detailed research to link forms that were previously considered as separate entities into an evolutionary sequence.

In Victoria, owing to the scarcity of shelly fossils, attention must be concentrated on the graptolites as a means of subdividing the sequence and for regional correlation with sequences elsewhere in the world.

The waxing and waning of the main faunas, the Anisograptid, Dichograptid, Isograptid, Diplograptid and Leptograptid faunas, form the basis for subdivision of the Australian Ordovician and Silurian sequence, which is outlined below.

The Anisograptid Fauna (*Lancefieldian*)

By the recognition of the Anisograptid fauna Bulman has introduced certain difficulties for field geologists, due to the fact that in compressed forms bithecae cannot always be identified, and also for the taxonomist, as forms included by him in this group have not yet been proved to possess bithecae.

The assemblages of the Anisograptid Fauna in Australia are as yet not as complete as in the lower part of the sequence in Sweden (Tjernvik, 1958) and the lowest horizon in Victoria lies above the typical *Dictyonema flabelliforme* beds and is to be correlated with a higher zone such as that described by Bulman (1950) for Quebec.

These early forms are very variable and attempts to separate them into species on the basis of measurements of morphologic features are fraught with difficulties ; the variability of these forms is so great that even the individual specimens on the same slabs are seldom exactly comparable. This feature has been realized by most workers, and Bulman (1954, p. 7) has stated that " the variability of *Dictyonema flabelliforme* is so great that hardly any two specimens are exactly comparable and in any large collection the range of variability and diverse combination of characters is bewildering. Thecal characters have been employed but little in the subdivision of the species. Admittedly, there is some variation in number of thecae per unit stipe length but often this is of geographical importance affecting all varieties of one district or area rather than a true distinction of different varieties." Such observations are borne out in thick graptolite shales in Victoria, where bedding surfaces one-tenth of an inch apart (or even less) are literally crowded with forms differing considerably in measurements from those on the next bedding surface, whereas the general similarities of the forms are unmistakable. Some beds are crowded with smaller specimens which might have perished at the same stage of development or might have been stunted by some particular environmental factor at that time, but lithologically and stratigraphically the beds form essentially the same " band " and the small forms are to be found associated with larger ones on adjacent bedding planes.

The lowest graptolite horizon in the Ordovician sequence of Victoria (La1) contains *Staurograptus* and two species of siculate *Dictyonema* (Pl. 1). About 1000 feet higher in the sequence are the typical Middle Lancefield Beds (La2) with two large species of *Dictyonema* (*D. pulchellum*, *D. magillivrayi*), Clonograpti (*C. rigidus* and *C. tenellus* and the very large *C. magnificus*), Bryograpti (Adelograpti) (*A. victoriae*, *A. clarki*, *A. antiquus*), two primitive Didymograpti (*D. pritchardi*, *D. taylori*) and *Tetragraptus decipiens*.

This fauna shows some remarkable features as *A.* (?) *antiquus* very rarely shows the third branch and the majority of the forms show only two and thus most of the forms are to be considered as being Didymograpti. "*Didymograptus pritchardi* ", apart from the one specimen figured by T. S. Hall (1899), has only two branches ; the third branch in this figured specimen originates from the sicula so that this form could be called a *Triograptus*, yet in general aspect, thecal characters and thickness of stipe it cannot be compared with any of the published species of *Triograptus*. The six-branched *Tetragraptus decipiens* figured by Hall is the only one yet found and it may be an accident of preservation rather than a true form, yet undoubted five-branched forms occur. The *Phyllograptus* recorded at this horizon by T. S. Hall (1899) is an incomplete phyllocarid crustacean. This horizon contains many transitional forms and it is generally correlated with the upper part of the Tremadocian. The Didymograpti resemble those described from Oslo by Monsen (1925) and *D. primigenius* Bulman (1950) from Quebec.

The succeeding assemblage in Victoria (La3) is marked by the incoming of large forms of *Tetragraptus* (*T. approximatus* [of R. A. Keble] and *T. acclinans*), which are probable " end forms " of a variable group as there are innumerable variants between these extremes, and they are accompanied by many of the forms present in the lower zone, La2. These Tetragrapti are world-wide in their distribution and restricted in their range so that they are ideal for world-wide correlation. No *Dichograptus* has been recorded from the Lancefieldian, and it is evident that both *Tetragraptus* and Didymograptus were well established before *Dichograptus* made its appearance.

In Scandinavia the assemblage of this horizon is complicated by the occurrence of *Tetragraptus phyllograptoides* and *Phyllograptus cor*, not only because of their reclined habit but also because of the partial concrescence of their branches (Strandmark, 1901).

The Dichograptid Fauna (Bendigonian to Gisbornian)

Bendigonian—The base of the Bendigonian is defined by one of the most significant bursts of new forms in the succession of graptolite assemblages. Upward in the sequence from this horizon pendent Tetragrapti (*T. fruticosus, T. pendens*), reclined Tetragrapti (*T. amii, T. bryonoides, T. serra*) and extensiform Didymograpti (*D. extensus, D. latus, D. abnormis, D. similis, D. suecicus, D. asperus,* etc.) are abundant. *Phyllograptus, Dichograptus, Goniograptus, Loganograptus, Trochograptus, Schizograptus* and others can be expected in the Dichograptid Fauna.

In the Victorian sequence there is no concentration of Dichograpti followed by Tetragrapti and Didymograpti in any beds. There is no succession of Didymograpti from those with slender to those with broad proximal partitions (Elles, 1933); in Victoria the only forms approaching *Didymograptus hirundo*, i.e. with broad proximal parts, are the forms of *D. latus* and its variety which occur at the base of this stage.

It is of interest that assemblages similar to those present in this part of the sequence in Victoria have also been found in Newfoundland (Kindle and Whittington, 1958) where a form recorded as *Didymograptus* cf. *hirundo* (Salter) has been found in association with *Tetragraptus approximatus* (Nicholson); confirmation of the possibility that the form recorded as *D.* cf. *hirundo* may be *D. latus* is awaited with interest.

The form considered to be *Didymograptus extensus* in Britain differs from both the American and Australian forms of this species, and is probably a variant of *D. nitidus*.

The great variation in the Didymograpti of the earlier Dichograptid fauna in Victoria is comparable with that of Quebec (J. Hall, 1965) and of Norway (Monsen, 1925) and it is a cause of embarrassment to all taxonomists.

In Be1, *Tetragraptus approximatus* together with four-branched *T. fruticosus* form a high percentage of the forms present, but in Be2 *T. approximatus* is not found and it appears to have become extinct. In the upper part of the Bendigonian stage (Be3–Be4) the three-branched form of *T. fruticosus* becomes dominant and, after a period of co-existence in Be3, the four-branched form becomes extinct. With the appearance of the three-branched forms, two-branched forms also appear which resemble *Didymograptus v-fractus. Goniograptus thureaui* is more particularly abundant in the lower horizons and the smaller forms of *G. macer* in the higher. In the upper beds new types of Didymograpti make their appearance and are represented by forms which can be compared with *D. nitidus, D. balticus, D. mundus* and their numerous variants.

Chewtonian—The base of the Chewtonian is determined by the incoming of the dependent Didymograpti such as *D. protobifidus*; this form appears first with *Tetragraptus fruticosus*, together with all the forms present in the upper Bendigonian as well as some new ones, but this pendent form is the most abundant form present. The association with *T. fruticosus* is short-lived and it is represented by one of the thinnest zones in Victoria, not exceeding 40–60 feet.

After the disappearance of *T. fruticosus, D. protobifidus* becomes even more abundant and it remains a characteristic form throughout a thickness of 2000 feet. One of the earlier mutations of *Isograptus caduceus* is present in the upper part of this zone.

The Isograptid Fauna (Castlemainian to Darriwilian)

Castlemainian—The evolution and development of the family Isograptidae was investigated in detail by the late Dr. W. J. Harris (1933) and this work was being extended until his death. The Castlemainian zones are defined by the progressive development from *Isograptus caduceus* var. *primula* to var. *lunata* to var. *victoriae* to var. *maxima* var. *maximo-divergens* and var. *divergens*. The Castlemainian in Victoria, apart from the development of *I. caduceus*, both in size and numbers, is characterized by the relative paucity of other forms. Except for extensiform Didymograpti only a few Phyllograpti are present, some which are close to *Phyllograptus typus*, and the other forms are narrow types described both from South America and from Sweden as varieties of *P. angustifolius*.

In the higher beds *Loganograptus logani* becomes abundant and the maximum development of *I. caduceus* is accompanied by the incoming of the numerous variants of this form.

Yapeenian—The Yapeenian is characterized by the presence of variants of *Isograptus caduceus* together with *Oncograptus* in Ya1 and with *Cardiograptus* in Ya2 (it should be noted that *O. upsilon* has been recorded sparingly with *Glyptograptus intersitus*). According to Harris (1933) the two last-named forms developed from *I. caduceus* by concrescence, but doubt has been cast on this after study of serial sections of an *Oncograptus* from the El Paso Limestone of Marathon, Texas (Bulman, 1936); from these it is doubtful whether *Oncograptus* is even an isograptid. Harris' general picture is logical, however, and because of its strong stratigraphical support it should not be dismissed too lightly. The incoming of the variant forms of *I. caduceus* in force characterizes the Yapeenian, and the stratigraphic horizons of *Oncograptus* and *Cardiograptus* are similar to the occurrences in North Ireland, North America and China.

Although many of the dichograptids from lower horizons still persist, there are other forms which first appear in the Yapeenian. One of the most characteristic and easy to identify of the Didymograpti is *D. v-deflexus*, but others such as *D. nitidus*, *D. nicholsoni* and *D. uniformis* are also present.

Biserial forms make their appearance in force at this horizon. Of great interest is *Skiagraptus* which is a biserial isograptid. Early forms of *Glossograptus* also occur and, in forms such as *G. ? crudus*, the proximal thecae appear to develop as in the Isograpti.* *Trigonograptus* also makes its appearance and one specimen (Pl. 5, fig. 63) in which the periderm has been stripped suggests that this form is a retiograptid with a thick periderm.

Cryptograptus becomes increasingly abundant upwards in the succession.

The Diplograptid Fauna (Darriwilian to Keilorian)

The incoming of the diplograptids of which the first Australian representative is *Glyptograptus austrodentatus*, marks a very important evolutionary advance. The abundance of the Diplograpti in association with the equally strong dichograptid element and the absence of the tuning-fork graptolites *Didymograptus bifidus*, *D. murchisoni* and their variants, which are so abundant in Europe, gives an individuality to this biostratigraphic unit in Australia. The lowest part of the Darriwilian is characterized by *Glyptograptus austrodentatus*, and this is followed by the zone of *G. intersitus* and then by *Diplograptus decoratus*; *G. austrodentatus* and *G. intersitus* are small forms, the former having a blunter proximal end. The large forms of *Glyptograptus dentatus*, so common and characteristic of other parts of the world, are unaccountably absent in Australia. *Diplograptus decoratus* resembles *D. coelatus*, but the heart-shaped vesicle at the distal end, although not always present, is very characteristic. *Lasiograptus* is very common in the lowest zone, the most abundant form being *L. etheridgei*.

This fauna is considered in Victoria to be Middle Ordovician and this age determination has also been accepted by Stormer (1953). Although in size and perhaps even in numbers the Orthograpti reach their acme in late Ordovician times, the abundance of biserial forms associated with equally abundant dichograptid and isograptid elements and the absence of Leptograpti makes this horizon easy to identify in the field.

Glyptograptus austrodentatus is the predominant graptolite in the lowest part and, after co-existing with *D. intersitus*, it apparently died out before that form; *G. intersitus* is then associated with the *Diplograptus decoratus*, the characteristic form of the succeeding zone, which marks the incoming of the large diplograptids.

Lasiograptus etheridgei enters the sequence with *Glyptograptus austrodentatus* and *Glossograptus acanthus*; *D. decoratus* is associated with *Didymograptus nodosus*, which has spines arising from the thecae and from nodes in the dorsal side of the stipe. *Didymograptus compressus* and *Pterograptus* first make their appearance in the zone of *Glyptograptus intersitus* and other characteristic forms of the higher beds are *Lasiograptus proteus*, *Cardiograptus crawfordi*, *Didymograptus cognatus*, *D. cuspidatus*, *Atopograptus woodwardi*, *Phyllograptus nobilis*, *Brachiograptus etaformis* and *Amplexograptus confertus*, *A. differtus* and *A. modicellus*.

The zone of *Glyptograptus teretiusculus* is now included in the Middle Ordovician (Darriwilian) of Victoria and this horizon is one of the most important horizons in correlation as it marks the passage beds where the dichograptid element disappears before the incoming of the leptograptids. *Glossograptus hincksii* and *Pterograptus lyricus* are abundant and, at the base of the zone, *Tetragraptus clarkfieldi*, *Isograptus ovatus* and *Isograptus caduceus* var. *tenuis* are characteristic. The Climacograpti appear in force at this horizon, where they are

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* The downward growing first theca of many forms in *Lasiograptus* and *Glossograptus* is suggestive of derivation from the Isograptidae.

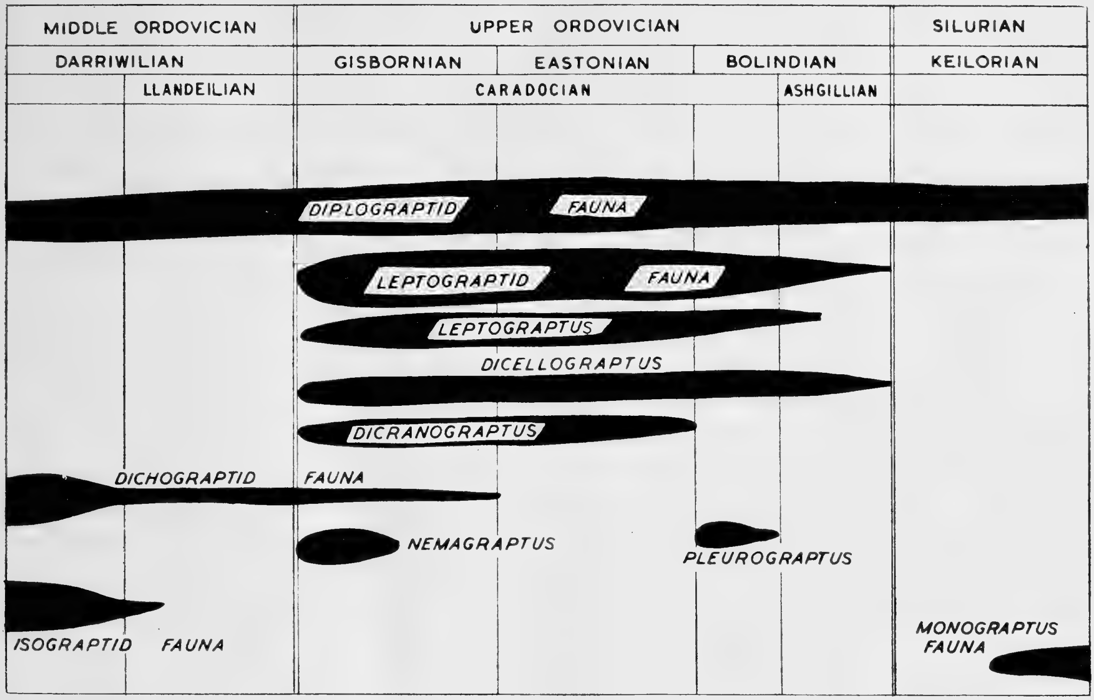


Fig. 4
Ranges of Upper Ordovician graptolites.

represented by *Climacograptus riddellensis,* which is closely allied to *C. antiquus*; *Retiograptus speciosus* is another characteristic form.

The Leptograptid Fauna (*Gisbornian to Bolindian*)

Dicellograptus has always been considered by Dr. Harris and myself to belong to the Leptograptidae as at times it is very difficult to separate this form from *Leptograptus.* The development is the same, and some Dicellograpti have leptograptid thecae. It is considered here as belonging to a group of leptograptids in which thecal elaboration has proceeded further than in the case of the other Leptograpti. *Dicranograptus,* a form without a nema, and with a proximal biserial portion, is totally distinct and should be regarded as the only known genus of the Dicranograptidae.

In Victoria the following three divisions of the Upper Ordovician, in ascending order, are recognized: (1) Gisbornian; (2) Eastonian; (3) Bolindian.

The entry of the Leptograptid Fauna in force marks the base of the Upper Ordovician as used in Victoria. It is readily distinguished by the presence of such genera as *Dicranograptus, Dicellograptus, Leptograptus* associated with *Nemagraptus* at the base and at a higher horizon with *Pleurograptus,* the two last-named forms being branched Leptograpti; also, except for *Didymograptus,* which only extends into the Gisbornian, the dichograptids are absent.

The diplograptid element is even stronger than in the Middle Ordovician and is characterized by large Orthograpti as Elles has pointed out, but the absence of dichograptids and the presence of the leptograptid elements are notable features.

In the Upper Ordovician rocks of Victoria some bedding planes are covered with forms at approximately the same stage of growth with only an occasional fully grown specimen present, while on other bedding planes, often only a fraction of an inch away, the majority of forms are of other species, which may or may not be fully developed. In our Victorian Upper Ordovician sequence it is therefore important in each locality to take samples from many bedding planes to ensure that the assemblage obtained is characteristic of these horizons.

There are two " bursts " of branched leptograptids in the Upper Ordovician, the Nemagrapti at the base of the Gisbornian and the Pleurograpti at the base of the Bolindian; the earlier " burst " is one of the really striking events in the evolution of graptolites as it marks the incoming of the leptograptid fauna, while the later burst, apart from *Orthograptus quadrimucronatus,* contains no large Orthograpti and no *Dicranograptus* ; the absence of *Dicranograptus* in the assemblages of this later burst of Pleurograpti is a feature of world-wide stratigraphic significance.

Gisbornian

The Zone of Nemagraptus gracilis—The burst of the " Leptograptid " Fauna at the base of the Gisbornian takes place very suddenly and, although *Nemagraptus* itself occurs rather sporadically, the assemblage in these horizons is readily recognizable. *Glyptograptus teretiusculus* is still abundant, together with larger forms of Orthograpti such as the varieties of *O. calcaratus* and varieties of *O. truncatus* and *O. whitfieldi.* Climacograpti have also become quite abundant and these are represented by forms allied to *C. antiquus* and *C. bicornis* ; in the forms allied to *C. bicornis* the large pendent proximal spines appear to be normal.

Cryptograptus tricornis remains abundant in this zone, while *Dicellograptus sextans* is exceedingly abundant in certain bands ; these are associated with *Dicellograptus intortus, D. divaricatus, Dicranograptus nicholsoni, D. ramosus* and, among the Leptograpti, *L. validus* and *L. grandis.*

The Zone of Climacograptus peltifer *and* Diplograptus multidens—As Elles pointed out (1925, p. 341) " the changes in the appearance of *Climacograptus bicornis* on successive horizons can be used as indices of age. In this zone the spines at the proximal end become more conspicuous and stout stiff structures with a slight downward tendency. In the succeeding zone the two basal thecae are entirely modified to spines which are thick downward growing structures ". In this zone *Dicranograptus zig zag, D. rectus, D. nicholsoni* and *D. ramosus* are abundant, while *Dicellograptus sextans* and var. *exilis, D. divaricatus* and *D. patulosus* are characteristic. *Diplograptus multidens* and the large forms of the *Orthograptus calcaratus* group are also very abundant.

The zone is characterized by the absence of Nemagrapti and the presence of *Climacograptus peltifer* and/or *Diplograptus multidens.*

Eastonian

The Zone of Climacograptus baragwanathi—The large Orthograpti such as *O. vulgatus* and *O. truncatus* var. *intermedius,* together with *Diplograptus ingens,* are very abundant in this zone. In Victoria there is no record of *Climacograptus wilsoni,* but its variety *tabularius* has been used as a zonal form in New South Wales. Its place in Victoria is taken by *Climacograptus baragwanathi,* in which the proximal sac is replaced by an anastomizing meshwork. Dicranograpti are abundant, as are also the Leptograpti and Dicellograpti.

The Zone of Dicranograptus hians—The zonal form, *Dicranograptus hians,* is exceedingly abundant and it is characterized by a small parallel-sided spinose biserial portion and long arms ; the angle of divergence of the arms shows considerable variation.

Typical of this zone are *Dicellograptus morrisi, D. elegans, D. caduceus, Climacograptus caudatus, C. tubuliferus, Orthograptus calcaratus, O. truncatus, Leptograptus flaccidus* and *L. eastonensis.*

The assemblages are characterized by the large Diplograpti, including *Diplograptus ingens,* Dicranograpti of the type of *D. hians,* as well as the better known *D. nicholsoni, D. ramosus* and its varieties, and in the upper part by *D. thielei,* probably the last of the Dicranograpti in Victoria. In the higher beds forms such as *O. quadrimucronatus* are common and the Leptograpti present are close to *L. flaccidus,* while *Amphigraptus* also occurs sparingly.

Hallograptus, Neurograptus, Nymphograptus and *Plegmatograptus* are characteristic and many of the forms pass upwards to the beds containing *Pleurograptus.*

Bolindian

The Bolindian stage as at present accepted commences with the zone of *Pleurograptus linearis.* The lower division of the Bolindian is characterized by the " burst " of the many branched *Pleurograptus* which takes place after the disappearance of the Dicranograpti.

The zonal form *Pleurograptus,* as in the case of the earlier *Nemagraptus,* occurs sporadically. The Dicellograpti continue to be abundant, and many of the forms occurring in the older beds also persist. *Dicellograptus elegans* and *D. forchammeri* are characteristic, and these are associated with many Leptograpti of the type of *L. capillaris, L. flaccidus* and its varieties including *L. eastonensis* ; *Climacograptus caudatus, C. tubuliferus, C. bicornis, Orthograptus quadrimucronatus, Orthograptus pageanus* and *O. truncatus* var. *pauperatus* are also abundant. Records of the occurrence of *Dicranograptus* in the *Pleurograptus* zone are not reliable.

The Zone of Dicellograptus *cf.* complanatus—There is a gradual change in lithology at this horizon and up to the present it has been impossible to separate the two zones of the Ashgillian as in Great Britain. The common *Dicellograptus* is of the *complanatus* group with the characteristic thecae but with a somewhat broader axil than in the English form. Most of the large Orthograpti are now absent and the commonest biserial form is *Orthograptus truncatus* var. *abbreviatus* and var. *socialis. Climacograptus scalaris* and var. *miserabilis* and var. *normalis* are characteristic, as well as *C. uncinatus,* but owing to the method of preservation no biprofile view of this form has been obtained. This horizon also marks the reappearance of Glyptograpti with forms such as *G. tamariscus, G. sinuatus,* which also pass up into the Silurian. *Retiograptus pulcherrimus* is also abundant.

Silurian

The Monograptid Fauna—The general succession for Britain as summarized by Elles (1922) has been utilized in the zoning of the Silurian in Victoria. Elles has shown that the uniserial scandent Monograpti developed along two main lines, not mutually exclusive, one by the increase of isolation and the other by lobation of the thecae. The hooked variant of this line carried on longer, reaching its acme in *M. priodon,* then declined in a gradual process of unhooking so that there is a reversion to simple thecal types as in *M. dubius* and *M. tumescens.* The simple type of thecae, however, may persist in certain forms right through the range of the Monograptid fauna.

Four divisions of the Silurian are recognized in Victoria and they are correlated with the Silurian of Britain as follows :

Victoria	*Britain*
4. Tanjilian	Upper Ludlow
3. Melbournian	Lower Ludlow
2. Eildonian	Wenlock
1. Keilorian	Llandovery

Graptolites are found in the three lowest divisions, but they are rare in the Eildonian in Victoria and somewhat more abundant in equivalent horizons in New South Wales. As yet it has not been possible to map the boundaries of any of the major divisions with certainty owing to the lack of mappable units ; however, there is a facies change in the Upper Silurian east of Melbourne where the green mudstones and shales pass into black siltstones in which *Monograptus uncinatus* and its variants occur in association with *Baragwanathia,* one of the oldest land plants. In the Silurian black mudstones east of Melbourne shelly fossils are absent and no zonal sequence based on graptolites has yet been possible.

Work along the lines carried out by Jaeger (1958) in Europe will no doubt enable the variants of *Monograptus uncinatus* to be separated as some forms occur low in the Lower Ludlow while others are found at much higher horizons. The statistical work necessary for this, however, needs well-preserved material. The *M. uncinatus-Baragwanathia* beds are succeeded by the *Panenka-Styliolina-" Orthoceras "* assemblage of the Tanjilian, which occurs beneath the basal conglomerates of the Walhalla beds, generally regarded as the base of the Lower Devonian.

Keilorian

The lower beds are characterized by an assemblage of Diplograpti, Climacograpti and other forms which are now being investigated, some of which are *Akidograptus* and *Dimorphograptus.* The lowest Victorian Monograptid recorded is *Monograptus concinnus,* which occurs with *Glyptograptus tamariscus, G. sinuatus* and *Climacograptus* spp. Up to the present *Diplograptus modestus* and its varieties have not been found. At about the same horizon *Monograptus fimbriatus* also occurs.

Above the first conglomerate in Jackson's Creek (Thomas and Keble, 1953) *Monograptus sedgwicki* has been recorded and slightly higher *M. turriculatus, M. exiguus, M. marri, M. pandus, M. spiralis* var. and *Stomatograptus australis* have been found. These horizons are widespread in south-eastern Australia and they have been found at several localities in Victoria, New South Wales and lately in Queensland. Forms with lobate and hooked thecae are very characteristic and, while *Monograptus priodon* appears with these forms, it also extends into higher beds. The upper half of the Keilorian (Llandovery) is easily recognized by the abundance of the coiled and twisted forms such as *Monograptus convolutus, M. spiralis, M. discus, M. turriculatus,* etc.

Eildonian

Graptolites are quite rare in this stage. *Monograptus priodon* and *M. vomerinus* and some of its variants, however, are found.

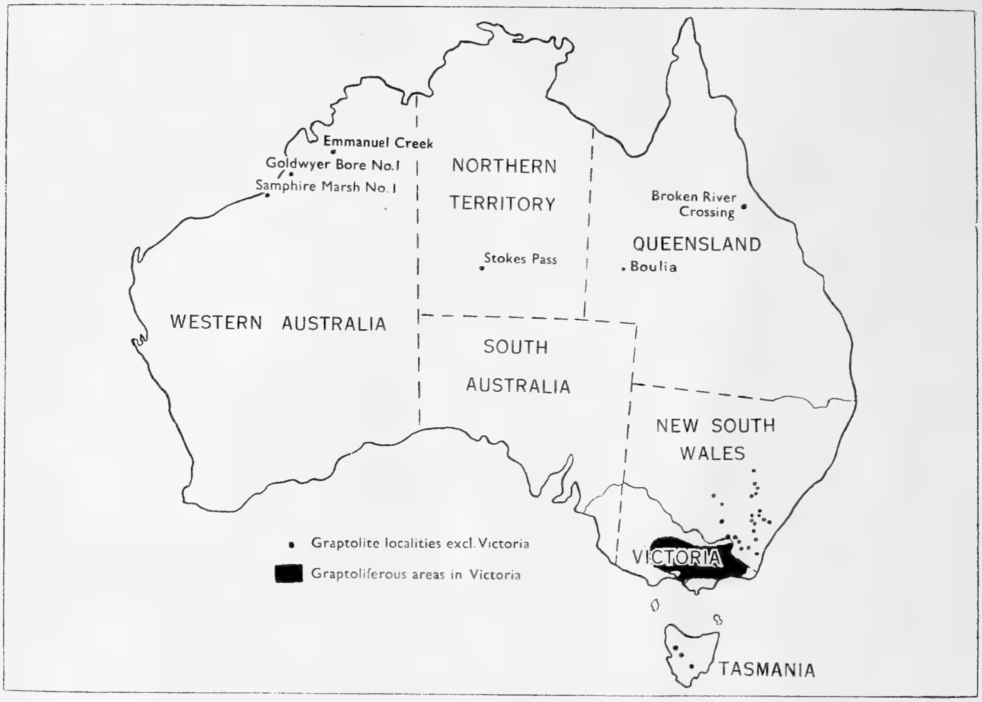


FIG. 5
Graptolite distribution in Australia.

Towards the top of the Eildonian *M. testis* has recently been found as well as *M. dubius*, which ranges into the Melbournian.

The characteristic burst of Cyrtograpti appears to be absent in Australia although *Cyrtograptus insectus* is present in New South Wales and a new species is present in Tasmania. No doubt detailed search will yield many more of these forms in the future. The great abundance of the pseudo-branched Cyrtograptids, which is typical of the Middle Silurian of Europe, is unfortunately absent in Australia.

Melbournian

In the higher beds of the Silurian graptolites belonging to the *Monograptus colonus* group are of frequent occurrence and typical forms have been recorded. Many have the " biform thecae ", e.g. *M. colonus* et vars., *M. roemeri*, *M. dubius* and *M. varians*. The only record in Australia of *Linograptus* sp. is from New South Wales. Among the characteristic forms from the Lower Ludlow are : *Monograptus bohemicus*, *M. colonus*, *M. colonus* var. *compactus*, *M. varians*, *M. nilsoni*, *M. comis*, *M. roemeri*, *M. dubius*, *M. crinitus*, *M. chimaera*, *Plectograptus* sp. and in the black mudstones east of Melbourne, *M. uncinatus* and varieties.

Recent Discoveries in Australia

Within recent years graptolites have been found in most States of Australia, whereas previously all undoubted records were confined to Victoria and to the southern parts of New South Wales. In recent times there have been discoveries from Queensland (from the Broken River crossing, inland from Townsville) and careful work and collecting in Tasmania have yielded graptolites of various ages.

Graptolites from Queensland are found in siltstones and mudstones indistinguishable lithologically from those of Victoria and New South Wales. The following forms are present (see Pl. XV).

Monograptus griestoniensis
M. convolutus
M. marri, etc.

The horizon is high Llandovery or in Victorian nomenclature high Keilorian.

From Tasmania, due to the careful and persistent collecting by M. R. Banks, there are several occurrences now known. Three horizons are indicated : Junee area with *Didymograptus gracilis*, *Clonograptus*, *Tetragraptus*, *Didymograptus* of the type of *mundus*, *Didymograptus* *gracilis* and *Phyllograptus*. The horizon of these is Lower Ordovician. Farther to the N.W. in the Queenstown district two horizons are indicated : *Cyrtograptus* sp. nov. indicative of Middle Silurian (Wenlock) age and many forms from the Bell Shale among which can be identified *Monograptus colonus* et var. indicative of Melbournian age (Lower Ludlow).

In the Tasman geosyncline graptolites have been found to extend over a distance of very nearly 2000 miles and the distance from the well known exposures in New South Wales to the newly discovered ones in Queensland is approximately 1000 miles. No doubt close collecting in this geosyncline is going to yield many new graptolite localities.

In Western Australia graptolite-bearing Ordovician rocks have been found outcropping at Emmanuel Creek. Through the kindness of Professor Prider I have been able to examine these forms and have identified *Didymograptus*, *Tetragraptus* and *Clonograptus*. They occur in limestone and are exceedingly well preserved but no doubt intensive collecting in this locality will yield a varied fauna. The horizon is Lower Ordovician (Arenig).

Through the kindness of Dr. Ross McWhae of Ampol and the Bureau of Mineral Resources, Geology and Geophysics, cores have been submitted which contain graptolites. From the Samphire No. 1 bore *Amplexograptus arctus* and *A. perexcavatus* have been obtained, indicating a Middle Ordovician horizon. Goldwyer No. 1 bore has yielded *Tetragraptus* and *Clonograptus*, indicative of Arenig age.

About 120 miles west of Alice Springs at Stokes Pass the Bureau of Mineral Resources, Geology and Geophysics have found Lower Ordovician graptolites in limestone. This form is very close to *Didymograptus patulus* and the horizon indicated is Lower Ordovician (Arenig). No doubt in the near future many more localities will be found.

A summary of the New South Wales graptolites has been given by Mrs. Sherrard in various publications, and I have been informed by Dr. G. Packham that he has found Lower Ordovician graptolites in the Snowy River area. Work he has carried on in the Silurian sequence will, when published, increase our knowledge of these forms and assemblages.

Acknowledgments

This compilation could not have been prepared without the knowledge passed on and the discussions with the late Dr. W. J. Harris and Mr. R. A. Keble.

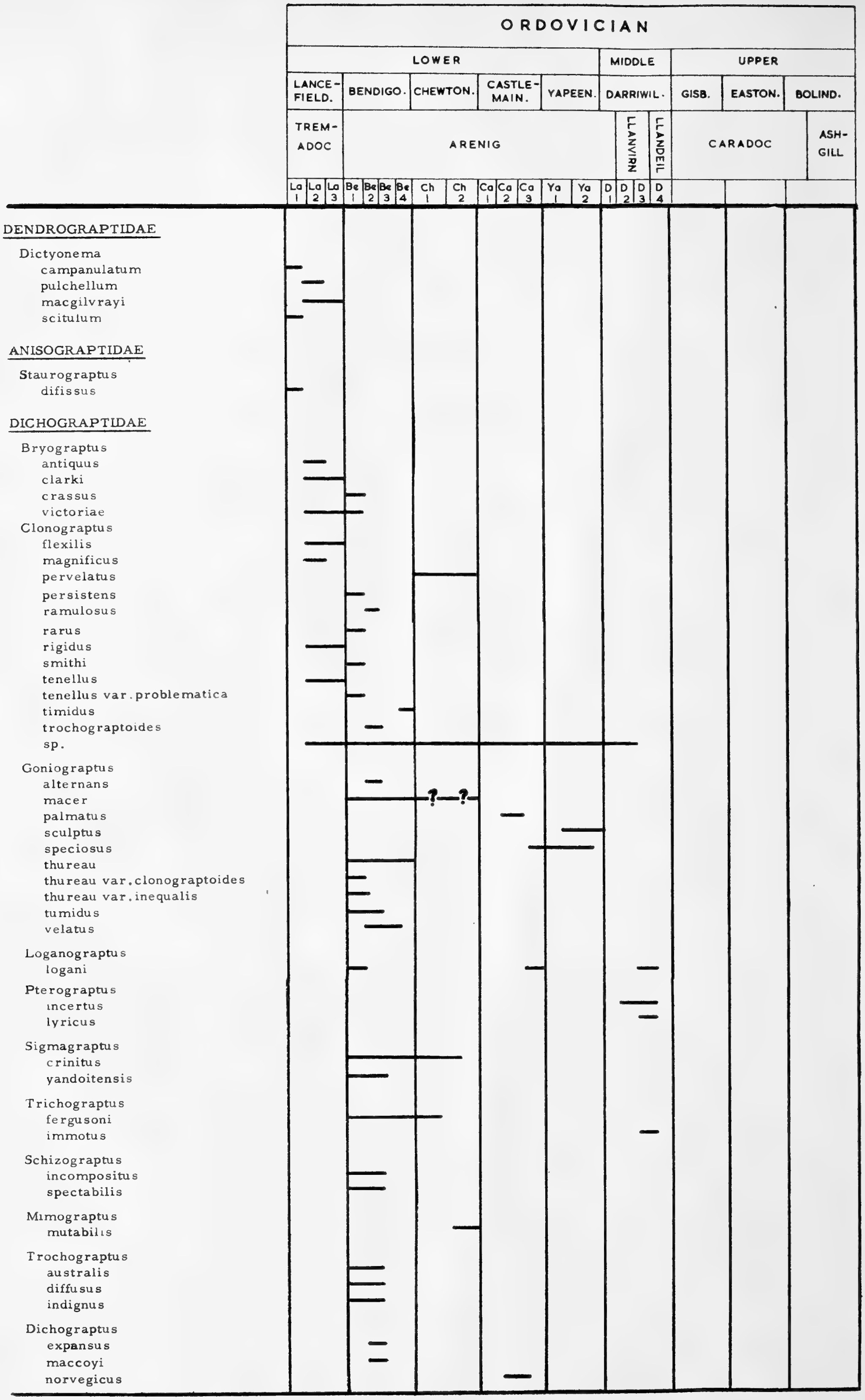
Thanks are due to Professor Prider for making available material from Emmanuel Creek ; to Dr. McWhae for specimens from the wells in Western Australia ; to Mr. Maxwell Banks by whose untiring efforts graptolites have been found in Tasmania ; and to these people for permission to refer to these discoveries.

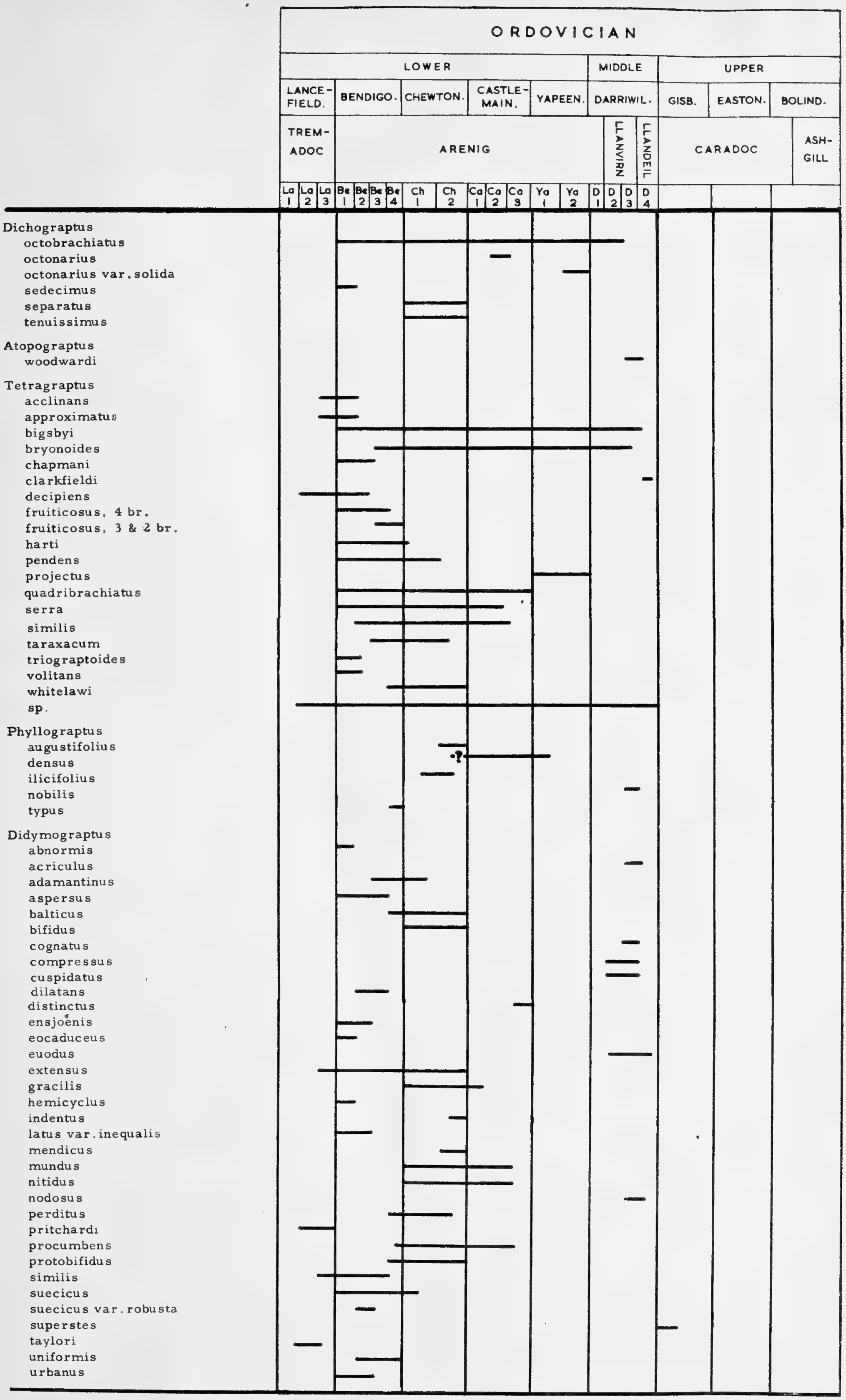
Many thanks are also due to the Bureau of Mineral Resources who sent me their collections from the Northern Territory, Western Australia and Queensland.

Without co-operation from all these people and Mrs. Sherrard in N.S.W., it would not have been possible to summarize these occurrences.

To members of my staff I owe a great deal, and in particular to Mr. G. Bell, who has prepared the plates, photographed these forms, and prepared the Bibliography and the tables of zonal ranges.

Geological Survey of Victoria,
Melbourne, Victoria.


ORDOVICIAN
LOWER
MIDDLE
UPPER
LANCEFIELD.
BENDIGO.
CHEWTON.
CASTLEMAIN.
YAPEEN.
DARRIWIL.
GISB.
EASTON.
BOLIND.
TREMADOC
ARENIG
LLANVIRN
LLANDEIL
CARADOC
ASHGILL
La 1
La 2
La 3
Be 1
Be 2
Be 3
Be 4
Ch 1
Ch 2
Ca 1
Ca 2
Ca 3
Ya 1
Ya 2
D 1
D 2
D 3
D 4
DENDROGRAPTIDAE
Dictyonema
campanulatum
pulchellum
macgilvrayi
scitulum
ANISOGRAPTIDAE
Staurograptus
difissus
DICHOGRAPTIDAE
Bryograptus
antiquus
clarki
crassus
victoriae
Clonograptus
flexilis
magnificus
pervelatus
persistens
ramulosus
rarus
rigidus
smithi
tenellus
tenellus var. problematica
timidus
trochograptoides
sp.
Goniograptus
alternans
macer
?
?
palmatus
sculptus
speciosus
thureau
thureau var. clonograptoides
thureau var. inequalis
tumidus
velatus
Loganograptus
logani
Pterograptus
incertus
lyricus
Sigmagraptus
crinitus
yandoitensis
Trichograptus
fergusoni
immotus
Schizograptus
incompositus
spectabilis
Mimograptus
mutabilis
Trochograptus
australis
diffusus
indignus
Dichograptus
expansus
maccoyi
norvegicus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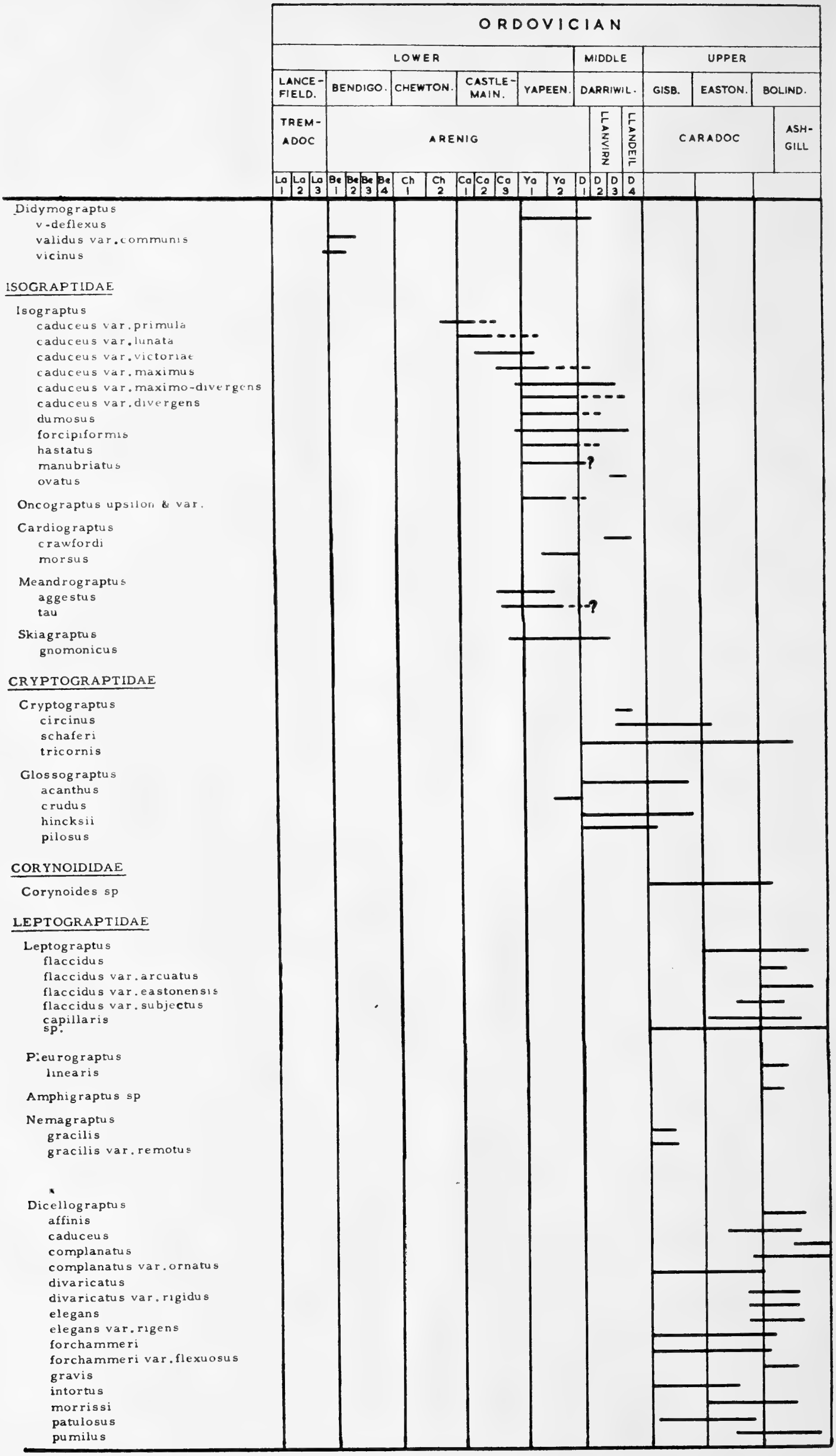
CHEWTON.
CASTLEMAIN.
YAPEEN.
DARRIWIL.
GISB.
EASTON.
BOLIND.
TREMADOC
ARENIG
LLANVIRN
LLANDEIL
CARADOC
ASHGILL
La 1
La 2
La 3
Be 1
Be 2
Be 3
Be 4
Ch 1
Ch 2
Ca 1
Ca 2
Ca 3
Ya 1
Ya 2
D 1
D 2
D 3
D 4
Dichograptus
octobrachiatus
octonarius
octonarius var. solida
sedecimus
separatus
tenuissimus
Atopograptus
woodwardi
Tetragraptus
acclinans
approximatus
bigsbyi
bryonoides
chapmani
clarkfieldi
decipiens
fruiticosus, 4 br.
fruiticosus, 3 & 2 br.
harti
pendens
projectus
quadribrachiatus
serra
similis
taraxacum
triograptoides
volitans
whitelawi
sp.
Phyllograptus
augustifolius
densus
?
ilicifolius
nobilis
typus
Didymograptus
abnormis
acriculus
adamantinus
aspersus
balticus
bifidus
cognatus
compressus
cuspidatus
dilatans
distinctus
ensjoenis
eocaduceus
euodus
extensus
gracilis
hemicyclus
indentus
latus var. inequalis
mendicus
mundus
nitidus
nodosus
perditus
pritchardi
procumbens
protobifidus
similis
suecicus
suecicus var. robusta
superstes
taylori
uniformis
urbanus


ORDOVICIAN
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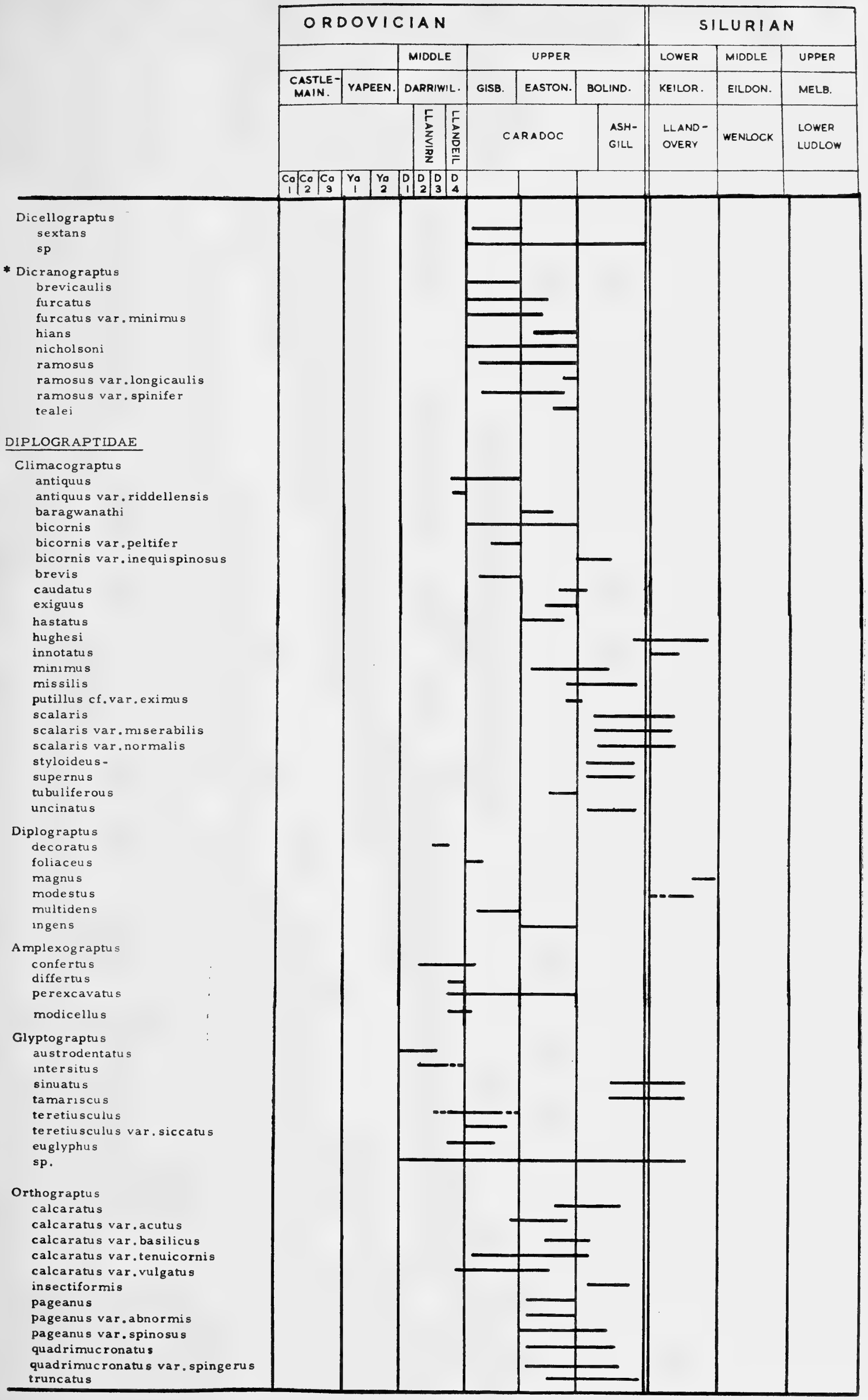
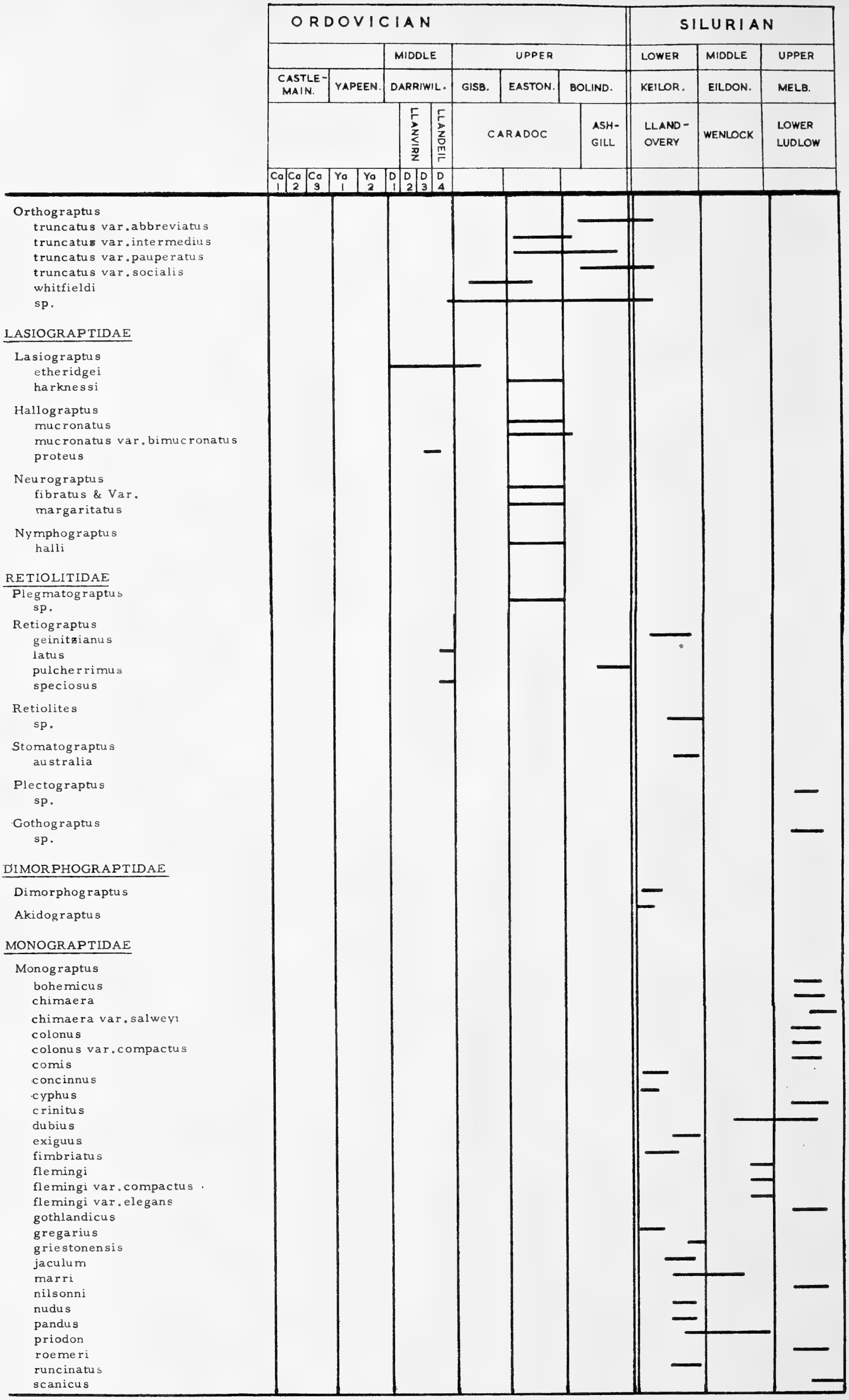
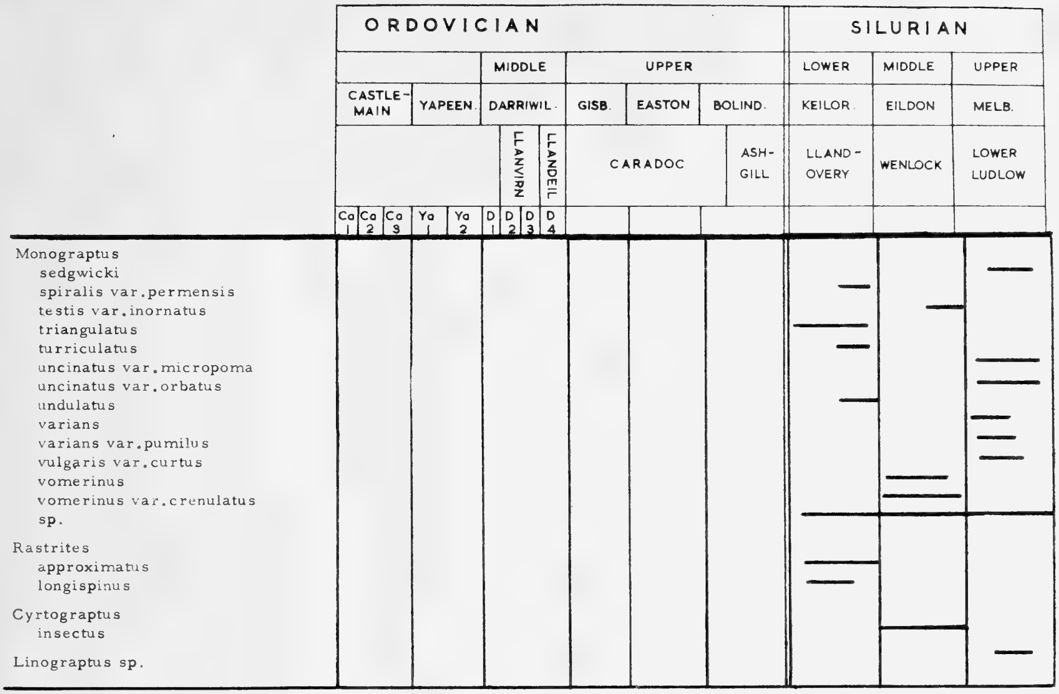
BENDIGO.
CHEWTON.
CASTLEMAIN.
YAPEEN.
DARRIWIL.
GISB.
EASTON.
BOLIND.
TREMADOC
ARENIG
LLANVIRN
LLANDEIL
CARADOC
ASHGILL
La 1
La 2
La 3
Be 1
Be 2
Be 3
Be 4
Ch 1
Ch 2
Ca 1
Ca 2
Ca 3
Ya 1
Ya 2
D 1
D 2
D 3
D 4
Didymograptus
v-deflexus
validus var. communis
vicinus
ISOGRAPTIDAE
Isograptus
caduceus var. primula
caduceus var. lunata
caduceus var. victoriae
caduceus var. maximus
caduceus var. maximo-divergens
caduceus var. divergens
dumosus
forcipiformis
hastatus
manubriatus
ovatus
Oncograptus upsilon & var.
Cardiograptus
crawfordi
morsus
Meandrograptus
aggestus
tau
Skiagraptus
gnomonicus
CRYPTOGRAPTIDAE
Cryptograptus
circinus
schaferi
tricornis
Glossograptus
acanthus
crudus
hincksii
pilosus
CORYNOIDIDAE
Corynoides sp
LEPTOGRAPTIDAE
Leptograptus
flaccidus
flaccidus var. arcuatus
flaccidus var. eastonensis
flaccidus var. subjectus
capillaris
sp.
Pleurograptus
linearis
Amphigraptus sp
Nemagraptus
gracilis
gracilis var. remotus
Dicellograptus
affinis
caduceus
complanatus
complanatus var. ornatus
divaricatus
divaricatus var. rigidus
elegans
elegans var. rigens
forchammeri
forchammeri var. flexuosus
gravis
intortus
morrissi
patulosus
pumilus
?
?
?



* The title DICRANOGRAPTIDAE was inadvertently omitted here.


ORDOVICIAN
SILURIAN
MIDDLE
UPPER
LOWER
MIDDLE
UPPER
CASTLEMAIN.
YAPEEN.
DARRIWIL.
GISB.
EASTON.
BOLIND.
KEILOR.
EILDON.
MELB.
LLANVIRN
LLANDEIL
CARADOC
ASHGILL
LLANDOVERY
WENLOCK
LOWER LUDLOW
Ca 1
Ca 2
Ca 3
Ya 1
Ya 2
D 1
D 2
D 3
D 4
Orthograptus
truncatus var. abbreviatus
truncatus var. intermedius
truncatus var. pauperatus
truncatus var. socialis
whitfieldi
sp.
LASIOGRAPTIDAE
Lasiograptus
etheridgei
harknessi
Hallograptus
mucronatus
mucronatus var. bimucronatus
proteus
Neurograptus
fibratus & Var.
margaritatus
Nymphograptus
halli
RETIOLITIDAE
Plegmatograptus
sp.
Retiograptus
geinitzianus
latus
pulcherrimus
speciosus
Retiolites
sp.
Stomatograptus
australia
Plectograptus
sp.
Gothograptus
sp.
DIMORPHOGRAPTIDAE
Dimorphograptus
Akidograptus
MONOGRAPTIDAE
Monograptus
bohemicus
chimaera
chimaera var. salweyi
colonus
colonus var. compactus
comis
concinnus
cyphus
crinitus
dubius
exiguus
fimbriatus
flemingi
flemingi var. compactus
flemingi var. elegans
gothlandicus
gregarius
griestonensis
jaculum
marri
nilsonni
nudus
pandus
priodon
roemeri
runcinatus
scanicus



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Appendix

Revised Bibliography of Australian Graptolites

Species and Synonyms

Abbreviations

aff.	related to
auct. non.	not author
Barr.	Barrande
Brongn.	Brongniart
Bul.	Bulman
Carr.	Carruthers
cf.	compare
Chapman & T.	Chapman and Thomas
desc.	description
Elles & W.	Elles and Wood
emend.	emendation
Eth.	R. Etheridge Jun.
fig.	figure
Harris & K.	Harris and Keble
Harris & T.	Harris and Thomas
His.	Hisinger
Hopk.	Hopkinson
Keble & B.	Keble and Benson
Keble & H.	Keble and Harris
Lapw.	Lapworth
Linn.	Linnarson
Murch.	Murchison
Nich.	Nicholson
nom. nud.	nomen nudum
Rued.	Ruedemann
syn.	synonym
Thomas & K.	Thomas and Keble
Torn.	Tornquist
Tull.	Tullberg
Sherr.	Sherrard
var.	variety
var. nov.	new variety
vide	see

Species and Synonyms	*Reference in Bibliography*
Amphigraptus divergens var. *radiatus* (Lapw.)	192
Anthograptus nidus Torn.	168
Archaeolafoea serialis Ch. & T.	176 (desc.) (cf.)
Atopograptus woodwardi Harris	*105* (desc.), 112, 131, 134, 135, 138, 157, 158, 169 ?
Brachiograptus etaformis Harris & K.	*121* (desc.), 135, 138, 157, 180, 190, 193
Bryograptus antiquus T. S. Hall, cf. *Leptograptus antiquus*	*39* (desc.), 40, 59, 69, 70, 87, 97, 111, 134, 135, 142, 156, 157
clarki T. S. Hall	*39* (desc.), 40, 87, 97, 134, 135, 137
crassus Harris & T.	*155* (desc.), 157, *177*
hunnebergensis Moberg	157
simplex Torn.	157
victoriae T. S. Hall, syn. with *Adelograptus* Bul.	*39* (desc.), 40, 59, 69, 70, 87, 97, 120, 121, 134, 135, 156, 157
Callograptus arundinosus Sherr.	196 (desc.)
disjectus Sherr.	196 (desc.)
salteri J. Hall	47 (cf.), 51 (cf.)
Cardiograptus crawfordi Harris	*105* (desc.), 121, 127, 131, 134, 138, 157, *169*
morsus Harris & K.	*81* (desc.), 90, 98, 105, 112, 119, 120, 121, 122, 127, 137, 138, 157, 193
Cladograptus furcatus J. Hall, syn. of *Dicranograptus furcatus, q.v.*	
ramosus J. Hall, syn. of *Dicranograptus ramosus, q.v.*	
Clathrograptus geinitzianus J. Hall, syn. of *Retiograptus geinitzianus, q.v.*	
Climacograptus affinis T. S. Hall	*42* (desc.), 180, 192
antiquus J. Hall	98, 126, 135, 157, *167*, 175, 180 (cf.) *187*, *192*, 196
var. *bursifer* Elles & W.	126, 175 (desc.)
var. *lineatus* Elles & W.	126, 175 (desc.)
var. *simulans* Thomas & K. M.S.	126

Species and Synonyms	*Reference in Bibliography*
baragwanathi T. S. Hall, syn. of *C. wilsoni*	*53* (desc.), 119, 191, 194 (desc.)
bicornis J. Hall	6, 8, 14, 19, 22, 30, 38, 40, 46, 52, 53, 57, 63, 69, 70, 75, 84, 90, 102, 116, 123, 126, 134, 135, 150, 161, 156, 157, 166, 169, 172, 175 (desc.), 179 (desc.), 172, 173*a*, 180, 181, 183, 184, 185, 187, 191, 192, 194, 195, 196
var. *longispina* T. S. Hall	*47* (desc.), 57, 84, 119
var. *peltifer* Lapw.	84, 90, 102, 123, 126, 134, 135, 157, 166, 172, 175 (desc.), 179 (desc.), 180, 187, 191, 192, 194
var. *tridentatus*, syn. of *C. bicornis*	179 (desc.), 192, 194
brevis Elles & W.	126, 131, 172, 173*a*, 179 (desc.), 180, 191, 192
caudatus Lapw.	37, 69, 70, 84, 86, 123, 126, 134, 135, 157, 159, 172, 173*a*, 175 (desc.), 179 (desc.), 180, 181, 185, 187, 191, 192, 194 (desc.)
var. *wellingtonensis*, syn. of *C. caudatus*	86
coelatus Lapw., cf. *Diplograptus coelatus*	47, 194
exiguus Keble & H.	*102* (desc.), 123, 126 (cf.), 194 (desc.)
hastata T. S. Hall	*47* (desc.), 51, 75, 84, 89, 175 (desc.), 194 (desc.), 192 (desc.)
hughesi (Nich.)	153, 175 (desc.), 189, 192
initui	195 (cf.)
innotatus Nich.	51 (cf.), 84 (cf.)
mensoris T. S. Hall	*53* (desc.), 84, 102, 119
minimus Carr.	123, 126, 131, 172, 183 (cf.), 185, 192
miserabilis, vide *C. scalaris* var. *miserabilis*	
missilis Keble & H.	*102* (desc.), 131, 161, 172
normalis Lapw.	42
putillus var. *eximius* Rued.	123, 126 (cf.), 175 (desc.)
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(*Neurograptus*) *fibratus* Lapw.	86 (cf.), 179 (desc.) (cf.)
(*Nymphograptus*) *halli* Harris & T.	194 (desc.)
(*Thysanograptus*) *harknessi* Nich.	172, 179 (desc.), 185, 192
(*Neur.*) *margaritatus* Lapw.	59, 84, 157, 179, 191, 194 (desc.)
(*Hallograptus*) *mucronatus* J. Hall, cf. *Diplograptus mucronatus*	156 (cf.), 157, 175 (desc.), 179 (desc.), cf. 187, 192
var. *bimucronatus*	192 (desc.)
(*H.*) *proteus* Harris & T.	*134* (desc.), 135, 138, 157
Leptograptus antiquus T. S. Hall, syn. of *Bryograptus antiquus, q.v. capillaris* Carr	102, 126, 159 (cf.), 181 (cf.), 192 (desc.)
eastonensis Keble & H.	*102* (desc.), 126, 131, 157, 191
flaccidus J. Hall	53, 70, 84, 86, 102, 126, 131, 145, 172, 175 (desc.), 191, 192 (desc.)
var. *angustus* Keble & B. (non Keble & H.)	*111* (desc.)
var. *subjectus* Keble & H.	*102* (desc.), 126
flexuosus Harris & T.	191
validus Lapw.	126 (cf.), 192 (cf.), 195 (cf.)
Linograptus	175, 186, 192
Loganograptus logani J. Hall	8, 11, 13, 14, 19, 22, 25, 28, 37, 40, 43, 68, 77, 78, 81, 90, 98, 105 (cf.), 120, 121, 131, 138 (cf.), 157, 162 (desc.), 175 (desc.)
var. *australis* McCoy	*14* (desc.), 22
var. *kjerulfi* Herrmann	117
rectus Harris & T.	162 (desc.), 177
Meandrograptus aggestus Harris	*127* (desc.)
tau Harris	*127* (desc.), 138
Mimograptus mutalibis Harris & T.	163 (desc.), 193

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Monograptus aplini T. S. Hall, emend. Keble & H., syn. of *M. exiguus*	*76* (desc.), 107, 131 (emend.), 136, 154, 170, 180
barrandei Lapw.	141, 143, 159
bohemicus (Barr.)	126, 136, 141, 143, 152, 153, 154, 159, 175 (desc.), 180, 186 (desc.), 192, 195
var. *tenuis*	195, 196
chimaera Barr.	107, 126, 136, 152, 159, 180, 192
var. *salweyi* Hopk.	186 (desc.), 192, 196
colonus Barr.	107, 118, 126, 136, 159, 180
var. *compactus* Wood	126, 132, 153, 154, 180
comis Wood	126, 154 (cf.)
concinnus Lapw.	66 (?), 71 (cf.), 107 (cf.), 136 (cf.), 176 (cf.), 178 (cf.), 180
convolutus His.	118
crenulatus Torn.	57, 71, 99 (cf.), 104, 107 (cf.), 136 (cf.), 180 (cf.)
crinitus Wood	154, 175 (desc.), 186 (desc.), 192
crispus Lapw.	107, 136 (cf.), 178 (desc.), 180
cutellus Torn.	101 (cf.), 107 (cf.), 180 (cf.)
cyphus Lapw.	67 (?), 71 (cf.), 107 (cf.)
decipiens Torn.	143 (cf.), 159 (cf.), 180 (cf.)
dubius (Suess.)	40 (cf.), 45 (cf.), 53, 57 (cf.), 71 (cf.), 99 (?), 104, 107, 118, 126, 131 (cf.), 136 (cf.), 154, 169 (cf.), 175 (desc.), 180, 186 ? (cf.), 188, 192, 195 (cf.)
exiguus (Nich.)	76, 107, 118, 126, 131, 141, 143, 154, 159, 169, 170, 174, 180, 188, 190, 192
fimbriatus Nich.	126, 140 (cf.), 180 (cf.)
flemingi (Salter)	150, 186, 192, 180
var. *compactus* Elles & W.	185 (desc.), 192
var. *elegans* Elles & W.	185 (desc.), 192
var. *primus*	189, 192
galaensis Lapw.	37 (cf.), 126, 139, 154, 164, 188 (cf.), 192 (cf.)
gregarius Lapw.	126, 178 (cf.), 188, 192
griestoniensis (Nicol)	126, 195 (cf.)
halli	178 (cf.)
initialis	195 (cf.)
intermedius Carr.	189, 192 (desc.)
jaculum Lapw.	126, 180
jaekeli Perner	99 (cf.)
leintwardensis var. *primus* (Pack & Stevens)	195, 196
linnarasoni	195 (cf.)
leptotheca Lapw.	101, 107
lobiferus McCoy	36, 40
ludensis Murch., cf. *M. priodon*	6, 8, 11, 16, 19, 40
marri Perner	126, 175 (desc.), 178 (desc.), 180, 188, 189, 192, 195
McCoyi Lapw.	101, 107 (cf.), 180
melbournensis Thomas & K., M.S.	126
nilssoni Barr	118, 126 (cf.), 141, 150 (cf.), 153, 154 (aff.), 159, 165 (cf.), 175 (desc.), 180, 186 (desc.), 192, 195, 196
nodifer Torn.	107, 177 (cf.)
nudus Lapw.	154 (?), 180, 189 (?)
pandus Lapw.	126, 131, 169, 175 (desc.), 178 (desc.), 195
pragensis pragensis	195

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priodon Bronn., cf. *M. ludensis* Murch.	19, 37, 40, 71, 76, 107, 118, 126, 136, 154, 175 (desc.), 180, 188, 189, 192, 195
probosciformis	195
proetus Barr.	101 (cf.), 180
riccartonensis Lapw.	71, 107, 111, 118, 128, 136, 139, 154, 180
roemeri Barr.	107, 126, 186 (desc.), 180, 192
runcinatus Lapw.	153, 175 (desc.)
scanicus Tull.	131, 186
sedgwicki Portlock	126, 136, 180 (cf.)
spiralis Geinitz	159, 175 (desc.), 190
var. *permensis* Keble & H.	126, 131 (desc.), 154, 169, 180
testis var. *inornatus* Elles & W.	185 (desc.), 192, 195 (cf.)
tortilis Perner	143 (cf.), 159, 180 (cf.)
triangulatus Hark.	189, 192 (desc.), 195
tumescens Wood	150 (cf.), 179 (cf.), 180 (cf.), 186 (cf.), 192 (cf.)
turriculatus Barr.	76, 107, 118, 131, 136, 169, 178 (desc.), 180, 190
uncinatus var. *micropoma* (Jaekel)	139, 154, 174
var. *orbatus* Wood	139, 154, 169
var.	153, 164, 170, 192
undulatus Elles & W.	143, 159, 178 (desc.)
varians Wood	107, 126, 136, 153, 154, 175 (desc.), 180
var. *pumilus* Wood	153, 175 (desc.)
vomerinus (Nich.)	150 (cf.), 154, 175 (desc.), 180, 186 (desc.), 185, 192
var. *crenulatus* (Torn.)	154, 180
vulgaris var. *curtus* Elles & W.	126, 175 (desc.), 188 (cf.), 192 (cf.), 195
Nemagraptus explanatus Elles & W.	192
var. *pertenuis* Lapw.	192 (desc.), 196
gracilis J. Hall, vide *Coenograptus gracilis*	16, 19, 22, 40, 70, 84, 90, 98, 126, 134, 135, 157, 172, 175 (desc.), 180, 187, 191
remotus Elles & W.	191
Oncograptus biangulatus Harris & K.	*81* (desc.), 98, 122, 127, 137, 138, 146, 157
upsilon T. S. Hall	*76* (desc.), 81, 90, 98, 112, 127, 138, 146, 157, 175 (desc.), 180, 193
Phyllograptus angustifolius J. Hall	32, 37, 40, 46, 53, 61, 77, 81, 101, 145, 157, 175 (desc.)
anna J. Hall	81, 132 (cf.), 134 (cf.), 175 (desc.), 190
folium et var. *typus*, syn. of *P. typus*	
ilicifolius J. Hall	135, 157, 175
nobilis Harris & K.	*121* (desc.), 123 (cf.), 127, 131, 137 (cf.), 138, 148, 157, 191
ovatus, syn. of *P. typus*	
typus (J. Hall)	6, 8, 11, 13, 14, 16, 19, 22, 25, 28, 32, 34 (cf.), 37, 40, 51, 53, 56, 57, 59, 61, 68, 70, 77, 81, 87 (cf.), 90 (cf.), 95, 96, 98, 121 (cf.), 127, 157 (cf.), 175 (desc.)
Plegmatograptus nebula Elles & W.	169, 192
Pleurograptus linearis Carr.	191, 192
var. *dispansa* Thomas & K., M.S.	126
Pterograptus incertus Harris & T.	*134* (desc.), 138, 157
lyricus Keble & H.	*131* (desc.), 138
Ptilograptus discurrens Sherr.	196 (desc.)
plumosus J. Hall	51 (cf.)
scalaris Sherr.	196 (desc.)

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Rastrites approximatus	189 (cf.)
barrandei Harkness	16
longispinus	189, 192 (?)
Reticulograptus undulosum Sherr.	196 (desc.)
Retiograptus latus Keble & B.	111, 126 (?), 161
pulcherrimus Keble & H.	126, *131* (desc.), 134, 135, 157, 159, 180, 181 (cf.), 192
geinitzianus J. Hall	47 (cf.), 69, 70, 84, 86 (?), 90, 98, 156, 175 (desc.), 188, 192 (desc.)
speciosus Harris	*98* (desc.), 102 (?), 126, 157
tentaculatus J. Hall	98, 127, 175 (desc.)
yassensis Sherrard & Keble	*150* (desc.), 161, 172, 192
Retiolites australis, syn. of *Stomatograptus australis* (McCoy)	
caudatus, syn. of *R.* (*P.*) *nebula*	*47* (desc.), 53
(*Plegmatograptus*) *nebula* Elles & W.	*47* (desc.), 53, 119, 179 (desc.)
Schizograptus incompositus Harris & T.	*155* (desc.), 157, 177
spectabilis Harris & T.	*155* (desc.), 157
Sigmagraptus crinitus, cf. *Goniog crinitus* T. S. Hall	160 (desc.)
laxus (T. S. Hall)	76, 101, 120, 121, 131, 142
yandoitensis Harris & T.	*155* (desc.), 177
Skiagraptus gnomonicus (Harris & K.), cf. *Diplograptus gnomonicus*	*81* (desc.), 119, 120, 121, 127, 137, 138, 193
Staurograptus diffisus Harris & K.	*109* (desc.), 120, 121, 134, 135, 157, 180
Stephanograptus gracilis J. Hall	37
Stomatograptus australis (McCoy)	*16* (desc.), 19, 37, 40, 71, 107, 118, 126, 131, 136, 169, 180
Strophograptus trichomanes (Rued.)	81, 120, 121, 175 (desc.)
Syndyograptus	
Temnograptus magnificus Pritchard, syn. of *Clonograptus magnificus*	
multiplex Nich.	23, 27
Tetragraptus acclinans Keble	*87* (desc.), 101 (cf.), 120, 121, 131, 134, 135, 155, 156 (cf.), 157, 180
amii Elles & W., syn. of *T. serra*	32
approximatus Nich.	51, 53, 56, 57, 64, 69, 70, 77, 81, 87, 91, 92, 93, 97, 120, 121, 127, 130, 131, 134, 135, 137, 155, 157, 175 (desc.), 177, 180
bigsbyi (J. Hall)	13, 29, 145
bryonoides (J. Hall)	11, 13, 14, 19, 22, 25, 28, 29, 53, 56, 59, 61, 70, 77, 87, 95, 101, 127, 134, 135
caduceus, vide *Isograptus caduceus*	
chapmani Keble & H.	*131* (desc.), 155 (?)
clarkei Rued.	77, 88, 175 (desc.)
clarkfieldi Thomas & K., M.S.	126, 157
decipiens T. S. Hall	11 (cf.), *39* (desc.), 40, 56, 57, 59, 69, 70, 87, 91, 92, 97, 101, 119, 120, 121, 123, 129, 130, 131, 133*a*, 134, 135, 137, 149, 156 (cf.), 157, 180
var. *bipatens* Keble & H.	*131* (desc.)
defensus Harris & T.	*134* (desc.)
denticulatus J. Hall	37
fruiticosus J. Hall	19, 22, 25, 28, 37, 40, 53, 57, 59, 68, 69, 70, 81, 87, 90, 129, 131, 138, 155, 157, 175 (desc.), 180

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fruticosus (2-branched), syn. of *Didymograptus pantoni*	
fruticosus (3-branched) J. Hall	13, 14, 51, 53, 56, 61, 70, 77, 81, 93, 101, 120, 121, 127, 130, 134, 135, 157
fruticosus (4-branched) J. Hall	14, 16, 51, 53, 70, 77, 81, 90, 93, 101, 120, 121, 130, 131, 134, 135, 156, 157, 177
harti T. S. Hall	*76* (desc.), 87, 101, 121, 149 (cf.), 155, 163
headi (J. Hall)	18, 22, 37, 40, 127 (?), 138, 175 (desc.)
pantoni Eth. non McCoy, vide *Didymograptus pantoni* Eth.	
pendens Elles	53, 56, 59, 61, 69, 70, 77, 81, 87, 90, 101, 120, 121, 145, 157, 175 (desc.)
projectus T. S. Hall	*40* (desc.)
quadribrachiatus J. Hall	6, 8, 11, 13, 14, 19, 22, 25, 27, 28, 32, 37, 40, 51, 53, 56 (cf.), 57, 59, 61, 68, 69, 70, 77, 81, 87, 90, 95, 96, 98, 101 (cf.), 105, 120, 121, 122, 123, 126, 127, 131, 134, 135, 138, 145, 167, 169 (cf.), 175, 180, 192
serra (Brongn.)	29, 37, 40, 51, 53, 56, 57, 58, 59, 61, 68, 69, 70, 77, 81, 87, 90, 95, 101, 121, 122, 127, 134 (cf.), 135 (cf.), 137, 138, 145, 157, 175 (desc.)
similis (J. Hall), cf. *T. bigsbyi*	77, 81, 87, 120, 121, 127, 131, 175 (desc.)
tabidus Keble & B.	108 (cf.), 126 (cf.), 169 (cf.)
triograptoides Harris & T.	*155* (desc.), 163
vestrogothus Torn.	157
volitans Harris & T.	*155* (desc.), 177
whitelawi T. S. Hall..	*76* (desc.)
Thallograptus succulentus (Rued.)	147 (cf.)
Thamnograptus capillaris Emmons	98, 127 (cf.), 175 (desc.)
typus J. Hall	25, 37, 98
Triaenograptus neglectus T. S. Hall	*76* (desc.), 112
Trichograptus fergusoni T. S. Hall	*70* (desc.), 134, 155, 157
immotus Harris & T.	*134* (desc.), 157
Trigonograptus ensiformis J. Hall	40, 90, 98, 105, 120, 121, 127, 134 (cf.), 137, 138, 145, 156, 157, 169, 175 (desc.), 180, 190, 192
wilkinsoni T. S. Hall	*40* (desc.), 82, 98
Trochograptus australis Harris & T.	*154* (desc.)
diffusus Holm	154 (cf.)
indignus Harris & T.	*154* (desc.)
Tylograptus (Mu), see *Didymograptus nodosus*	
Zygograptus (*clonograptus*)	
abnormis (J. Hall)	168 (desc.), 175 (desc.)
ferrarius Harris & T.	168 (desc.)
irregularis Harris & T.	168 (desc.)
junori Harris & T.	168 (desc.)

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Explanation of Plates I to XV

PLATE I

LANCEFIELDIAN, Substage 1

Figs. 1	*Staurograptus diffissus*, ×1
Fig. 2	*Dictyonema scitulum*, ×1
Fig. 3	*Dictyonema campanulatum*, ×1

LANCEFIELDIAN, Substages 2 and 3

Fig. 4	*Dictyonema macgilvrayi*, ×½
Fig. 5	*Dictyonema pulchellum*, ×1
Fig. 6	*Bryograptus victoriae*, ×1
Fig. 7	*Bryograptus clarki*, ×1
Fig. 8	*Bryograptus antiquus*, ×1
Fig. 9	*Clonograptus rigidus*, ×1
Fig. 10	*Clonograptus flexilis*, ×1
Fig. 11	*Tetragraptus decipiens*, ×1
Fig. 13*a*	*Tetragraptus approximatus*, ×1
Fig. 13*b*	*Tetragraptus approximatus* (large form), ×1
Fig. 14	*Didymograptus pritchardi*, ×1
Fig. 15	*Didymograptus taylori*, ×1

PLATE II

BENDIGONIAN, Substages 1, 2 and 3

Fig. 16	*Bryograptus crassus*, ×1
Fig. 17	*Goniograptus macer*, ×1
Fig. 18	*Goniograptus thureau*, ×1
Fig. 19	*Loganograptus logani*, ×1
Fig. 20	*Goniograptus thureau* var. *clonograptoides*, ×1
Fig. 21	*Sigmagraptus crinitus*, ×1
Fig. 22*a* & *b*	*Schizograptus incompositus*, ×1
Fig. 23	*Schizograptus spectabilis*, ×1
Fig. 24	*Trichograptus fergusoni*, ×1

PLATE III

Bendigonian, Substages 1, 2 and 3 continued

Fig. 25*a*	*Trochograptus australis*, $\times\frac{1}{2}$
Fig. 25*b* & *c*	*Trochograptus indignus*, $\times\frac{1}{2}$
Fig. 26	*Tetragraptus fruticosus*, ×1
Fig. 27	*Tetragraptus fruticosus*, three-branched form, ×1
Fig. 28*a*	*Tetragraptus fruticosus*, large three-branched form, ×1
Fig. 28*b*	*Tetragraptus fruticosus*, normal three-branched form, ×1
Fig. 28*c*	*Tetragraptus serra*, ×1
Fig. 29	*Tetragraptus serra*, ×1
Fig. 30	*Tetragraptus serra*, ×1
Figs. 31	*Tetragraptus pendens*, ×1

PLATE IV

Bendigonian, Substages 1, 2 and 3 continued

Fig. 32	*Dichograptus octobrachiatus*, ×1
Fig. 33	*Didymograptus abnormis*, ×1
Fig. 34	*Didymograptus dilatans*, ×1
Fig. 35	*Didymograptus ensjoensis*, ×1

Bendigonian, Substage 4, and Chewtonian

Fig. 36	*Clonograptus pervelatus*, ×1
Fig. 37	*Phyllograptus typus*, ×1
Fig. 38	*Didymograptus mendicus*, ×1
Fig. 39	*Didymograptus protobifidus*, ×1
Fig. 40	*Didymograptus nitidus*, ×1
Fig. 41	*Didymograptus* cf. *balticus*, ×1
Fig. 42	*Didymograptus nitidus*, ×1
Fig. 43	*Didymograptus extensus*, ×1
Fig. 44	*Isograptus caduceus* var. *primula*, ×1

PLATE V

Castlemainian

Fig. 45	*Isograptus caduceus* var. *lunata*, ×1
Fig. 46	*Isograptus caduceus* var. *victoriae*, ×1
Fig. 47	*Isograptus caduceus* var. *maxima*, ×1
Fig. 48	*Meandrograptus tau*, ×1
Fig. 49*a*	*Meandrograptus aggestus ?*, ×1 (may be *Isograptus dumosus* juvenile)
Fig. 49*b*	Same, ×4
Fig. 50*a*	*Meandrograptus aggestus*, ×1
Fig. 50*b*	Same, ×4

Yapeenian

Fig. 51	*Didymograptus V-deflexus*, ×1
Fig. 52	*Isograptus caduceus* var. *maximodivergens*, ×1
Fig. 53	*Isograptus caduceus* var. *divergens*, ×1
Fig. 54	*Isograptus forcipiformis*, ×1
Fig. 55	*Isograptus dumosus*, ×1
Fig. 56	*Isograptus hastatus*, ×1
Fig. 57	*Isograptus manubriatus*, ×1
Fig. 58	*Skiagraptus gnomonicus*, ×1
Fig. 59	*Oncograptus upsilon*, ×1
Fig. 60	*Oncograptus upsilon* var. *biangulatus*, ×1
Fig. 61	*Cardiograptus morsus*, ×1
Fig. 62	*Glossograptus crudus*, ×1
Fig. 63	*Trigonograptus ensiformis*, ×1

PLATE VI

Darriwilian, inclusive of the zone of *Glyptograptus teretiusculus*

Fig. 64	*Pterograptus lyricus*, ×1
Fig. 65	*Pterograptus incertus*, ×1
Fig. 66*a*	*Atopograptus woodwardi*, ×1
Fig. 66*b*	Same, ×4
Fig. 67	*Cryptograptus circinus*, $\times 1\frac{1}{4}$
Fig. 68	*Cryptograptus schaferi*, ×1
Fig. 69	*Cryptograptus tricornis*, ×1
Fig. 70	*Didymograptus compressus*, ×1
Fig. 71	*Didymograptus cognatus*, ×1
Fig. 72	*Didymograptus acriculus*, ×1 and ×2
Fig. 73*a*	*Didymograptus nodosus*, ×5. Cf. *Tylograptus intermedius* (Mu)
Fig. 73*b*	Same, ×1
Fig. 74	*Didymograptus nodosus*, ×1. Cf. *Tylograptus regularis* (Mu)
Fig. 75	*Cardiograptus crawfordi*, ×1
Fig. 76	*Isograptus ovatus*, ×1
Fig. 77	*Glossograptus acanthus*, ×1
Fig. 78	*Diplograptus* (sen. st.) *decoratus*, ×1
Fig. 79	*Amplexograptus confertus*, ×1
Fig. 80	*Amplexograptus modicellus*, ×1
Fig. 81	*Amplexograptus differtus*, ×1
Fig. 82	*Glyptograptus teretiusculus*, ×1
Fig. 83	*Glyptograptus teretiusculus*, ×1
Fig. 84	*Glyptograptus intersitus*, ×1
Fig. 85	*Glyptograptus austrodentatus*, ×1
Figs. 86	*Thysannograptus etheridgei*, ×1
Figs. 87	*Hallograptus proteus*, ×1

PLATE VII

Gisbornian

Fig. 88	*Nemagraptus gracilis*, ×1
Fig. 89	*Nemagraptus gracilis* var. *remotus*, ×2
Fig. 90	*Dicranograptus ramosus*, ×1
Fig. 91	*Dicranograptus ramosus* var. *spinifer*, ×1
Fig. 92	*Dicranograptus brevicaulis*, ×1
Fig. 93	*Dicranograptus nicholsoni*, ×2
Fig. 94*a*	*Dicranograptus nicholsoni*, ×1
Fig. 94*b*	*Glossograptus hincksii* (scalariform view), ×1
Fig. 94*c*	*Glossograptus hincksii* (biprofile view), ×1
Fig. 94*d*	*Glossograptus hincksii* (subscalariform view), ×1
Fig. 95	*Corynoides*, ×2
Fig. 96	*Dicellograptus forchammeri* var. *flexuosus*, ×1
Fig. 97	*Dicellograptus patulosus*, ×1
Fig. 98	*Dicellograptus intortus*, ×1
Fig. 99*a*	*Dicellograptus forchammeri* var. *flexuosus*, ×1
Fig. 99*b*	Same, proximal end, ×8

PLATE VIII

Gisbornian continued

Fig. 100	*Climacograptus antiquus* var. *riddellensis*, ×1
Fig. 101	*Climacograptus bicornis*, ×1
Fig. 102	*Climacograptus bicornis* var. *peltifer*, ×1
Fig. 103	*Climacograptus bicornis* var. *peltifer*, ×1
Fig. 104	*Climacograptus bicornis* var. *peltifer*, ×1
Fig. 105	*Climacograptus brevis*, ×1
Fig. 106*a*	*Glyptograptus teretiusculus* var. *siccatus*, ×1
Fig. 106*b*	Same, ×4
Fig. 107	*Diplograptus* (sen. st.) *multidens*, ×1

Fig. 108	*Orthograptus calcaratus* var. *tenuicornis*, ×1
Fig. 109	*Orthograptus calcaratus* var. *acutus*, ×1
Fig. 110	*Orthograptus calcaratus* var. *vulgatus*, ×1

PLATE IX

EASTONIAN

Fig. 111	*Leptograptus capillaris*, ×1
Fig. 112	*Dicranograptus hians*, ×1
Fig. 113	*Dicranograptus hians*, ×1
Fig. 114	*Dicranograptus tealei*, ×1
Fig. 115	*Dicranograptus tealei*, ×1
Fig. 116	*Dicranograptus ramosus* var. *longicaulis*, ×1
Fig. 117	*Dicellograptus caduceus*, ×1
Fig. 118	*Dicellograptus elegans*, ×1
Fig. 119	*Dicellograptus elegans*, ×1
Fig. 120	*Dicellograptus morrisi*, ×1
Fig. 121	*Climacograptus bicornis* var. *inequispinosus*, ×1
Fig. 122*a*	*Climacograptus baragwanathi* (proximal end), ×4
Fig. 122*b*	*Climacograptus baragwanathi*, ×1
Fig. 123	*Climacograptus caudatus*, ×1
Fig. 124	*Climacograptus caudatus* (bispiniform variety), ×1
Fig. 125	*Climacograptus tubuliferous*, ×1
Fig. 126*b*	*Climacograptus tubuliferous* (scalariform view), ×1, with *Nymphograptus halli* (126*a*)
Fig. 127	*Climacograptus minimus*, ×1
Fig. 128	*Climacograptus exiguus*, ×1
Fig. 129	*Climacograptus exiguus*, ×1
Fig. 130*a*	*Climacograptus hastata*, ×1
Fig. 130*b*	*Climacograptus hastata* (proximal end), ×4

PLATE X

EASTONIAN continued

Fig. 131	*Diplograptus* (sen. st.) *ingens*, ×1
Fig. 132	*Orthograptus calcaratus*, ×1
Fig. 133	*Orthograptus calcaratus* var. *basilicus*, ×1
Fig. 134	*Orthograptus pageanus*
Fig. 135	*Orthograptus pageanus* var. *spinosus*, ×1
Fig. 136	*Orthograptus quadrimucronatus*, ×1
Fig. 137	*Orthograptus quadrimucronatus*, ×1
Fig. 138	*Orthograptus quadrimucronatus* var. *spinigerus*, ×1
Fig. 139	*Orthograptus quadrimucronatus* var. *spinigerus*, ×1
Fig. 140	*Orthograptus truncatus*, ×1
Fig. 141	*Orthograptus truncatus* var. *intermedius*, ×1
Fig. 142	*Orthograptus truncatus* var. *pauperatus*, ×1
Figs. 143	*Hallograptus mucronatus* var. *bimucronatus* (scalariform views showing scopulae), ×4 and ×2 respectively
Figs. 144	*Neurograptus margaritatus*, ×1
Figs. 145	*Neurograptus fibratus*, ×1
Figs. 146	*Nymphograptus halli*, ×1
Figs. 147	*Pseudoplegmatograptus* sp., ×1

PLATE XI

BOLINDIAN

Fig. 148*a*	*Pleurograptus linearis* var. *simplex*, ×1
Fig. 148*b*	*Leptograptus flaccidus* var. *arcuatus*, ×1
Fig. 149	*Leptograptus flaccidus* var. *eastonensis*, ×1
Fig. 150*a*	*Leptograptus flaccidus*, ×1
Fig. 150*b*	Same, ×4
Fig. 151	*Dicellograptus divaricatus* var. *rigidus*, ×1
Fig. 152	*Retiograptus pulcherrimus*, ×1
Fig. 153	*Climacograptus missilis*, ×1
Fig. 154	*Glyptograptus sinuatus*, ×1
Fig. 155	*Climacograptus scalaris*, ×1
Fig. 156	*Climacograptus uncinatus*, ×4
Fig. 157	*Orthograptus truncatus* var. *abbreviatus*, ×1
Fig. 158*a*	*Orthograptus truncatus* var. *socialis*, ×1
Fig. 158*b*	Same, ×4

PLATE XII

KEILORIAN

Fig. 159	*Climacograptus hughesi*, ×1
Fig. 160	*Climacograptus innotatus*, ×1
Fig. 161	*Glyptograptus tamariscus*, ×1
Fig. 162	*Retiolites geinitzianus*, ×2
Fig. 163	*Stomatograptus australis*, ×1
Fig. 164	*Monograptus concinnus*, ×1
Fig. 165	*Monograptus exiguus*, ×1
Fig. 166	*Monograptus griestoniensis*, ×1
Fig. 167	*Monograptus fimbriatus*, ×1
Fig. 168	*Monograptus marri*, ×1
Fig. 169	*Monograptus runcinnatus*, ×1
Fig. 170	*Monograptus pandus*, ×1
Fig. 171	*Monograptus pandus*, ×1, proximal and distal fragments
Fig. 172	*Monograptus priodon*, ×1
Fig. 173	*Monograptus spiralis* var. *permensis*, ×1
Fig. 174	*Monograptus turriculatus*, ×1
Fig. 175	*Monograptus sedgewicki*, ×1

PLATE XIII

EILDONIAN

Fig. 176	*Monograptus vomerinus*, ×1
Fig. 177	*Monograptus dubius*, ×1
Fig. 178	*Monograptus vomerinus* var. *crenulatus*, *a* ×2, *b* ×4
Fig. 179	*Monograptus testis* var. *inornatus*, ×1
Fig. 180	*Cyrtograptus insectus*, ×1

MELBOURNIAN

Fig. 181	*Monograptus bohemicus*, ×1
Fig. 182	*Monograptus colonus* var. *compactus*, ×1
Fig. 183	*Monograptus comis*, ×1
Fig. 184	*Monograptus roemeri*, ×1
Fig. 185	*Monograptus scanicus*, ×1
Fig. 186	*Monograptus* cf. *nilsonni*, ×1
Figs. 187	*Monograptus uncinatus* var. *orbatus*, ×1

Figs. 188	*Monograptus uncinatus* var. *micropoma*, ×1
Fig. 189	*Monograptus varians*, ×1
Fig. 190	*Monograptus vulgaris* var. *curtus*, ×1
Fig. 191*a*	*Plectograptus* sp., ×1
Fig. 191*b*	Same, ×2
Fig. 192	*Linograptus*, ×4

PLATE XIV

Fig. 193	*Dictyonema* sp., ×4, Junee loc. 52632 etc.
Fig. 194	*Dictyonema* spp., ×1
Fig. 195*a*	*Didymograptus*, ×4
Fig. 195*b*	*Didymograptus*, ×4
Fig. 196*a*	*Didymograptus*, ×4
Fig. 196*b*	*Didymograptus*, ×4
Fig. 197	*Didymograptus*, ×4
Fig. 198	*Didymograptus* cf. *gracilis*, ×12, Junee loc. 52665
Fig. 199*a*	*Monograptus* sp., near Queenstown
Fig. 199*b*	*Monograptus* spp., near Queenstown
Fig. 200	*Cyrtograptus*, 63-mile post
Fig. 201*a*, *b* & *c*	*Amblexograptus* cf. *arctus*, Goldwyer Bore 1, 2867′–2876′
Fig. 201	*Amplexograptus* cf.
Fig. 202*a*	*Amplexograptus*, Goldwyer Bore 1, 2994′–3002′
Fig. 203*b*	*Amplexograptus* sp., Goldwyer Bore 1, 2994′–3002′

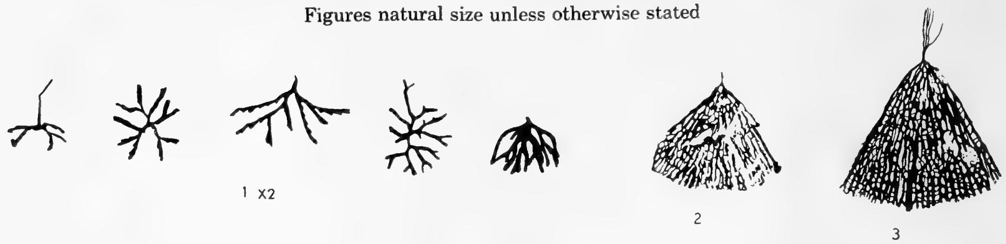
PLATE XV

Fig. 204	*Tetragraptus* sp., ×2, Emmanuel Creek 42640
Fig. 205	*Tetragraptus* spp., ×2, Emmanuel Creek 42644
Fig. 206	*Tetragraptus* sp., ×2, Emmanuel Creek 42643
Fig. 207	*Didymograptus*, ×2, Emmanuel Creek 42643
Fig. 208	*Didymograptus* cf. *nitidus ??*, ×2, Emmanuel Creek 42640
Fig. 209	*Didymograptus*, ×2, Emmanuel Creek 42642
Fig. 210	*Tetragraptus*, ×2, Samphire Marsh Bore 1, 4090′–4100′
Fig. 211	*Amplexograptus*, ×2, Loc. ?
Fig. 212	*Didymograptus patulus*, ×2, Stokes Pass, Loc. NT153
Fig. 213*a*	*Didymograptus patulus*, ×2, Stokes Pass, Loc. NT153
Fig. 213*b*	*Didymograptus patulus*, ×2, Stokes Pass, Loc. NT153
Fig. 214	*Monograptus* cf. *priodon*, ×2, Broken River Crossing, BRS100
Fig. 215	*Monograptus* cf. *convolutus*, ×2, Broken River Crossing, BRS81
Fig. 216	*Monograptus* cf. *priodon*, ×2, Broken River Crossing, BRS100
Fig. 217	*Monograptus* cf. *pandus*, ×2, Broken River Crossing, BRS101
Fig. 218*a*, *b* & *c*	*Monograptus griestoniensis*, ×2, Broken River Crossing, BRS101

PLATE I

LANCEFIELDIAN Substage 1

Figures natural size unless otherwise stated



LANCEFIELDIAN Substages 2 & 3

Figures natural size unless otherwise stated

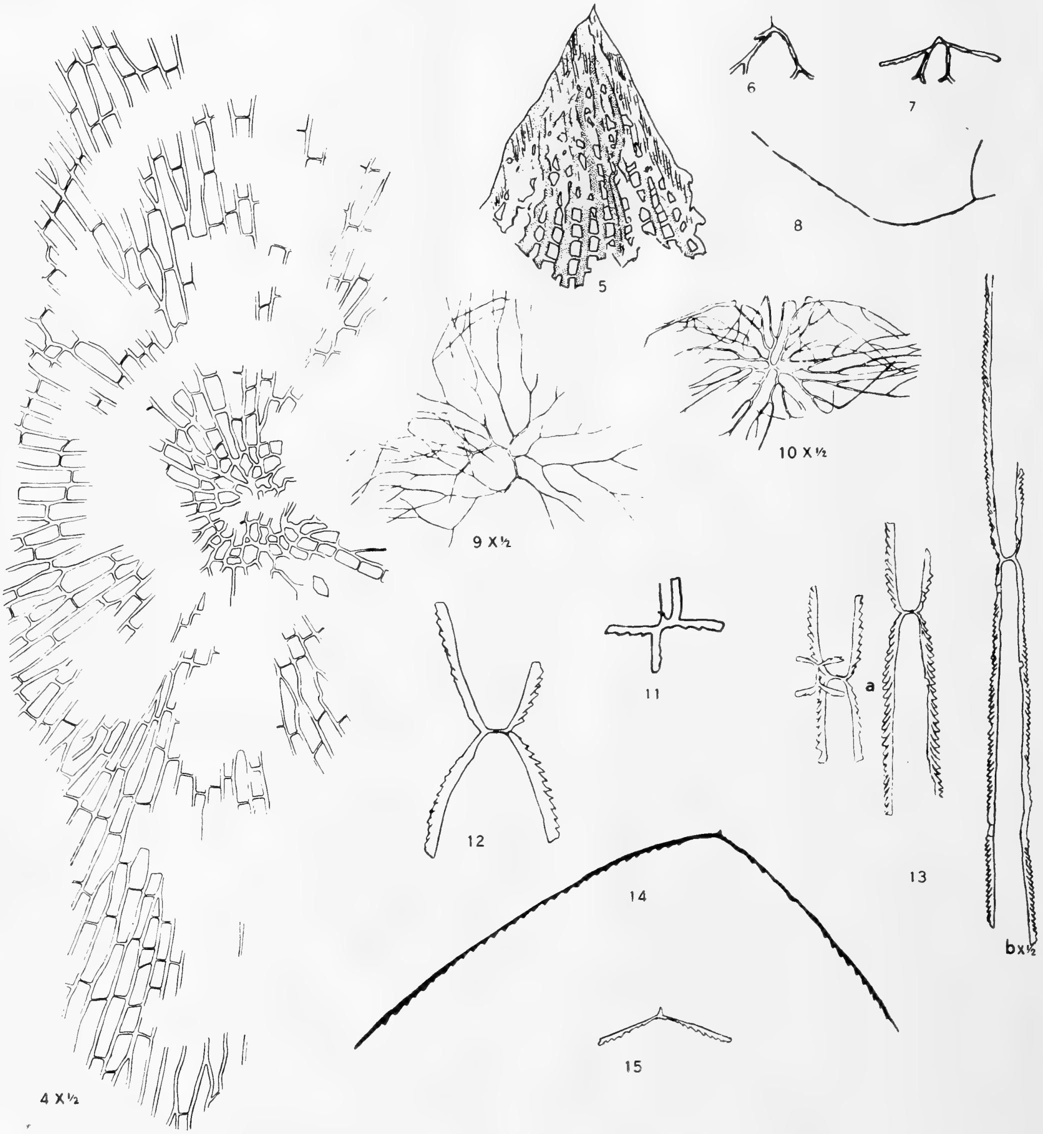


PLATE II

BENDIGONIAN Substages 1 2 & 3

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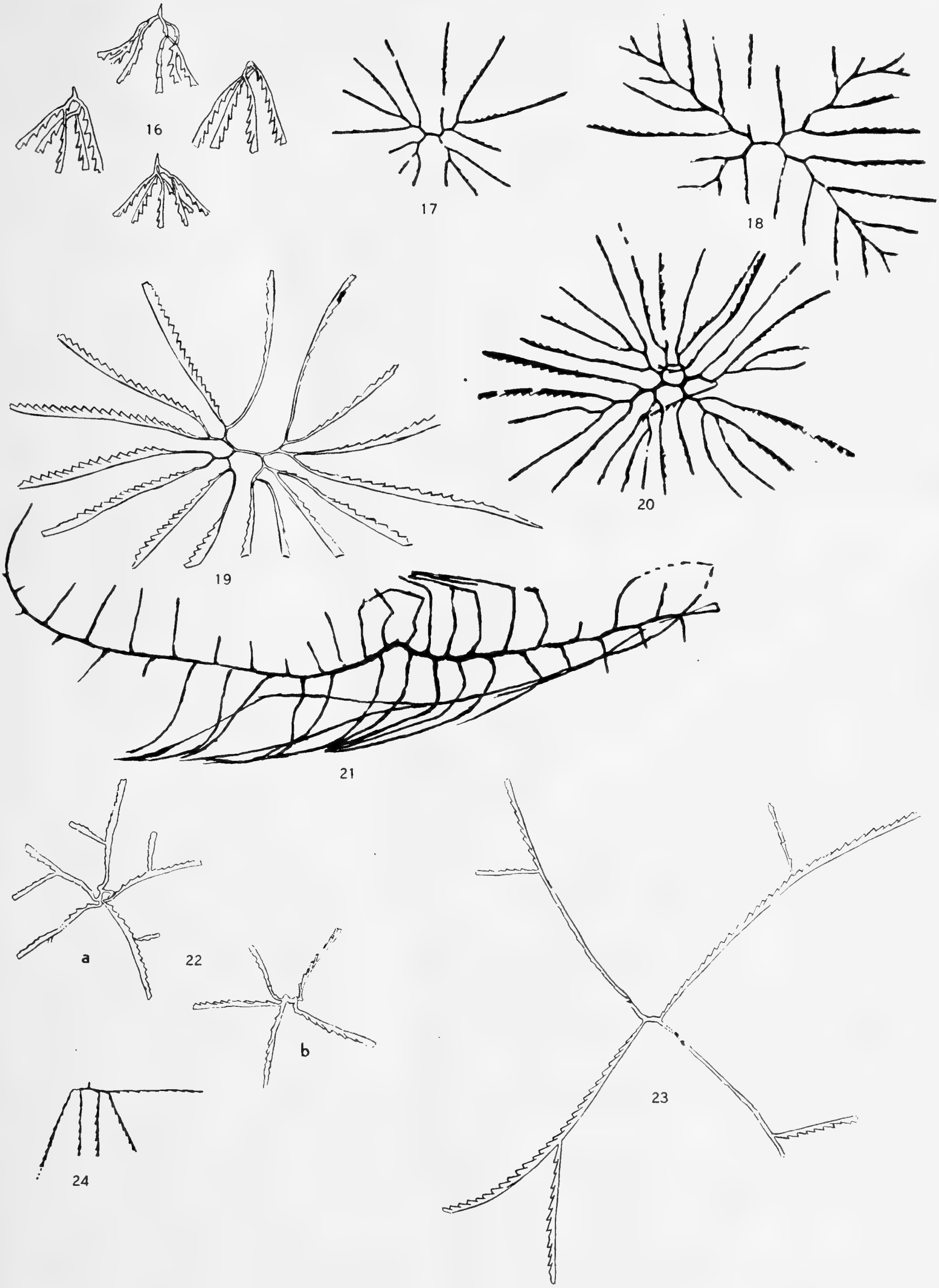

PLATE III

BENDIGONIAN Substages 1 2 & 3 (continued)

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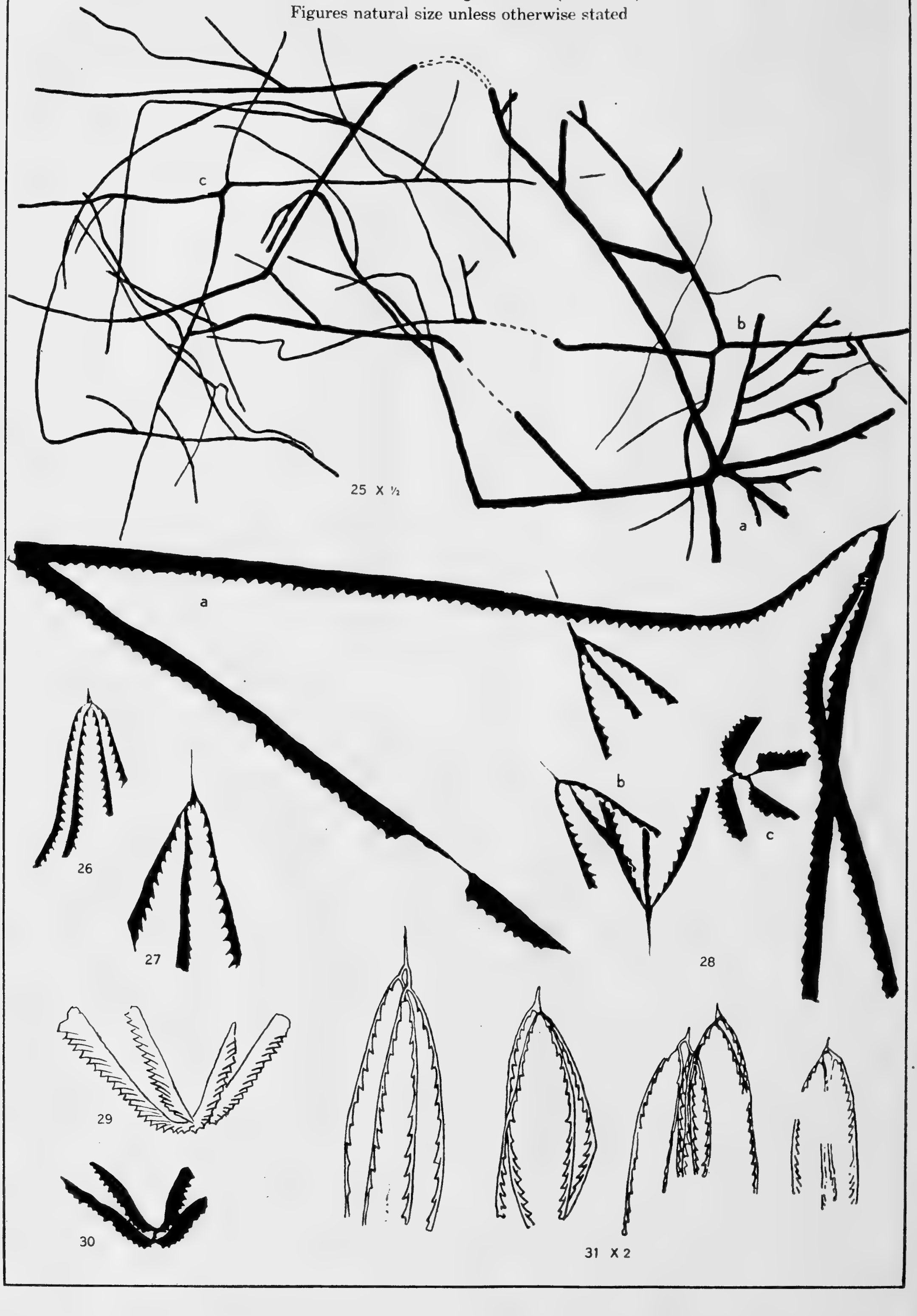

PLATE IV

BENDIGONIAN Substages 1 2 & 3 (continued)

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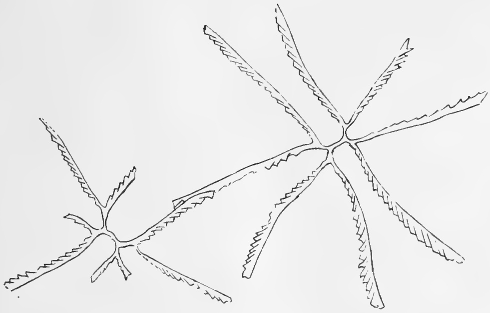

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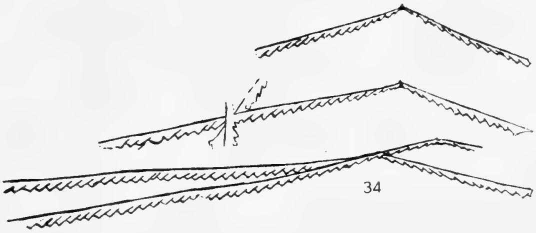

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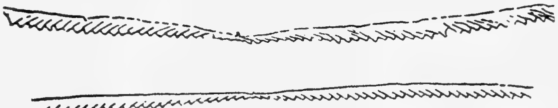

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BENDIGONIAN Substage 4 and CHEWTONIAN

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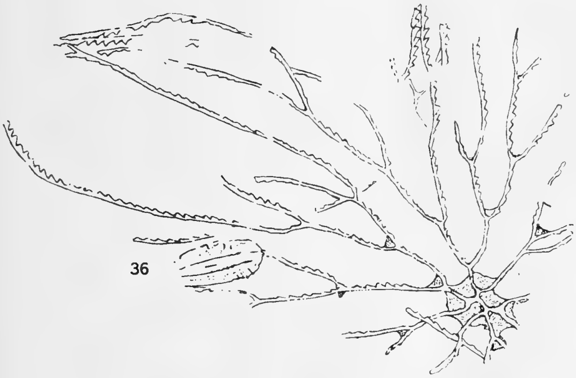

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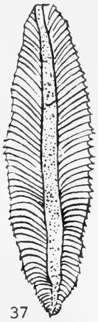

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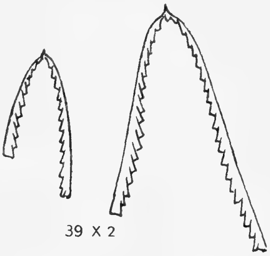

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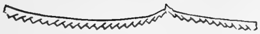

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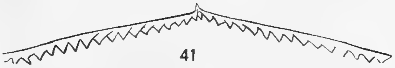

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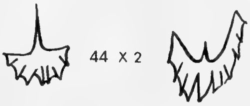

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PLATE V

CASTLEMAINIAN

Figures natural size unless otherwise stated

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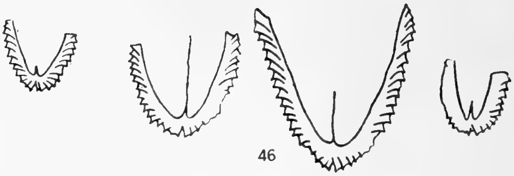

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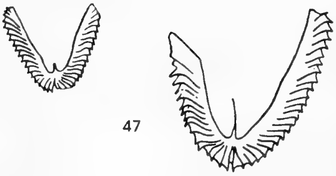

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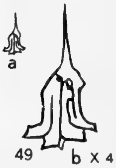

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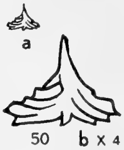

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YAPEENIAN

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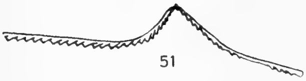

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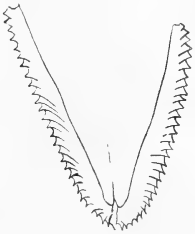

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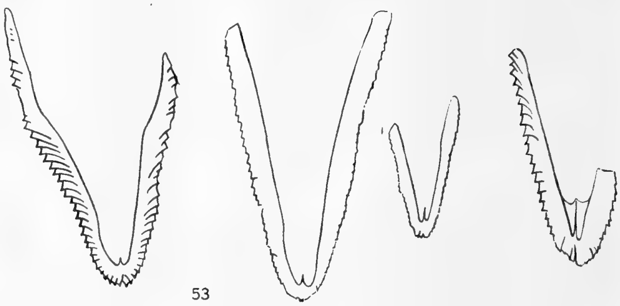

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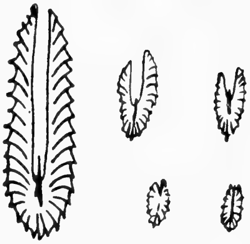

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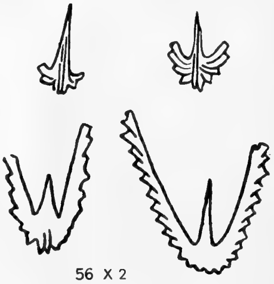
55 x 2



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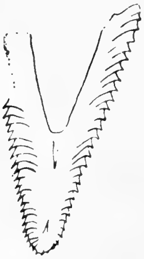

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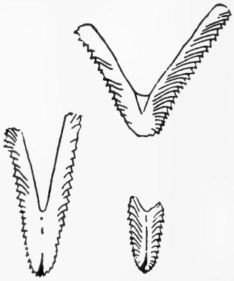

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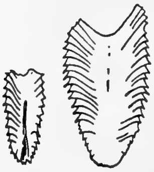

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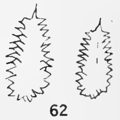

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PLATE VI

DARRIWILIAN (inclusive of zone of Glyptograptus teretiusculus)

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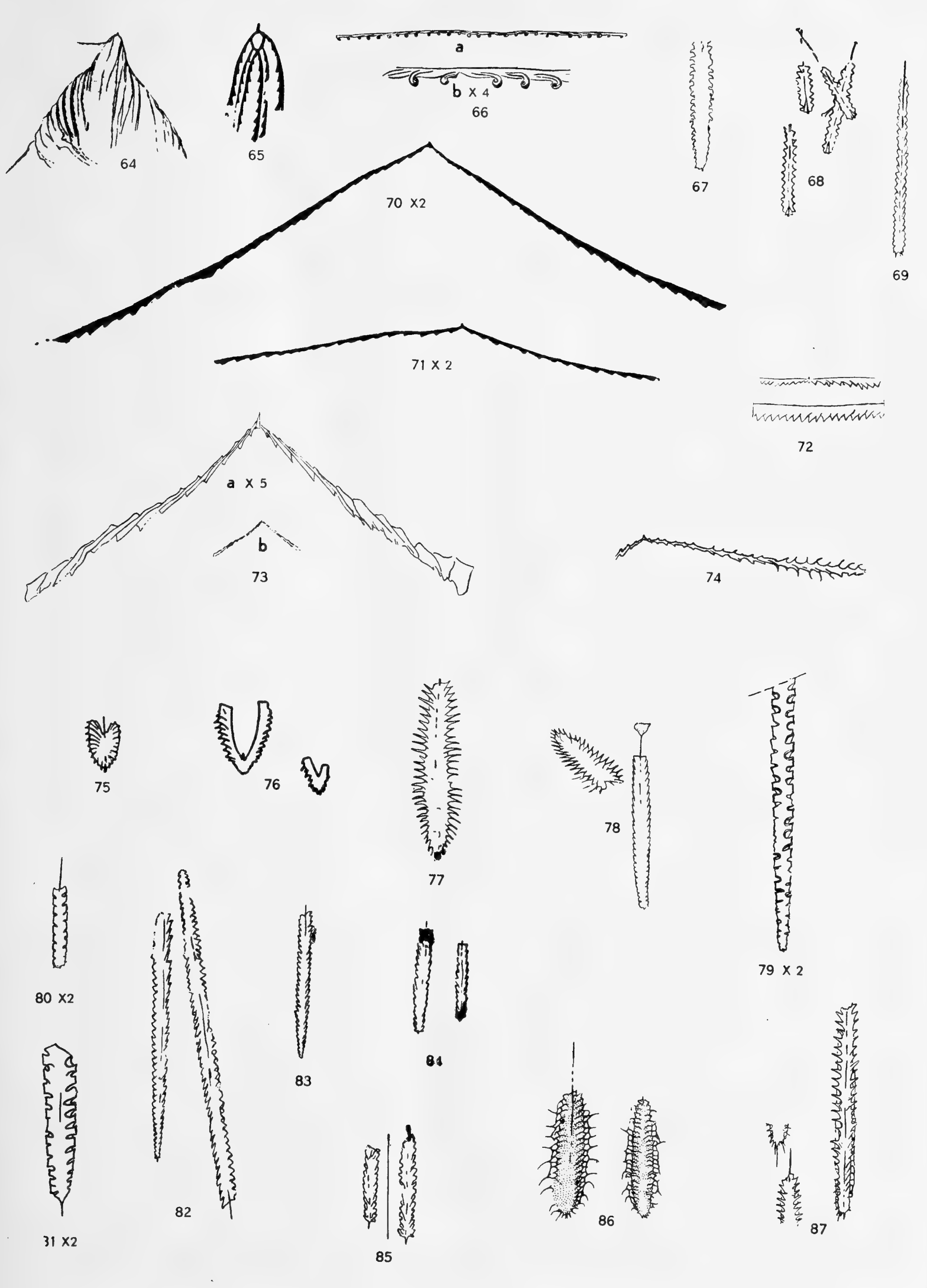
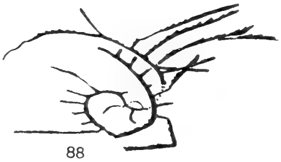


PLATE VII

GISBORNIAN

Figures natural size unless otherwise stated



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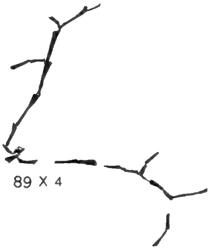

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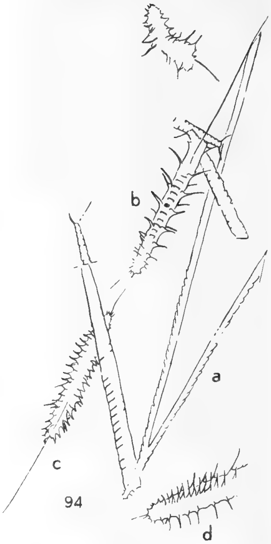

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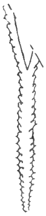

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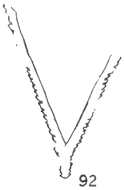

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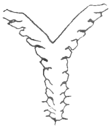

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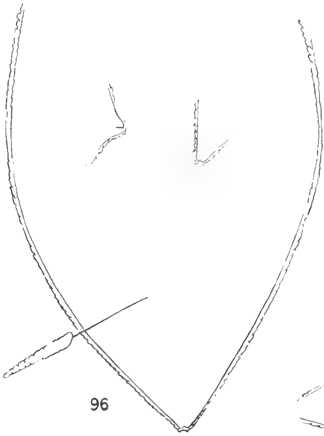

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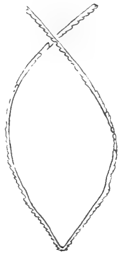

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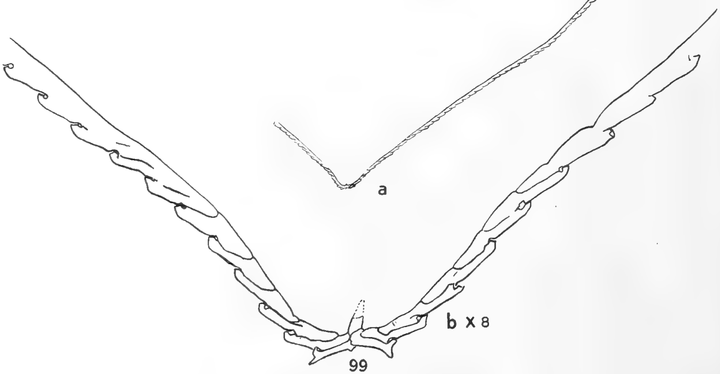

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PLATE VIII

GISBORNIAN (continued)

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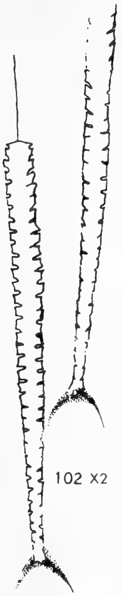

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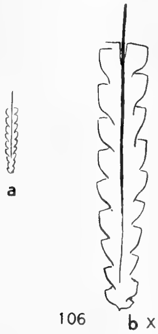

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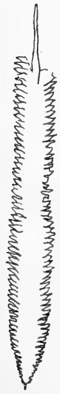

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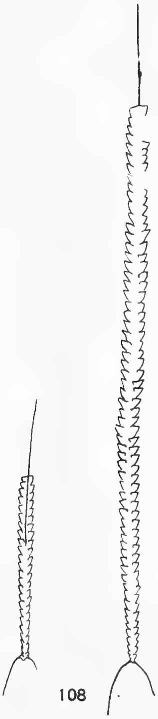

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EASTONIAN

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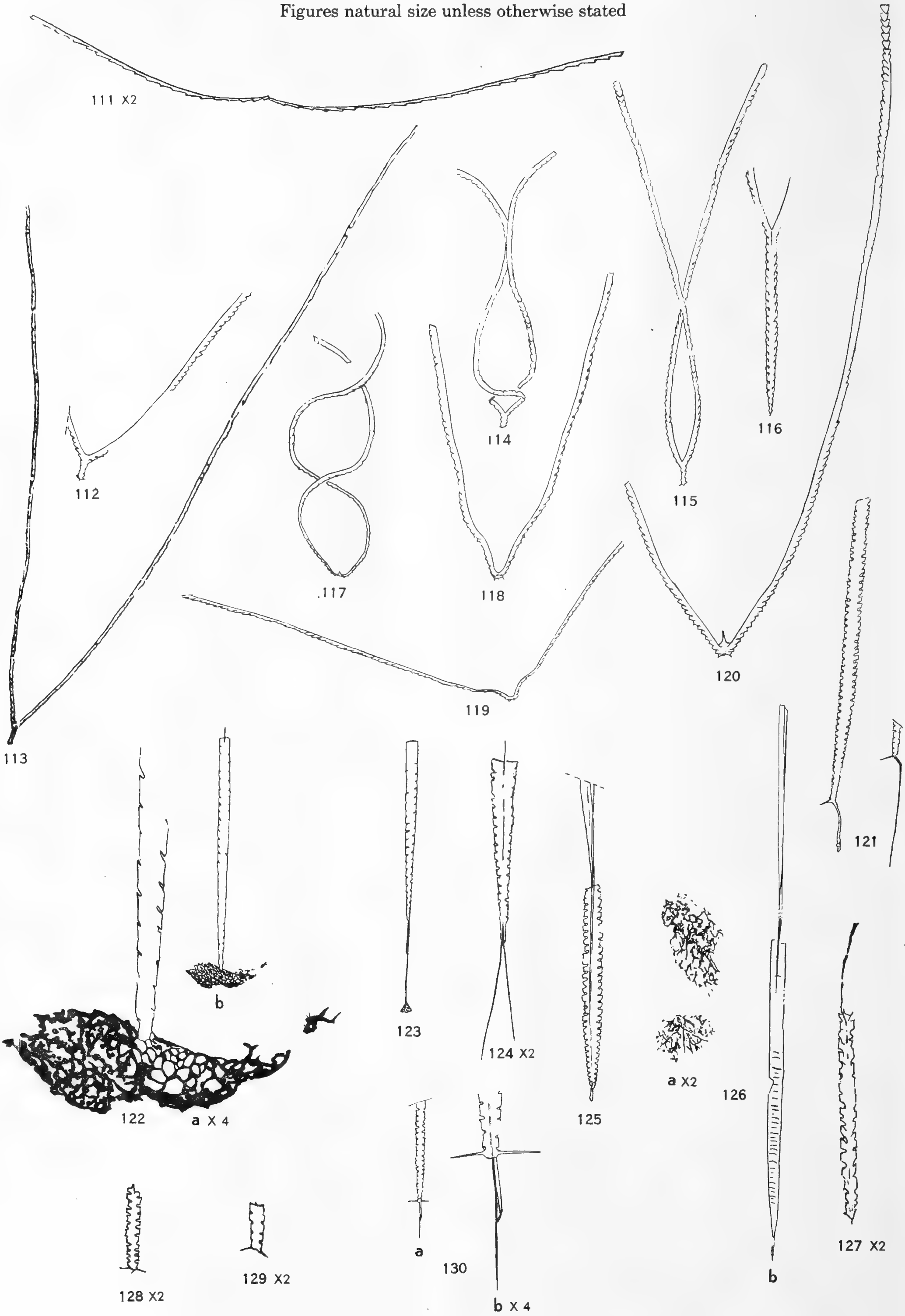

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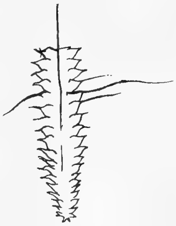
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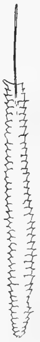
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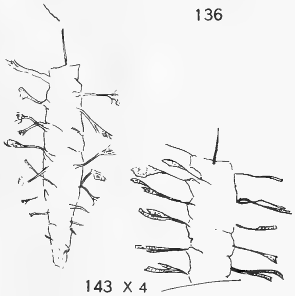
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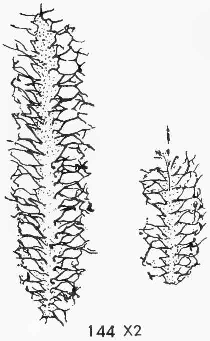
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BOLINDIAN

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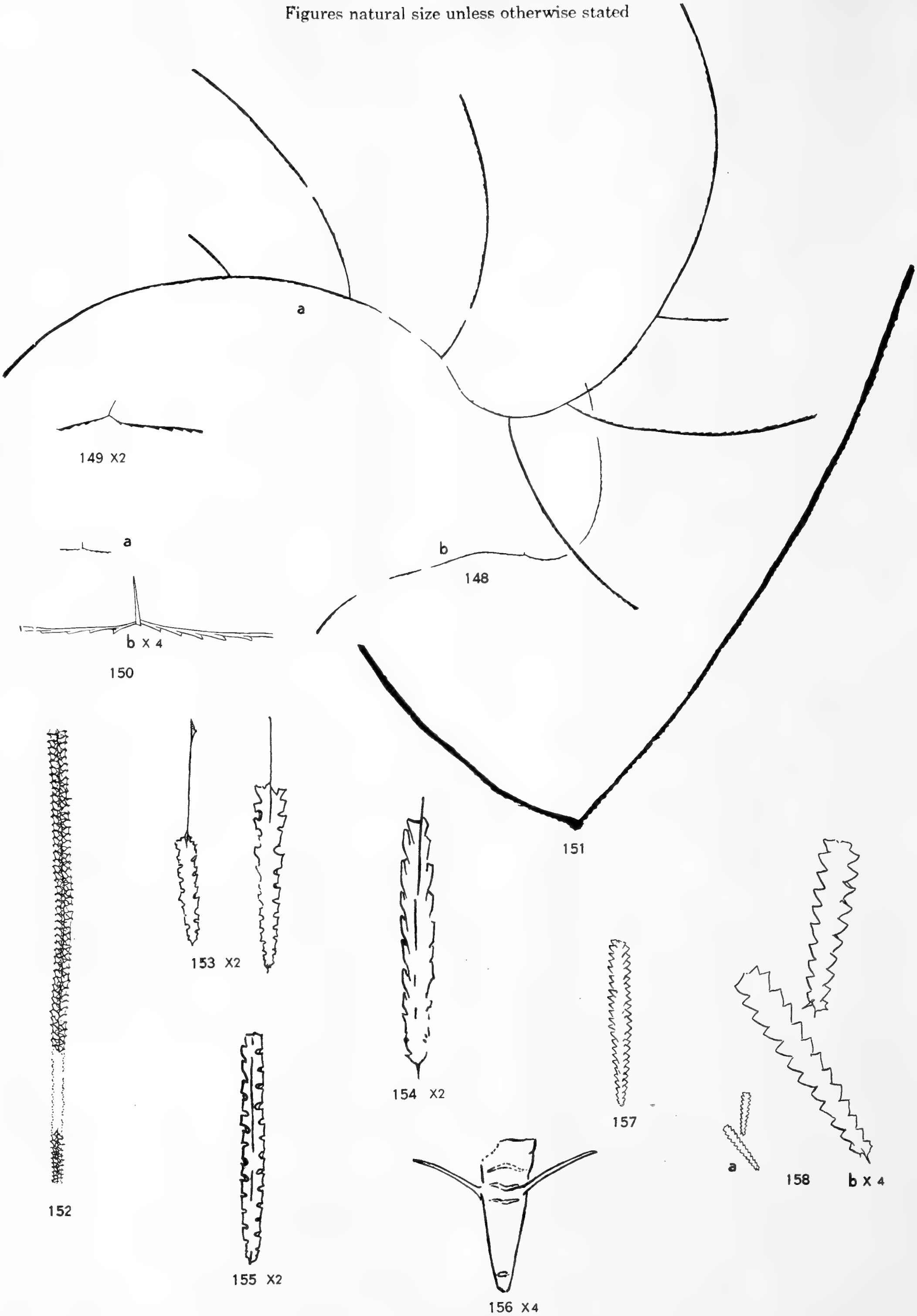

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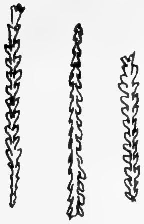
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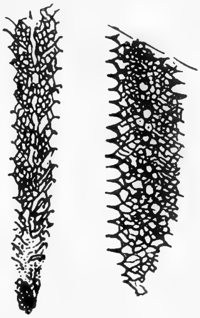
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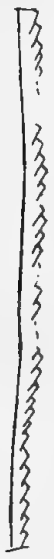
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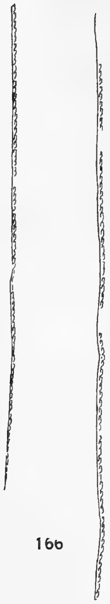
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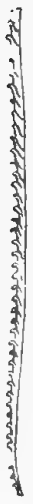
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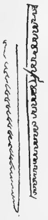
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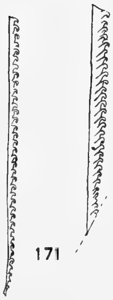
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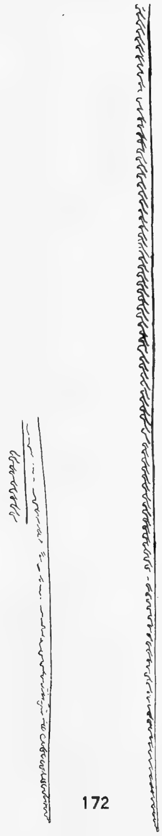
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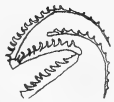
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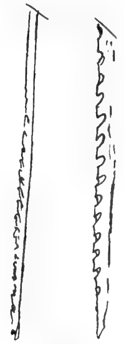
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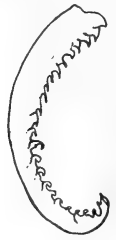
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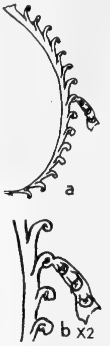
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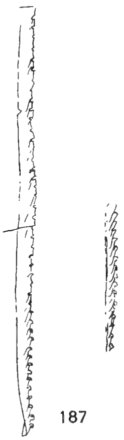
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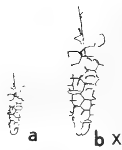
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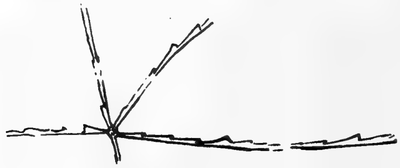
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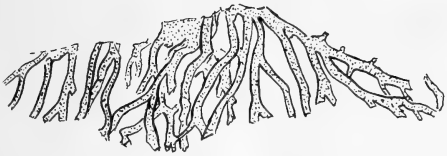
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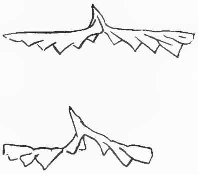
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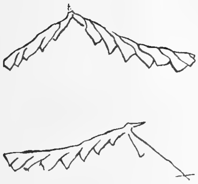
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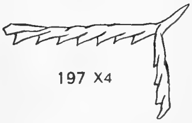
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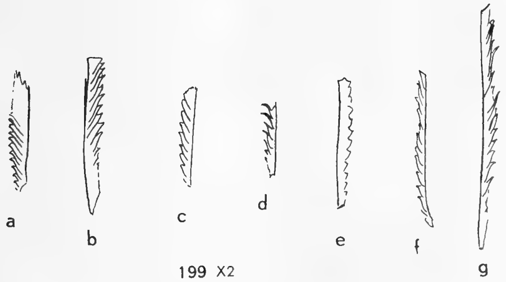

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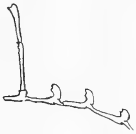
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WESTERN AUSTRALIA (Goldwyer)

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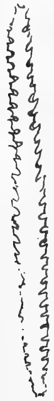
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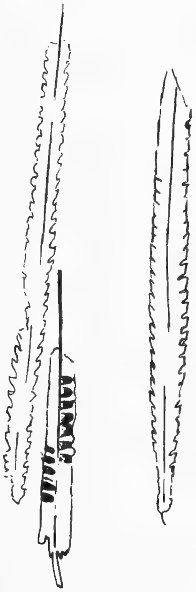
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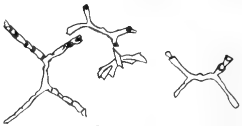

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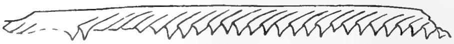

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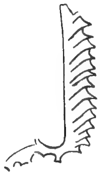

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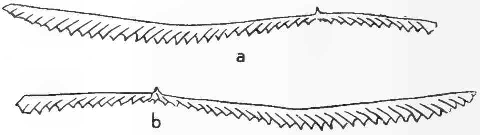

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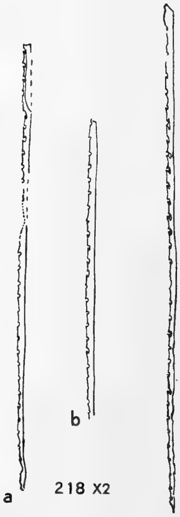

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Papers should be prepared according to the general style adopted in this Journal. They should be as concise as possible, consistent with adequate presentation. Particular attention should be given to clarity of expression and good prose style.

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.

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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.

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JOURNAL AND PROCEEDINGS OF THE ROYAL SOCIETY OF NEW SOUTH WALES

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Journal and Proceedings, Royal Society of New South Wales, Vol. 94, pp. 59–70, 1960

Research, Development and the Maintenance of Standards in Heat at the National Standards Laboratory*

A. F. A. Harper

Introduction

In this address I shall attempt to review for you the work of that part of the National Standards Laboratory with which I have been associated since 1939. In doing so I hope to give you by illustration some understanding of the functions and activities of a standards laboratory so that you will be able the better to appreciate just what it does and how and why it does it. I hope too that in the wide variety of topics I shall be touching upon, each one of you will find something of particular interest.

A further reason for selecting this topic is that the National Standards Laboratory is about to " come of age " and this seems a good time and opportunity to review from whence we have come and to contemplate whither we may be going.

I wish to stress at the very outset that most of what I will be describing has been done by my co-workers : in many cases I have been little more than an interested onlooker. I am indebted to the various members of the Heat Section, both past and present, for their contribution to its record. I also wish to pay sincere tribute to my erstwhile Chief, Dr. G. H. Briggs, a member of this Society, for his guidance and direction in connection with the work I shall be describing.

The National Standards Laboratory

The decision to establish the National Standards Laboratory was made in 1937 in implementation of a recommendation made by a Committee, the Secondary Industries Testing and Research Committee, which had been charged with the task of advising how the Council for Scientific and Industrial Research (as it was then called) could best assist the development of secondary industries (Commonwealth of Australia, 1937). It was not surprising that such a recommendation should have been made, for similar standards laboratories exist in almost all industrially developed countries. They have taken very different forms however ; in some cases an organization which is little more than a national testing and calibrating laboratory has been established while in others this aspect has been very much subservient to the activities of the laboratory in scientific research, often of a fundamental nature.

In a country such as Australia, with a relatively small population, isolated and not yet mature industrially, a national standards laboratory has, I believe, a wider function to perform than the equivalent laboratories of say Great Britain, U.S.A. or Canada. As a corollary to this we must expect that with the further development of Australia the functions of the laboratory should change.

Aspects of our activities in these initial years which illustrates this lack of development have been the need to take our standards right to the ultimate user—e.g. by the calibration of equipment actually in use in industry—whereas in more industrialized countries only sub-standards would need to be supplied ; by the pressure to solve ad hoc industrial problems which would be the province of Research Associations in Great Britain ; and by the need to provide assistance in fields such as medicine, biology, veterinary science and agriculture in which physical assistance is not yet readily available.

The functions a standards laboratory needs to fulfil in this country, at least for the present, seem to be as follows :

(i) It must maintain the national standards for the measurement of physical quantities of importance to industry, commerce and science. These quantities embrace much more than the " weights and measures " of early legislation—length, volume and so on. They include, for instance, temperature, viscosity and humidity, to which I will be referring later. In fact, a standards laboratory will usually be called upon to give guidance as to *what* national standards of measurement are required by the country. This is an important function if trade and commerce are to be protected and yet not hampered. In Australia this is in process of being worked out now. An Act, the Weights and Measures (National Standards) Act (Commonwealth of

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* Presidential Address delivered before the Royal Society of New South Wales, April 6, 1960.

Australia, 1948), has been passed to provide for national standards of measurement in place of the few and not always consistent State standards previously in use. Regulations are being prepared to cover the various physical quantities for which it seems it would be beneficial to have Commonwealth units and standards of measurement. When promulgated these will become the sole legal units and standards for use in transactions involving those physical quantities.

(ii) A standards laboratory must also concern itself with the development of improved standards and improved methods of measurement in terms of them. A standard can seldom be left static—as greater accuracies become available the value of *still* greater accuracies become apparent. This calls for a type of scientific work to which not many are suited. To increase the accuracy of a measurement by an order of magnitude usually requires also an increase of the complexity of the equipment by an order of magnitude. Special staff, accumulated over the years, are the backbone of a standards laboratory, for members are needed who have the patience for meticulous work and yet a flair for seeing worthwhile departures from long established ways of doing things.

(iii) Calibrations must be made, in terms of the standards maintained: no standard is of any use until it is disseminated to those requiring to use it. A standards laboratory should go further than this and should help to foster calibration services which will be more directly accessible to industry. These will be provided in testing laboratories and in the industrial concerns themselves. Fortunately, in Australia a Government sponsored body has been established for just this purpose: the National Association of Testing Authorities, and the National Standards Laboratory is doing a good deal to further the objects of this Association by the service of its members on N.A.T.A. Committees, by calibrating equipment, by providing technical assistance and advice in the establishment of testing laboratories and by training personnel for work in them.

(iv) In a somewhat similar way a standards laboratory has to be able to assist Committees of the Standards Association of Australia with specialized knowledge relevant to existing or projected specifications and must be prepared to represent Australia on committees of the corresponding international body, the International Standardisation Organization.

To fulfil the foregoing functions it is necessary to maintain an active organization of high scientific standing. If this is not done the laboratory will soon become moribund for the very nature of its work can, or the wrong staff, exert a strong stultifying influence. Yet I hope to show that even in fields where all development might be thought to have ceased a generation ago an original approach can break through, in an exciting way, into new territory.

To have a virile laboratory of high standing calls for the continued recruitment of good staff, for a flow of personnel through the laboratory should be expected and indeed encouraged because in this way the specialized knowledge of the laboratory can be more widely disseminated. Experience has shown elsewhere and here that to recruit staff of the requisite calibre it is necessary to provide them with research opportunities and that the position is further improved if the laboratory can gain recognition not solely as a standards laboratory but also as a physical research centre. To this end an active research school should be maintained, not necessarily in a field closely associated with the standards activity. In the Heat Section of the Laboratory this has been done in the fields of low temperature and solid state physics.

The Heat Section

The Heat Section—which as will soon become apparent by no means restricts its activities to "heat"—is roughly half of the Division of Physics, which in its turn is one of the three Divisions of C.S.I.R.O. which comprise the National Standards Laboratory. The others are the Divisions of Metrology and Electrotechnology.

The Section's major fields of activity are concerned with temperature, humidity, viscosity, low temperature physics and solid state physics. Other activities include aspects of medical physics and the study of the thermal properties of materials.

Because many of its fields of work are of direct concern to industry this Section has always endeavoured to maintain a close liaison with industrial personnel. Nearly 200 technicians, drawn from every State in the Commonwealth, have passed through its training courses and many thousands of problems have been dealt with either by advice or investigation. This close contact with industry was established very early in the history of the Laboratory because of the exigencies of the War. Lack of alternative facilities made it necessary for us to undertake the calibration of furnaces and temperature measuring equipment used for defence work. It was soon realized that it was to the advantage of the Laboratory staff as well as of industry for us to undertake this work as it provided valuable insight into problems of practical thermometry and pyrometry. Accordingly this facility has been maintained to a limited extent, although every encouragement has been given to industry to become self-sufficient in these matters. Inevitably this class of work should ultimately pass entirely to laboratories such as those registered with the National Association of Testing Authorities, but, as this happens, I expect as a parallel development that there will be a greater awareness of the potentialities of the Laboratory for the solution of more recondite problems.

Temperature

The statutory functions of the Section in connection with temperature measurement involve the establishment and maintenance of what is known as the International Temperature Scale (I.T.S.) (Comite International des Poids et Mesures, 1948). This is a scale of temperature adopted by international agreement in 1927 (Septieme Conference General des Poids et Mesures, 1930) to provide a uniform means for measuring temperatures throughout the world, which would conform with the thermo-dynamic scale of temperature as nearly as was practicable at the time. Such a scale is clearly an empirical one but it is only rarely, as in the measurement of the thermo-dynamic constants of chemicals, that differences from the thermo-dynamic scale are significant. From the nature of the scale the lines of its further development are not difficult to foresee; one can expect attempts to improve its internal consistency, to extend its range and to improve its conformity with the thermo-dynamic scale. All three of these aspects have been and are still being actively pursued throughout the world. Two of them are currently receiving attention here.

The Scale is defined by allocating temperatures to several so-called " fixed points ", such as the melting point of ice, the boiling points of oxygen and sulphur and the melting points of silver and gold, and by prescribing means of interpolation (and extrapolation) between these temperatures, e.g. by the use of platinum resistance thermometers in which the physical characteristics of the platinum and the interpolation formula to be used are laid down.

The accuracies of reproducibility of the initial scale were of the order of 0·01 deg. C at —190° C, the lower limit of the Scale, 0·001 at 0° C, 0·01 at 400° C, 0·1 at 1,000° C and 2 deg. C at 2,000° C. Inevitably these have proved inadequate. This may seem somewhat surprising for they *are* quite high accuracies, but it must be borne in mind that it is rarely convenient to make practical measurements of temperature directly in terms of equipment of the type used to realize the I.T.S. so that one or more intercomparisons are usually involved, each with its consequent lowering of accuracy. In certain measurements the accuracies quoted are directly significant; thus in the sale of chemicals purity is often the criterion for the price and is judged by melting point. We were consulted on just such a case not long ago where a few thousandths of a degree meant many thousands of pounds.

Some improvements have resulted from subsequent minor changes in the definition of the Scale: thus the platinum used for platinum resistance thermometers must now be of greater purity than was originally required. The Scale has been terminated at —183° C because below this it rapidly departs from the thermo-dynamic scale, and the approximate Wien law of radiation used for high temperature measurements has been replaced with the exact Planck law.

Greatest precision, in the numerical sense, is usually required in the vicinity of room temperature and this has received a fillip from the replacement of the ice point with the triple point of water (0·010° C). It is not at all difficult to realize with this latter point a temperature which is constant and reproducible from cell to cell to 0·0001 deg. C.

The position is not as satisfactory at the boiling point of water, the second of the fundamental points used to define the thermo-dynamic scale. This has the weakness of all boiling points, that they are markedly sensitive to pressure—a change of 1 mm. of mercury in the pressure changes the boiling point of water by 0·04 deg. C. The position is aggravated by the difference in density between the vapour and the atmosphere above the vapour so that any variations in the condensation line will result in a change in the pressure at the point in the vapour at which the temperature is being measured. The other major problem is the establishment or measurement of the pressure at which boiling is occurring. Each standards laboratory in which the I.T.S. is realized has to face up to this problem and will meet it in its own particular way. In all cases where high accuracy is desired a controlled atmosphere will be used, usually of hydrogen or helium to take advantage of the sharp condensation line which results from the high thermal conductivities of these gases. The pressure will be either adjusted to one standard atmosphere or kept near it and measured.

Such a system, with which we hope to obtain pressures accurate to 0·001 mm. Hg, is now nearing completion in the Heat Section. The mercury of the manometer is contained in a stainless steel system kept at constant temperature. The position of the upper and lower mercury surfaces relative to flat plattens separated by precision end bars is determined by measurements of electrical capacitance. Space above one mercury surface will be continuously evacuated and over the other will be filled with helium. The boiler (hypsometer) to be employed with this is already in use. It has been modelled on one developed at the National Bureau of Standards, U.S.A. (Stimson, 1955), and found to give very satisfactory results.

As with many other aspects of the work of the National Standards Laboratory, advantage can be taken in this case of the specialized techniques developed in other parts of the Laboratory. We are utilizing the facilities of the Division of Metrology for the construction and measurement of precision end bars and very accurately lapped flat surfaces, of the Division of Electrotechnology for the very precise comparison of electrical capacitances and of our own Section for accurate temperature control.

Although the completion of the manometer will, it is hoped, increase the accuracy of realizing the steam point to 0·0002 deg. C, this will clearly always be a less satisfactory fixed point than the triple point of water. It would be very convenient if it could be replaced with a satisfactory freezing point. Benzoic acid (freezing point 122° C) has been suggested (Schwab and Wickers, 1945) but has not proved sufficiently reproducible. Organic materials are usually at a disadvantage because of low latent and specific heats and poor thermal conductivity, as was found by us in some investigations on the use of diphenyl ether as a secondary fixed point located conveniently near ambient temperatures at about 28° C. An accuracy of better than 0·01° C proved very difficult to achieve.

The present International Temperature Scale covers the range from 0° to 630° C by the use of platinum resistance thermometers calibrated at 0°, 100° and 444·6° C. These calibration points are not ideally spaced so it is worth contemplating the replacement of the steam point (100° C) with a freezing point at say 150° C. Indium which melts at 156° C is a possible substance. We have commenced work to investigate the suitability of this.

If the steam point is a somewhat unsatisfactory boiling point, the boiling point of sulphur (444·6° C) is even worse, for here, the chemists tell us, we are dealing with a molecule which can adopt many forms : S_2, S_4, S_6 etc. and which will slowly change from one to the other with time in a non-equilibrium thermal environment. Fortunately there is a melting point conveniently close to the sulphur point, namely zinc (419·5° C), and a good deal of work is proceeding in various standardizing laboratories throughout the world on investigating this (Preston-Thomas, 1955). We have found it to give temperatures repeatable to 0·0002° C in agreement with the findings of others and there seems little doubt that the zinc point will replace the sulphur point in a future revision of the I.T.S.

A word of warning is called for in the use of melting points in place of boiling points, however, for while they are insensitive to pressure, they can be very sensitive to impurity, unlike the condensation temperature of a vapour. In our work on zinc and indium (and also on cadmium which we are examining for use as a secondary fixed point) we are finding it necessary to resort to zone melting refining techniques to obtain the purities we desire.

The extrapolation of the I.T.S. from about 450° to 630° C is not particularly satisfactory and the possible use of a higher melting point as a fixed point may repay investigation. The temperature 630° C is indeed the melting point of antimony but this has not proved to be a very satisfactory fixed point, perhaps because of the difficulty of obtaining it in a pure state. An alternative is that if the stability of resistance thermometers at high temperatures could be increased, the upper limit for resistance thermometry could be extended to the melting point of silver (960·8° C) or even gold (1063° C). In the latter case the thermocouple range of the I.T.S. would be eliminated.

At low temperatures the cessation of the Scale at −183° C (the boiling point of oxygen) has not been a serious limitation because of the relative paucity of technological interest at temperatures much below this. However, the increasing use of liquid helium and liquid hydrogen and of pumped liquid nitrogen for scientific purposes is leading to technological applications and is making the extension of the Scale to lower temperatures desirable. Growing interest in rocket propulsion and interplanetary and interstellar space investigations must inevitably lead to an increased need for reproducible measurements at low temperatures.

The Scale was only cut off at —183° C because the interpolation formula used with platinum resistance thermometers gives results which diverge rapidly from the thermo-dynamic scale below this temperature. Difficulties have been experienced by a number of workers in obtaining a reproducible scale in terms of the electrical resistance of platinum at these low temperatures; but in some recent work (Lowenthal *et al*, 1958, 1960) we have been able to show that these difficulties can be overcome by suitably taking account of peculiarities in the resistance-temperature characteristics of platinum and a method has been given for defining a satisfactory scale, reproducible to 0·005° down to 20° K (—253° C). Below this temperature the vapour pressures of hydrogen and of helium are possible means of defining a scale. Platinum resistance thermometry would not be suitable because of the low resistances involved.

In the upper region of the I.T.S. where temperatures are measured in terms of the emission of radiation by the hot body the position is again interesting. Here the measurements are usually made with what is known as a disappearing filament optical pyrometer. It is operated by the observer determining the current of a lamp filament at which its luminance is exactly the same as that of the body on which the instrument is sighted, so that the filament " disappears " against the background. The measurement is made in more or less monochromatic light. One of the disadvantages of the method is that the filament rarely does disappear completely owing to variations in the luminance of the filament across its width. Work done some years ago in conjunction with the Light Section of the Division of Physics (Giovanelli and Kemp, 1950) showed that this could be overcome by taking advantage of the change in polarization of the light with its angle of emission.

More serious is the fact that the answer is significantly dependent on the colour vision of the observer since it is not usually practicable to make observations in truly monochromatic light. In any case the subjective criterion of whether a filament has disappeared is not a very satisfactory basis for accurate measurement. In some work recently undertaken in the Section to set up with greater accuracy this portion of the I.T.S., errors resulting from this source were so considerable that it was necessary to have each of eight observers take over 90 observations under carefully controlled conditions to obtain an accuracy of setting at the gold point of ±0·25° C.

In an endeavour to obviate this source of trouble work is proceeding on the development of an instrument which will eliminate the effect of the human eye on the settings made. It is simple in conception but less simple in execution. It consists of a photoelectric device which scans across the filament and background and by the use of a suitable phase sensitive electronic detector gives a null reading on a sensitive meter when the luminance of the centre of the filament is the same as that of the hot body being observed. Edge effects of the filament are thus eliminated. This instrument has proved itself to be very sensitive; individual settings can be made to 0·05° C (at about 1100° C) where for a trained human observer the mean of ten successive readings would have a standard deviation of about 2° C. Some difficulties have been experienced in obtaining satisfactory long term stability with the instrument but it is believed these have now been overcome.

The various lines of investigation or development in relation to the I.T.S., referred to above, indicate that this is a field in which there are plentiful opportunities for worthwhile work. Numbers of other investigations have been made or are awaiting attention as opportunity occurs; the responses of resistance thermometers at low temperatures have been studied (Lowenthal and Harper, 1960); we have participated in international intercomparisons of the realization of portions of the I.T.S. and a study has been made of factors affecting the accuracy of optical pyrometry (Mortlock and Harper, 1953).

With the completion of the photoelectric optical pyrometer a whole new range of investigations will be opened up, for the examination of phenomena which affect visual optical pyrometry and yet are on the border line of observation using visual techniques will become practicable.

Other investigations planned include studies of the reproducibility of the melting point of tin (232° C) and cadmium (321° C) to examine their potentialities as secondary fixed points and of the triple point of neon (27° K) as a possible calibration point for an extended I.T.S. (Lowenthal *et al*, 1958).

The calibration of instruments in terms of the I.T.S. is often effected relative to an intermediate substandard which is not itself an instrument of the type covered by the I.T.S. specifications. Thus liquid-in-glass thermometers, unless they are to be calibrated to the highest possible accuracy, are compared with other liquid-in-glass thermometers which have in their turn been calibrated against I.T.S. resistance thermometers. This, and our natural concern with the types of measuring equipment in practical use and submitted for calibration, means that attention must be given to the limitations of such instruments, to possible ways of improving them and to finding ways of solving unusual problems of temperature measurement or control.

Two of the matters of this type investigated have been the effect of strain on the thermoelectric properties of metals (Mortlock, 1953) and factors affecting the stability of liquid-in-glass thermometers.

Because thermometers are so widely used by all scientists it might be of interest to mention explicitly one of the findings of the latter study. It is well known that with time the volume of the bulb of a thermometer alters, giving rise to what is known as secular change in the thermometer. This is usually allowed for by taking readings from time to time at a fixed temperature such as the ice point and correcting for the observed change. If the thermometer has recently been heated the bulb will not immediately return to its initial volume so a further change will be superimposed on the secular change ; they may be of opposite sign. This transient effect will disappear at room temperature in a more or less exponential manner. If the best accuracy is desired from thermometers it is usual, therefore, to measure the ice or other reference point after the thermometer has been left resting for at least a couple of days. This has been our practice for many years. Despite this precaution the measured ice points of some of our best secondary standards were found to behave in a rather irregular manner, even when the thermometers were of such a range that they were never heated above say 30° C. These variations amounted to as much as 0·01° C for thermometers graduated in 0·02° C. Our first reaction was to blame the ice points themselves or stiction of the mercury of the thermometers, but further study showed this was not the cause. The answer became apparent as soon as we tried storing the thermometers at constant temperature (0° C) for 48 hours or so before measuring their ice points. Immediately the ice point corrections became virtually constant, indicating that the previous variations had been due to variations in ambient temperature during the so-called " resting " period.

The further we study the behaviour of liquid-in-glass thermometers the more convinced we become that if their apparent accuracy is to be achieved, they must be used with a very full understanding of their idiosyncrasies and previous thermal history.

The Section is constantly being approached with requests for assistance in the solution of unusual problems of temperature measurement or control. Often special instruments have to be devised or special techniques evolved. Examples are the design of a resistance thermometer for measuring, in the field, the rectal temperatures of cattle ; and of another resistance thermometer for measuring the temperatures of estuarine muds in connection with oyster studies. Recently a request was received for measurements of the temperatures of biscuits as they pass at high speed through a 300 ft. baking oven ; and a somewhat similar problem of measuring the temperatures of oil drums as they pass, after painting, through a 200 ft. furnace was solved some time ago.

Often apparently simple enquiries can lead into strange by-ways. One such case was when a request for the loan of a thermocouple resulted in our becoming involved in that fascinating development in medicine known as hypothermia—the lowering of body temperature for medical purposes.

By such a lowering of temperature the metabolism of the body is slowed down so that its need for oxygen is reduced and the blood supply to the brain can be stopped for ten minutes or so without the production of permanent injury whereas at normal temperatures this could only be done for about three minutes. It soon became apparent to us that the physical problems involved in cooling a human patient from the normal temperature of 37° C down to say 30° C, holding him at that temperature perhaps for several hours, and then bringing the patient back to near normal temperature, went far beyond the comparatively simple measurement of his temperature. The heat to be removed is of the order of a million calories. In an interesting collaboration between medical men, engineers and ourselves equipment and techniques were developed which allowed surgery to proceed in parallel with the removal (or provision) of heat so that the patient's temperature would be under control at all times (Cass *et al*, 1956). This equipment has been used on well over a hundred cases, mainly children suffering from cardiac defects, with very satisfactory results. The simple request for a thermocouple has taken us still further, however, for it has brought before us other physical problems associated with this type of surgery.

There are many operations for which the ten minutes provided by hypothermia would not be sufficient, and for these either much lower body temperatures must be used or a machine must be provided to maintain the circulation of oxygenated blood while the heart is stopped—a so-called heart-lung machine.

The pump to circulate the blood is comparatively straightforward although it has to meet quite stringent requirements. It is with the oxygenator that the ideal has proved the hardest to attain, as is indicated by the many different models designed. The problem is to expose to oxygen a sufficient number of the blood corpuscles passing through the unit to be able to supply the patient with an adequacy of arterial-type blood. The demands, of course, may be reduced by combining hypothermia with the extra-corporeal circulation, as can easily be done.

Most oxygenators tend to copy the human lung by spreading the blood out on a large surface area. This tends to result in a large unit which requires a good deal of blood to prime it—a serious disadvantage, and particularly so if the techniques are to be applied extensively to newborn children in need of assistance for the first few hours or days of their lives.

In an endeavour to overcome these difficulties we have adopted a new approach to the problem. In most of the large-surface type oxygenators those corpuscles exposed to the oxygen spend much longer so exposed than is required, because the process of oxygenation is almost instantaneous. This tends to increase the size and hence the priming charge unnecessarily. In the device we are working on the blood flows down a screw-like helix as a stream. It is hoped that by adopting a suitable shape for the helix " thread " the internal circulation of the stream will be such as to bring virtually every blood corpuscle to the surface for the brief time required for its oxygenation. The method undoubtedly works but we are unable to say yet whether it will have a high enough efficiency to provide the compact, low priming charge oxygenator desired by our medical collaborators.

The activities of the Section on temperature measurement represent its major effort in standards work and provide its closest industrial connections. Each year over 300 Certificates and Reports are issued on calibrations and tests performed in this field and a great deal of other work which does not give rise to formal reports is undertaken. In parallel with this, improvements in the facilities for the realization of the International Temperature Scale and for measurements in terms of it, and research in the field of temperature measurement and control are constantly in progress.

Hygrometry

Humidity, in the meteorological sense, has long been recognized as a quantity of significance for our comfort and wellbeing and of prime importance in agriculture and animal husbandry. Industrially we know that it was a factor in determining the location of spinning and weaving mills before the days of air-conditioning. In none of these cases has a precise knowledge of humidity been of much interest. There are other industries, however, such as the food processing, photographic, tobacco, sugar and printing industries in which tolerances of humidity or its related quantity, moisture content, can become quite critical. Other special cases exist in which more difficult measurements of humidity are required, as in the checking of the moisture content of the breathing oxygen for pilots to ensure there will be no risk of ice blocking the control valve, or in the control of the atmosphere of furnaces used for the surface carburization of steel to harden it. Scientific investigations of innumerable kinds call for a good knowledge of the humidity, often under unusual conditions. In fact, one of the characteristics of work in hygrometry is the wide variety of circumstances under which measurements are required and the correspondingly wide variety of instruments which have been developed. The majority of these are empirical and many have been crude in the extreme. It is not my purpose to review such instruments here, however.

While the work of the Section in hygrometry includes the calibration of a certain number of instruments for use as sub-standards, by far the greater part of the effort is devoted to research and developmental activities. We believe that if improved methods of measuring, recording and controlling humidity can be provided then industry will in time learn to take advantage of the additional accuracy and control thereby made available.

Over the years particular attention has been devoted to four basic types of hygrometer, one or other of which is applicable to almost any humidity measuring problem. The work has in all cases gone a good deal deeper than the mere development of an instrument.

The most commonly used instrument for the measurement of humidity is the wet and dry bulb hygrometer—the " psychrometer ". This semi-absolute instrument has the disadvantage that the response of its wet thermometer is dependent on air velocity unless this velocity is greater than about 10 ft. per second. A far more versatile instrument is obtained if the thermometers are replaced with thermocouples (or a differential thermocouple). An investigation of the basic characteristics of such instruments revealed that if fine wires were used for the thermocouples, then the full depression of the temperature of the wet junction relative to that of the dry could be obtained with an air velocity of only 0·5 ft. per second (Wylie, 1949). The instrument obviously lends itself to remote reading.

A second instrument which will be familiar to most is the dew point hygrometer. Anyone who has used this instrument will know that the detection of the presence of dew on the surface is usually so difficult that very great care is needed if the temperatures for appearance and disappearance of the dew are to agree to within 0·1° C. Photoelectric detection of the formation of the dew leads to an appreciable increase in the precision of measurement. Such an instrument has been made automatic by causing the photo-current to control the temperature of the condensing surface. This instrument is particularly well suited to recording automatically the humidity of a stream of gas.

Each of the above instruments has the disadvantage that it requires a largish sample of the gas whose humidity is to be determined and by its operation adds or removes water from the gas studied, i.e. affects the conditions being measured. There are many problems in which a humidity " probe " is required for measuring the conditions at a point without significantly affecting these conditions. Typical of the many such cases on which we have been consulted is that of measuring the humidity in the fleece on a sheep's back. I understand this was required in connection with the following problem: when a female louse on a sheep decides to lay an egg it leaves the sheep's skin, climbs out along the wool fibre and at a certain place turns around, lays the egg and crawls back again. What determines where she will turn around? Temperature or humidity (for there will be a gradient of each)? To meet this type of problem use has been made of a method which while empirical in nature has the advantage that it is quick in response, uses only minute quantities of water, can be incorporated in an electrical circuit and is relatively stable (Cutting *et al*, 1955). The sensitive element comprises a small disk or rod of aluminium, the surface of which has been anodized to form a thin layer of aluminium oxide over which a moisture permeable gold film is evaporated as an electrode. Measurements are made of the electrical resistance or capacitance of the anodized layer, each of these quantities being a function of the relative humidity of the gas with which the probe is in equilibrium. The response of these probes is to some extent dependent on their previous hygrometric history and to overcome this a special calibrator unit has been developed which contains a number of cells in which known humidities are maintained by means of saturated salt solutions. It is thought this apparatus will find particular application to field work.

The fourth instrument to which I wish to refer is in a class by itself for it represents a new technique in hygrometry which provides facilities not hitherto available (Wylie, 1955*a*). With it measurements can be made to an order of magnitude better than the best dew point measurements with a time constant of the order of only a second. Unlike the dew point hygrometer and the psychrometer, measurements can be made at sub-zero temperatures without there being any uncertainty as to whether the measurements are relative to the vapour pressure of water or ice. It is interesting that this technique was the outcome of fundamental studies of the condensation process on solid surfaces and yet the idea could have been developed several decades ago. This is a good example of the fact that even in fields which seem to have become static opportunities will exist for worthwhile advances.

This hygrometer, christened the electrolytic condensation hygrometer, is quite simple in conception. The sensitive element is a water-soluble ionic crystal. If this is cooled in the presence of the gas to be examined a temperature will be reached at which the crystal will begin to exhibit " deliquescence ", i.e. a film of saturated solution will begin to form on the surface of the crystal. This will occur when the vapour pressure of the water in the gas first exceeds the saturation vapour pressure of the saturated solution. As long as the vapour pressure exceeds this critical value, additional solution will form and the film will thicken; if the vapour pressure becomes less than the critical value the film will evaporate. The presence of such a film may be easily detected electrically by placing electrodes on the crystal; a decrease or increase in the electrical resistance will correspond respectively to a thickening or thinning of the film. The instrument may be made self balancing by placing the crystal in a temperature controlled enclosure containing the gas sample and arranging for the temperature of the space to be brought to such a value that there will be a predetermined resistance (i.e. film thickness) between the crystal electrodes. The equilibrium temperature should be independent of this thickness for a wide range of thicknesses and this has been found to be so to better than 0·005° C (Wylie, 1957).

Because the response of the instrument is electrical it is particularly well suited to the automatic recording and control of humidity. It can be adapted to the measurement of a wide range of absolute humidities by selecting appropriate crystal materials. Patents have been taken out on this device (Wylie, 1955*b*, 1956, 1959) and it is hoped that it will soon be available as a commercially manufactured instrument.

The electrolytic condensation hygrometer provides more than an instrument for practical hygrometer, however. It also represents a valuable research tool which can be applied to a wide range of investigations. It has already served to show that films of saturated solution of average thickness as little as 8 mμ still have essentially the properties of bulk liquid and it has provided information on the fine structure of the crystal surfaces. It is proposed to apply it to further fundamental studies of the condensation process, accurate measurements of the interaction constant between gas and water molecules and to the determination of the vapour pressures (relative to the vapour pressure of water) of a number of saturated salt solutions. The field of hygrometry, far from being worked out, has proved to be redolent with opportunities for research, development and practical application.

Viscometry

A " standards " function of the Heat Section which bears little relationship to heat is the calibration of viscometers in terms of the absolute units of viscosity, the poise and the stokes, although, it is true, the accurate control of temperature plays an important part in precision viscometry. This field, which is of considerable industrial and economic importance, particularly in the lubricating oil industry, is the subject of a large number of standard specifications and codes of practice designed to effect reproducibility in viscometric measurements (e.g. British Standards Institution, 1957). It is true that high absolute accuracy is seldom important, in fact for many years virtually empirical scales were in almost universal use, but a study of standards specifications will reveal the lengths to which those interested in such measurements will go to obtain high reproducibility.

Modern practice is to refer all measurements to the viscosity of water at 20° C (1·0038 centistokes), and since any one viscometer can usually only cover a range of about a decade in viscosity this means that a long series of stepping up procedures is necessary if a viscosity of say 100 stokes is to be measured. In any such procedure errors are likely to accumulate, and this is particularly so with viscosity measurements. This is the reason for much of the complexity of standard codes for viscometry. The root of the trouble is that in an ordinary capillary tube viscometer the simple formula, which indicates that the rate of flow of a fluid through the capillary is inversely proportional to the viscosity of the fluid, requires an additional correction known as the kinetic energy correction. This term is hard to determine and yet in the stepping up calibration procedure will tend to introduce systematic errors. These errors can amount to several percent at higher viscosities.

To anyone familiar with the complications arising from the presence of this correction term, it will be as much a surprise as it was to us to discover that by a comparatively simple modification to the design of standard capillary viscometers, it can be made completely negligible (Caw and Wylie, 1958). The modification is to bell the ends of the capillary into a more or less exponential flare. This can be done quite simply by placing the sealed end of the capillary in a suitable linear temperature gradient and then blowing. The change of the viscosity of the glass with temperature causes the hotter portion to blow out to a much greater radius than the cooler.

A viscometer incorporating the long flares at the ends of its capillaries can be used over a much greater range of viscosities than would otherwise be possible and can be calibrated by measurement at a single viscosity. Each of these characteristics helps to make possible the simplification of viscometer specifications.

That this effect should have gone unrecognized for so long is indeed surprising. Perhaps this stems from the fact that in almost all of the early capillary tube viscosity measurements the experimenters were concerned with determining absolute values. The present simplification is only applicable to measurements made relative to some standard viscosity.

In the stepping up calibration procedure a suitable liquid is measured in one viscometer and then used to calibrate another. The rate of shear in the liquid will be markedly different in the two viscometers, so that the method tacitly assumes that the viscosity of the liquid is independent of its rate of shear, i.e. is a pure " Newtonian " fluid. This assumption is known to be invalid for many liquids but without an instrument in which the flow time is known to be simply related to the viscosity it has been difficult to check this point. The new type of instrument will accordingly be of considerable assistance in the selection of liquids suitable for use as sub-standards or transfer standards.

Because of the high accuracy of the modified viscometers for the measurement of relative viscosities one is being used for a redetermination of the viscosity of water as a function of temperature. A special instrument has been constructed in which the flow time is measured automatically on an electronic counter fed by a constant frequency source. If care is taken to ensure constancy of water temperature a repetition accuracy of 1 in 50,000 can be obtained in the flow time in this way. The best accuracy for visual timing with a stopwatch in this case would be about 1 in 1,000. The ability to compare viscosities to this order of accuracy clearly opens up many other possibilities in a field which has for many years been thought to be without promise for original work. The development has notable scientific as well as industrial applications.

Low Temperature and Solid State Physics

I indicated earlier that it would be most undesirable to endeavour to operate a standards laboratory without associating with it the stimulus of active research. In implementing this policy at the conclusion of the War the field of low temperature physics was selected as an appropriate one for active work. This selection was made for several reasons :

(i) It was a field to which our experience and the techniques and facilities developed in our standards work, particularly in thermometry and heat transfer, could be expected to be applicable ; per contra low temperature work could well contribute to our knowledge in these subjects.

(ii) It was known that no other facilities for the attainment of low temperature existed within Australia, although no country could consider its physical armoury complete without these facilities.

(iii) It was considered that low temperature technology, for which the name cryogenic engineering has since been coined, was bound to extend to this country and it was thought, therefore, that pilot experience in this field would prove valuable.

(iv) Finally the field of low temperature physics is a most attractive one for research. It is a temperature region in which on the one hand strange phenomena occur, such as the disappearance of all electrical resistance in some metals (super-conductivity) and the apparent disappearance of all viscosity in liquid helium (super-fluidity), while on the other hand many physical processes are greatly simplified because of the reduction in the thermal vibrations of the atoms and molecules. It is a field for the testing of physical theories and for investigations which lead to new ones.

All these expectations have been fulfilled.

Our decision to establish low temperature facilities was made at a fortunate time, for improved techniques for the production of the refrigerant used for most low temperature work (liquid helium) had just been developed (Collins, 1947). By taking advantage of these we were able, from the first, to produce liquid helium in sufficient quantities to supply not only our own experimental needs but to assist others from outside the Laboratory with low temperature experiments.

Our low temperature research has from the outset been concerned with the study of materials in the solid state, a comparatively new branch of physics which extends from pure physics into metallurgy and engineering and has been responsible for such major technological advances as the transistor.

Here I would say that it seems strange that while at least five C.S.I.R.O. Divisions are actively engaged in research on different aspects of solid state physics, it has been almost entirely neglected by our Australian Universities as a field in which to train physicists.

The conduction properties of metals and alloys was selected as the first subject for investigation (White, 1953). This has proved to be a fortunate choice for we have found the measurement of conductivities to be a most powerful technique for studying the imperfections which are present in all crystals, a knowledge of the nature and distribution of which is essential to the understanding of the physical behaviour of solids (Klemens, **1956**). Many types of imperfections in the regularity of the crystal lattice can occur and each of these introduces resistance to the flow of heat through the crystal; in a perfect infinite crystal there would be zero thermal resistance. Fortunately each type of imperfection leads to a different dependence of the thermal conductivity on temperature so that by making measurements over a range of low temperatures it is possible to identify the dominant types present. In this way it has been possible to study the imperfections introduced in solids by plastic deformation, quenching, radiation damage and fatigue, and to follow the course of the removal of these imperfections with annealing. The measurements have also been used to deduce the intrinsic conduction of perfect crystals subject only to the residual effects of thermal vibrations, and in this way to check current theories of the solid state and to study the laws of interaction between " conduction " electrons in the solid and the vibration of the crystal lattice.

Additional information about the nature of the mutual reactions between electrons, lattice vibrations, and imperfections in metals and alloys can be obtained from measurements of their thermoelectric forces, and work is proceeding to measure the exceedingly small e.m.f.s. involved.

Further studies of the basic structure of selected solids have been made through the measurement of their heat capacities down to low temperatures (Rayne, **1956**) and currently equipment is being set up for the measurement of thermal expansions. In all these cases the measurements can be extended from room temperature down to 1° or 2° K.

Another approach to the study of the solid state is through what is known as paramagnetic resonance. In the presence of a magnetic field atoms which are themselves magnetic will precess and by measuring these precession frequencies by resonance techniques it is possible to deduce the nature of the interatomic forces in the solid. The frequencies are in the microwave region. The technique can also be used for identifying and measuring the concentration of very small amounts of magnetic impurities; with equipment which has been set up for this work the presence of as few as 10^{13} magnetic atoms can be detected. The techniques can not only be applied to the detection of such substances as iron, nickel and chromium, but can also reveal the presence of free radicles in chemical compounds. They have been applied to a wide variety of specimens ranging from wool to coal.

Our low temperature facilities play a vital part in this work, too, for although some useful measurements of paramagnetic absorption can be made at room temperatures, the effects are much sharpened by the reduction of thermal vibrations which results from cooling the specimen and can therefore be interpreted more simply and accurately.

A good example of the unpredictable developments which can stem from fundamental research has recently arisen in connection with this field of investigation in the invention of what has been called the " Maser " (Bloombergen, **1956**). This device for the amplification of microwaves is hundreds of times more sensitive than any conventional amplifier and consequently can have very important applications to communication engineering. The idea has been enthusiastically received by the radio astronomers, too, for they see in the Maser a valuable ancillary to their radio telescope for the study of extra-galactic microwave radiation.

In conjunction with officers of the C.S.I.R.O. Division of Radiophysics a Maser is at present under construction for use on the large radio telescope being erected at Parkes, N.S.W. A pilot model has already been made to operate successfully. It employs a ruby as the basic material, the red coloration of which is due to the paramagnetic chromium ions. The ruby is cooled with liquid helium and has to be mounted in a magnetic field.

Theoretical studies made in the Section have revealed that in certain cases it should be possible to operate a Maser without requiring any external magnetic field (Bogle and Symmons, **1959**). This would be of considerable benefit in many cases and the practicability of such a device is being investigated.

The third major research activity involving the use of our low temperature facilities has been the study of low temperature thermometry. Various aspects of this have already been touched upon. Here, too, as with the other low temperature work, opportunities for interesting research abound.

Conclusion

In reviewing the work of the Section it is apparent that in the course of setting up the facilities which as a Standards Laboratory we are statutorily required to maintain, and in establishing a parallel research programme in the low temperature and solid state fields, numerous promising lines of investigation have been opened up. It is believed that there will be a good opportunity for developing these lines and others as yet unforeseen, for it would not be expected that the considerable effort which in the past has had to be devoted by the research personnel to purely standards work will need to continue. Nevertheless it would be unsafe to allow any of these standards fields to remain quiescent, for in that direction lies regression.

New fields of work present themselves for consideration ; others will arise from time to time. Thus in pyrometry the extension of our work to much higher temperatures must be seriously considered for technology is heading that way already. In viscometry consideration must be given to the complex but technically important field of rheology which deals with the flow properties of such things as pastes and paints.

In whatever direction development takes us, I feel confident the Section will find interesting and profitable work.

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Minor Planets Observed at Sydney Observatory During 1959

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The following observations of minor planets were made photographically at Sydney Observatory 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 automatically recorded on a chronograph by a contact on the shutter.

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

Table I

No.	1959 U.T.		Planet		R.A. (1950·0)			Dec. (1950·0)			Parallax Factors	
					h	m	s	°	′	″	s	″
816	Apr.	8·61448	24	Themis	14	00	34·62	—12	05	46·4	—0·02	—3·2
817	Apr.	30·53344	24	Themis	13	43	54·47	—10	39	37·4	—0·04	—3·4
818	July	22·61470	73	Klytia	20	52	49·97	—21	00	15·0	—0·01	—1·9
819	Oct.	1·63150	92	Undina	1	12	49·69	— 8	14	44·8	+0·08	—3·8
820	Nov.	3·53566	92	Undina	0	50	13·24	— 9	42	01·0	+0·11	—3·6
821	Mar.	5·65731	96	Aegle	11	44	42·20	—13	33	47·8	+0·12	—3·1
822	Apr.	6·52288	96	Aegle	11	15	56·82	—13	15	47·9	+0·04	—3·1
823	Aug.	5·52816	115	Thyra	20	03	14·30	—22	06	47·2	—0·06	—1·8
824	Aug.	13·51520	115	Thyra	19	54	44·73	—21	44	37·6	—0·01	—1·8
825	Apr.	29·48850	123	Brunhild	12	41	00·58	—14	26	53·8	—0·06	—2·9
826	Aug.	19·56481	172	Baucis	21	17	15·94	—19	47	51·6	+0·02	—2·1
827	Sep.	17·66485	181	Eucharis	1	48	38·54	—10	49	38·1	—0·01	—3·4
828	Sep.	30·65582	181	Eucharis	1	42	29·32	—13	02	37·0	+0·09	—3·1
829	Mar.	5·62150	198	Ampella	11	14	12·17	— 9	49	05·5	+0·08	—3·6
830	Mar.	5·69905	200	Dynamene	13	00	52·44	—13	43	51·2	+0·09	—3·0
831	Apr.	9·52032	200	Dynamene	12	33	05·74	—12	06	31·3	—0·11	—3·3
832	June	25·66660	210	Isabella	20	17	39·91	—27	37	34·8	0·00	—0·9
833	July	23·59070	210	Isabella	19	53	23·48	—29	15	30·5	+0·06	—0·7
834	Aug.	4·52790	210	Isabella	19	42	04·42	—29	36	41·7	—0·02	—0·6
835	Mar.	18·62486	242	Kriemhild	12	33	48·03	—10	42	14·6	+0·03	—3·4
836	Apr.	13·52374	242	Kriemhild	12	15	41·40	— 6	51	53·8	—0·03	—4·0
837	Aug.	12·68352	268	Adorea	23	17	41·39	— 6	47	18·5	+0·07	—4·0
838	Oct.	1·54211	268	Adorea	22	44	56·54	—10	28	26·0	+0·12	—3·5
839	Apr.	29·48850	283	Emma	12	33	00·11	—15	09	43·6	—0·04	—2·8
840	June	17·68858	292	Ludovica	19	59	28·71	—41	40	33·5	+0·05	+1·0
841	July	23·55348	292	Ludovica	19	21	44·13	—45	25	39·5	0·00	+1·8
842	July	29·55338	292	Ludovica	19	15	03·92	—45	29	38·6	+0·10	+1·7
843	Apr.	6·63378	322	Phaeo	14	11	47·21	—21	08	10·3	0·00	—1·9
844	May	5·49530	324	Bamberga	13	20	25·83	—23	33	10·8	—0·08	—1·6
845	May	12·50684	324	Bamberga	13	15	04·19	—23	57	17·8	+0·04	—1·5
846	June	11·55756	340	Eduarda	16	22	22·31	—26	31	26·9	+0·05	—1·1
847	June	25·50409	340	Eduarda	16	10	57·93	—26	07	31·8	+0·03	—1·2
848	May	28·56866	352	Gisela	15	51	37·05	—20	38	03·8	+0·03	—2·0
849	June	18·63938	356	Liguria	18	53	37·27	—34	23	44·7	+0·04	+0·1
850	July	27·53264	356	Liguria	18	16	16·69	—34	18	09·7	+0·11	0·0
851	July	2·65331	381	Myrrha	20	40	28·46	—16	03	35·6	—0·03	—2·7
852	July	28·61893	381	Myrrha	20	22	56·48	—18	54	18·2	+0·12	—2·3
853	Aug.	20·51588	381	Myrrha	20	07	22·97	—21	18	49·8	+0·03	—1·9

TABLE I—*continued*

No.	1959 U.T.		Planet	R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
				h m s	° ′ ″	s	″
854	Sep.	17·61394	387 Aquitania	0 34 34·42	—21 18 28·0	—0·01	—1·9
855	Oct.	1·60316	387 Aquitania	0 23 34·61	—23 20 48·2	+0·11	—1·6
856	Oct.	26·48709	387 Aquitania	0 07 59·73	—24 19 12·1	—0·01	—1·4
857	Mar.	5·65731	390 Alma	11 46 35·04	—15 35 15·8	+0·12	—2·8
858	Apr.	6·52288	390 Alma	11 17 27·47	—14 16 03·6	+0·04	—2·9
859	June	11·55756	406 Erna	16 17 19·72	—27 13 19·2	+0·06	—1·0
860	June	25·50409	406 Erna	16 06 20·93	—26 27 56·2	+0·04	—1·1
861	July	29·68394	422 Berolina	22 02 38·11	—21 41 34·0	+0·12	—1·9
862	July	2·62003	423 Diotima	19 22 16·83	—32 05 29·5	+0·04	—0·3
863	July	27·57580	423 Diotima	19 00 08·40	—33 35 49·0	+0·18	—0·2
864	Feb.	26·61669	426 Hippo	11 10 22·51	—14 59 48·7	+0·01	—2·8
865	Apr.	6·46909	426 Hippo	10 34 45·83	—14 38 25·3	—0·04	—2·9
866	July	28·66748	446 Aeternitas	22 03 59·69	—30 46 12·8	+0·06	—0·5
867	Aug.	13·61423	446 Aeternitas	21 50 24·00	—32 05 14·5	+0·06	—0·3
868	Aug.	20·58802	446 Aeternitas	21 43 45·81	—32 24 30·2	+0·05	—0·2
869	May	28·59960	448 Natalie	16 45 06·58	—33 01 28·8	—0·07	—0·1
870	July	2·50447	448 Natalie	16 13 31·44	—33 27 42·1	+0·09	—0·1
871	Aug.	5·65106	487 Venetia	22 45 38·71	—17 19 19·8	—0·02	—2·5
872	Sep.	17·54841	487 Venetia	22 14 18·56	—22 46 31·3	+0·10	—1·7
873	June	25·66660	488 Kreusa	20 19 31·72	—27 18 16·4	—0·01	—1·0
874	July	23·59070	488 Kreusa	19 58 06·47	—29 31 07·1	+0·05	—0·7
875	Aug.	4·52790	488 Kreusa	19 48 23·26	—30 11 03·0	—0·04	—0·6
876	Apr.	6·55802	500 Selinur	12 44 50·45	—20 45 35·5	—0·05	—2·0
877	Apr.	28·49540	500 Selinur	12 27 02·49	—18 32 47·2	—0·01	—2·3
878	July	2·58872	505 Cava	18 38 43·10	—25 14 42·7	+0·03	—1·3
879	July	23·51176	505 Cava	18 19 22·82	—26 11 50·5	+0·01	—1·1
880	Aug.	5·52816	534 Nassovia	20 05 03·62	—22 47 09·8	—0·06	—1·7
881	Aug.	13·63946	578 Happelia	22 31 10·18	—19 47 06·2	+0·04	—2·1
882	Sep.	17·54841	578 Happelia	22 02 27·11	—20 42 58·1	+0·12	—2·1
883	Sep.	30·58312	582 Olympia	23 50 19·69	—20 25 34·8	+0·11	—2·1
884	Oct.	7·53738	582 Olympia	23 45 03·59	—21 51 09·2	+0·03	—1·8
885	Sep.	30·62259	600 Musa	1 04 55·51	— 6 34 35·6	+0·06	—4·0
886	Nov.	4·49924	600 Musa	0 40 00·71	— 9 28 38·2	+0·03	—3·6
887	July	27·64506	624 Hektor	21 30 31·43	—26 13 25·4	+0·05	—1·2
888	May	28·63389	670 Ottegebe	17 33 33·11	—12 01 12·4	+0·01	—3·3
889	July	2·54254	670 Ottegebe	17 04 16·06	—11 24 54·1	+0·09	—3·4
890	June	25·63778	685 Hermia	19 24 40·99	—16 18 34·1	+0·04	—2·6
891	July	22·52862	685 Hermia	19 01 08·16	—15 50 46·3	—0·04	—2·7
892	July	2·58872	720 Bohlinia	18 32 53·82	—26 27 28·2	+0·04	—1·1
893	July	29·64399	732 Tjilaki	21 25 46·81	— 3 15 08·8	+0·07	—4·5
894	July	22·61470	758 Mancunia	21 02 10·54	—20 01 58·1	—0·03	—2·1
895	Aug.	20·55192	758 Mancunia	20 40 30·75	—22 01 08·3	+0·07	—1·8
896	Aug.	12·65030	770 Bali	22 51 08·89	—15 39 02·8	+0·02	—2·7
897	Sep.	30·45600	770 Bali	22 07 36·33	—18 29 10·1	—0·07	—2·3
898	May	28·56866	774 Armor	15 45 59·43	—21 21 39·2	+0·04	—1·9
899	Apr.	22·69497	774 Armor	16 11 05·09	—23 44 35·6	+0·08	—1·5
900	June	11·59798	793 Arizona	17 05 23·97	—40 18 31·6	+0·10	+1·0
901	June	18·52364	804 Hispania	16 17 25·24	—45 46 09·9	+0·01	+1·8
902	July	2·47022	804 Hispania	16 05 37·91	—44 29 21·7	—0·02	+1·6
903	July	2·62003	814 Tauris	19 25 11·98	—31 53 22·7	+0·03	—0·3
904	July	27·57580	814 Tauris	19 00 44·63	—34 52 59·3	+0·18	0·0
905	Oct.	1·66102	818 Kapteynia	1 58 14·02	— 7 52 06·4	+0·08	—3·9
906	Nov.	4·53940	818 Kapteynia	1 30 39·37	— 8 19 54·8	+0·05	—3·8
907	July	22·59038	824 Anastasia	20 02 07·76	—15 00 29·0	+0·02	—2·8
908	July	28·57659	824 Anastasia	19 57 16·02	—15 38 27·4	+0·04	—2·7
909	Apr.	30·61303	838 Seraphina	14 50 05·57	—20 55 10·2	+0·06	—2·0
910	Aug.	13·66894	850 Altona	23 17 39·10	—18 34 26·3	+0·03	—2·3
911	Sep.	30·54064	850 Altona	22 45 48·25	—24 12 09·2	+0·12	—1·5
912	Sep.	30·62259	861 Aida	1 14 48·51	— 4 37 57·7	+0·04	—4·3
913	Apr.	6·59446	896 Sphinx	13 23 42·86	—22 23 30·1	—0·02	—1·7
914	Apr.	28·53179	896 Sphinx	13 04 53·92	—19 09 07·4	+0·02	—2·2
915	Aug.	12·68352	930 Westphalia	23 27 09·61	— 6 16 33·6	+0·05	—4·1
916	Oct.	1·47136	930 Westphalia	22 34 32·98	— 3 15 18·2	—0·07	—4·5
917	Aug.	4·68835	942 Romilda	22 35 48·37	—25 10 22·1	+0·12	—1·4
918	Aug.	13·66894	953 Painleva	23 09 56·24	—19 58 41·2	+0·05	—2·1

TABLE I—*continued*

No.	1959 U.T.		Planet		R.A. (1950·0)	Dec. (1950·0)	Parallax Factors	
					h m s	° ′ ″	s	″
919	Sep.	30·49637	953	Painleva	22 31 38·08	—20 51 39·4	0·00	—2·0
920	Apr.	6·63378	957	Camelia	14 21 30·79	—22 16 14·5	—0·02	—1·7
921	Apr.	30·57184	957	Camelia	14 03 40·94	—19 20 17·7	+0·03	—2·2
922	May	14·50783	957	Camelia	13 53 59·66	—17 22 24·0	—0·03	—2·5
923	July	29·59796	1054	Forsytia	20 03 11·13	—30 08 27·3	+0·12	—0·6
924	Aug.	6·53934	1054	Forsytia	19 56 14·75	—30 44 39·6	0·00	—0·4
925	Mar.	18·62486	1068	Nofretete	12 37 56·87	—11 02 05·0	+0·02	—3·4
926	Apr.	13·56186	1068	Nofretete	12 16 48·19	— 9 28 49·0	+0·09	—3·6
927	Apr.	6·67081	1086	Nata	14 30 32·96	—27 04 39·6	+0·09	—1·1
928	Sep.	23·65264	1093	Freda	0 54 55·67	—32 35 03·2	+0·14	—0·3
929	Sep.	28·62663	1093	Freda	0 49 20·68	—32 27 22·2	+0·11	—0·3
930	Aug.	6·57252	1109	Tata	20 34 51·24	—13 44 37·6	+0·02	—3·0
931	Aug.	5·65106	1188	Gothlandia	22 45 44·17	—14 53 51·6	—0·02	—2·8
932	Sep.	23·46500	1188	Gothlandia	22 03 50·73	—15 37 04·3	—0·07	—2·8
933	Aug.	4·65110	1294	Antwerpia	22 00 36·59	—25 34 08·3	+0·07	—1·3
934	Sep.	28·67251	1362	Griqua	2 19 17·19	—29 29 09·8	+0·05	—0·7
935	Oct.	23·59936	1362	Griqua	2 06 12·86	—32 27 27·4	+0·07	—0·2
936	Nov.	3·57196	1362	Griqua	1 58 51·22	—32 11 06·1	+0·09	—0·3
937	Nov.	27·50145	1362	Griqua	1 49 29·36	—28 20 58·9	+0·10	—0·9
938	July	2·65331	1432	Ethiopia	20 39 58·48	—15 40 44·6	—0·03	—2·7
939	July	28·61893	1432	Ethiopia	20 23 51·63	—19 38 59·1	+0·12	—2·2
940	Aug.	4·60184	1560	Strattonia	21 05 21·98	—12 01 07·1	+0·03	—3·3

TABLE II

No.	Comparison Stars	Dependences			
816	Yale *11* 4947, 4956, 4968	0·23985	0·38034	0·37980	S
817	Yale *11* 4881, 4894, 4896	0·44889	0·23192	0·31919	R
818	Yale *13* I 8964, 8970, 8977	0·30226	0·22144	0·47630	S
819	Yale *16* 243, 247, 263	0·22736	0·32572	0·44693	W
820	Yale *11* 160, 170, 175	0·33698	0·24518	0·41784	S
821	Yale *11* 4354, 4356, 4370	0·34237	0·20065	0·45698	W
822	Yale *11* 4234, 4242, 4254	0·27812	0·32928	0·39260	S
823	Yale *14* 13971, 13983, 13996	0·33626	0·11967	0·54407	R
824	Yale *13* I 8538, 8573, *14* 13889	0·48870	0·34661	0·16468	S
825	Yale *11* 4585, 4608, *12* I 4868	0·20094	0·36614	0·43292	S
826	Yale *13* I 9118, 9140, 9156	0·19635	0·34604	0·45761	W
827	Yale *11* 403, 417, 430	0·44959	0·29098	0·25943	R
828	Yale *11* 380, 384, 400	0·37921	0·24096	0·37983	W
829	Yale *16* 4237, 4238, 4253	0·22600	0·49728	0·27671	W
830	Yale *11* 4675, 4680, 4698	0·54149	0·16576	0·29274	W
831	Yale *11* 4556, 4560, 4572	0·35596	0·31130	0·33275	S
832	Yale *13* II 13363, 13392, 13409	0·23191	0·52272	0·24537	R
833	Yale *13* II 13067, 13072, 13107	0·21450	0·25287	0·53262	S
834	Yale *13* II 12949, 12951, 12970	0·34208	0·50792	0·15000	R
835	Yale *11* 4557, 4570, *16* 4603	0·23987	0·34951	0·41062	S
836	Yale *16* 4523, 4531, 4536	0·53444	0·15359	0·31197	W
837	Yale *16* 8287, 8289, 8296	0·89212	0·42600	—0·31812	S
838	Yale *11* 8013, 8019, 8032	0·26713	0·31668	0·41619	W
839	Yale *12* I 4811, 4827, 4841	0·21792	0·40550	0·37657	S
840	Cord. D 14582, 14598, 14648	0·26888	0·49259	0·23853	W
841	Cord. D 14225, 14248, 14271	0·28977	0·25523	0·45500	S
842	Cord. D 14137, 14180, 14225	0·45104	0·21800	0·33097	W
843	Yale *13* I 5948, 5966, 5975	0·22175	0·39966	0·37859	S
844	Yale *14* 9862, 9867, 9896	0·15492	0·43029	0·41479	S
845	Yale *14* 9812, 9813, 9849	0·22918	0·34628	0·42454	S
846	Yale *14* 11457, 11483, *13* II 10256	0·35650	0·40745	0·23606	S
847	Yale *14* 11368, 11375, 11411	0·31082	0·35901	0·33017	R
848	Yale *13* I 6555, 6566, 6579	0·17991	0·25301	0·56708	R
849	Cape *17* 10271, 10279, 10312	0·16853	0·37855	0·45292	W
850	Cape *17* 9829, 9866, 9868	0·50011	0·24149	0·25840	W
851	Yale *12* I 7788, 7798, 7825	0·26499	0·52689	0·20812	S
852	Yale *12* II 8746, 8762, 8765	0·41379	0·15546	0·43075	W

TABLE II—*continued*

No.	Comparison Stars	Dependences			
853	Yale *13* I 8624, 8632, 8658	0·55660	0·13635	0·30705	W
854	Yale *13* I 138, 150, *14* 263	0·37596	0·35110	0·27294	R
855	Yale *14* 151, 168, 189	0·25464	0·42422	0·32113	W
856	Yale *14* 36, 46, 61	0·14116	0·67236	0·18647	S
857	Yale *12* I 4605, 4607, 4627	0·49700	0·17043	0·33257	W
858	Yale *11* 4237, 4254, 4260	0·30080	0·22482	0·47438	S
859	Yale *13* II 10199, 10256, *14* 11457	0·50960	0·39427	0·09612	S
860	Yale *14* 11322, 11354, 11375	0·52273	0·18930	0·28797	R
861	Yale *14* 15059, 15100, *13* I 9399	0·44356	0·30951	0·24693	W
862	Cape *17* 10567, 10590, 10611	0·45332	0·23795	0·30872	S
863	Cape *17* 10336, 10338, 10391	0·26492	0·37379	0·36128	W
864	Yale *12* I 4420, 4425, 4445	0·38994	0·33189	0·27816	S
865	Yale *12* I 4221, 4234, *11* 4039	0·24962	0·38034	0·37004	R
866	Cape *17* 11994, 12012, 12029	0·22052	0·34692	0·43256	W
867	Cape *17* 11881, 11918, 11926	0·26452	0·22278	0·51270	S
868	Cape *17* 11856, 11861, 11873	0·35166	0·43964	0·20870	W
869	Cape *17* 8768, 8796, 8805	0·26381	0·52896	0·20723	R
870	Cape *17* 8446, 8500, 8506	0·51766	0·21606	0·26628	S
871	Yale *12* I 8465, 8469, 8470	0·41580	0·13635	0·44785	R
872	Yale *14* 15145, 15173, 15176	0·39706	0·42737	0·17557	R
873	Yale *13* II 13392, 13409, 13430	0·39088	0·22472	0·38439	R
874	Yale *13* II 13133, 13154, 13167	0·31088	0·30015	0·38897	S
875	Cape *17* 10803, 10816, 10831	0·23349	0·52207	0·24443	R
876	Yale *13* I 5518, 5525, 5544	0·60948	0·11993	0·27059	S
877	Yale *12* II 5401, 5418, *12* I 4792	0·28351	0·44756	0·26894	S
878	Yale *14* 12957, 12965, 12989	0·17221	0·42757	0·40021	S
879	Yale *14* 12688, 12735, 12742	0·31364	0·38534	0·30102	S
880	Yale *14* 13983, 14009, 14017	0·33246	0·37145	0·29609	R
881	Yale *12* II 9534, 9546, *13* I 9549	0·20726	0·31650	0·47624	S
882	Yale *13* I 9393, 9399, 9410	0·42341	0·18809	0·38850	R
883	Yale *13* I 9919, 9943, 9951	0·45564	0·25171	0·29265	W
884	Yale *14* 15847, 15848, 15867	0·62865	0·16268	0·20867	R
885	Yale *16* 222, 223, 239	0·45147	0·22173	0·32680	W
886	Yale *11* 128, 143, *16* 139	0·36966	0·29022	0·34013	S
887	Yale *14* 14818, 14819, 14839	0·40498	0·44225	0·15277	W
888	Yale *11* 6009, 6011, 6026	0·32988	0·38131	0·28881	R
889	Yale *11* 5845, 5851, 5862	0·42509	0·25029	0·32462	S
890	Yale *12* I 7280, 7291, 7298	0·31471	0·46797	0·21732	R
891	Yale *12* I 7047, 7058, 7073	0·53335	0·19882	0·26784	S
892	Yale *14* 12875, 12902, 12932	0·36953	0·26545	0·36502	S
893	Yale *17* 7495, 7498, 7504	0·49741	0·25045	0·25213	W
894	Yale *13* I 9033, 9044, 9049	0·39422	0·39611	0·20967	S
895	Yale *14* 14355, 14379, 14383	0·31569	0·24265	0·44166	W
896	Yale *12* I 8483, 8495, 8503	0·25123	0·39510	0·35367	S
897	Yale *12* II 9413, 9432, 9436	0·37548	0·34288	0·28164	S
898	Yale *13* I 6523, 6528, 6555	0·34871	0·38809	0·26320	R
899	Yale *14* 11383, 11389, 11396	0·48791	0·32245	0·18964	R
900	Cord. D 12151, 12172, 12194	0·33193	0·26985	0·39822	S
901	Cord. D 11345, 11368, 11409	0·31242	0·32289	0·36470	W
902	Cord. D 11244, 11270, 11284	0·06542	0·36996	0·56462	W
903	Cape *17* 10590, 10611, 10630	0·40343	0·28243	0·31414	S
904	Cape *17* 10333, 10368, *18* 9898	0·26526	0·55227	0·18247	W
905	Yale *16* 415, 422, 428	0·35846	0·38661	0·25493	W
906	Yale *16* 308, 319, 322	0·30539	0·29521	0·39941	S
907	Yale *12* I 7533, 7542, 7556	0·29242	0·40798	0·29960	S
908	Yale *12* I 7507, 7514, 7520	0·40216	0·13792	0·45992	W
909	Yale *13* I 6177, 6178, 6191	0·55378	0·18840	0·25781	R
910	Yale *12* II 9775, 9784, 9786	0·27633	0·35051	0·37316	S
911	Yale *14* 15368, 15399, 15405	0·43133	0·26583	0·30283	W
912	Yale *17* 284, 292, 293	0·06760	0·71384	0·21857	W
913	Yale *13* I 5715, 5736, *14* 9913	0·36996	0·37140	0·25864	S
914	Yale *12* II 5622, 5624, 5649	0·43032	0·22028	0·34940	S
915	Yale *16* 8321, 8331, 8342	0·38592	0·42628	0·18780	S
916	Yale *17* 7839, 7853, 7854	0·29837	0·58557	0·11606	R
917	Yale *14* 15291, 15313, 15328	0·22953	0·38967	0·38080	R
918	Yale *12* II 9734, *13* I 9746, 9762	0·42142	0·37651	0·20207	S
919	Yale *13* I 9527, 9557, 9568	0·31357	0·39882	0·28761	W
920	Yale *14* 10392, *13* I 6009, 6028	0·36428	0·22886	0·40687	S

TABLE II—*continued*

No.	Comparison Stars	Dependences			
921	Yale *12* II 5917, 5935, 5940	0·33102	0·22987	0·43911	R
922	Yale *12* I 5217, 5232, 5236	0·51316	0·12810	0·35874	R
923	Cape *17* 10933, 10950, 10959	0·27983	0·47000	0·25017	W
924	Cape *17* 10868, 10881, 10907	0·17732	0·48007	0·34260	R
925	Yale *11* 4570, 4590, 4591	0·39681	0·14231	0·46088	S
926	Yale *16* 4525, 4534, 4543	0·40648	0·22698	0·36653	W
927	Yale *14* 10475, *13* I 9172, 9229	0·40400	0·33406	0·26194	S
928	Cape *17* 327, 337, 352	0·27731	0·41440	0·30829	S
929	Cape *17* 298, 315, 319	0·44290	0·27901	0·27808	W
930	Yale *11* 7275, 7294, *12* I 7780	0·26162	0·42086	0·31753	R
931	Yale *12* I 8459, 8464, 8478	0·25995	0·33412	0·40593	R
932	Yale *12* I 8264, 8279, 8286	0·32980	0·46221	0·20799	R
933	Yale *14* 15052, 15058, 15069	0·36682	0·22795	0·40523	R
934	Yale *13* II 898, 906, 915	0·38022	0·44501	0·17477	W
935	Cape *17* 748, 768, 771	0·35988	0·38237	0·25775	W
936	Cape *17* 695, 728, 729	0·38734	0·24599	0·36667	S
937	Yale *13* II 654, 671, 705	0·34557	0·41357	0·24086	R
938	Yale *12* I 7788, 7798, 7825	0·58237	0·21015	0·20748	S
939	Yale *13* I 8747, 8780, *12* II 8765	0·37321	0·37395	0·25284	W
940	Yale *11* 7481, 7497, 7500	0·47348	0·06167	0·46485	R

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 (825, 839, 844, 864, 899, 908, 926) 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 Miss M. Baker and Mrs. M. Wilson, who have also assisted in the computation.

Reference

ROBERTSON, W. H., 1959. *J. Proc. Roy. Soc. N.S.W.*, **93**, 11 ; *Sydney Observatory Papers*, No. **36**.

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Sydney

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Net Electric Charges on Stars, Galaxies and "Neutral" Elementary Particles

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ABSTRACT—The orthodox assumption in astronomy that stars cannot carry appreciable net electric charges is abandoned and as a result of the contrary assumption it has been found possible to account for the known orders of magnitude of five different astronomical phenomena and the directions relating to three of them, as well as to explain qualitatively or semi-quantitatively at least thirteen other phenomena. The first five are:

1. The maximum energy of about 5×10^{18} eV found for a primary cosmic ray particle.
2. The Sun's polar magnetic field vectors.
3. The approximate equality for the Sun and for Blackett's average of five magnetic stars, of P/U the ratio of the magnetic moment to the angular momentum of the star concerned.
4. The present state of magnetization of the Earth.
5. The existence and position of the outer Van Allen belt.

To provide a source for the charge on a star two alternative hypotheses are advanced.

1. Introduction

It has long been assumed in astronomy that a star cannot carry an appreciable net electric charge. In order to explain astronomical observations which indicate the presence of strong magnetic and electric fields it has therefore been customary until now to rely solely on hydro-magnetic theories.

In this note it is proposed to remove this restriction on stars and to examine briefly some of the principal consequences. It will be found that this widening of our outlook has many advantages and unifies a number of phenomena which hitherto have required ad hoc hypotheses for their explanation.

For convenience we consider first one possible source of the charge on a star.

2. The Fundamental Hypothesis H_1

We shall assume that in the interior of a hot star, like the Sun, the thermonuclear processes generate certain particles, provisionally named " astrons ", which have the following properties.

An astron has a small mass m (which may possibly be zero) and a small positive charge e_a such that

$$e_a/e \ll 1 \quad \ldots\ldots\ldots\ldots (1)$$

where $-e$ is the charge on an electron. Also an astron resembles a neutrino in its ability to penetrate matter freely.

In order to link up this hypothesis with what is assumed to be known about thermonuclear processes we may conveniently adopt the following two supplementary hypotheses h_1 and h_2:

(h_1) Astrons are neutrinos;

(h_2) A proton carries the same charge e as a positron and an electron carries an opposite charge $-e$.

From these hypotheses and the processes considered below we shall deduce that a neutron carries a negative charge, $-e_n$. For convenience of some later discussions we shall here relate e_n to the neutron's mass m_n by means of the formula

$$e_n = \beta_n G^{\frac{1}{2}} m_n \quad \ldots\ldots\ldots (2)$$

where β_n is a pure number. The physical meaning of β_n is that β_n^2 is the ratio of the electric force of repulsion between a pair of well-separated neutrons to the gravitational force of attraction.

It is well known that the following two processes can occur (see, for example, Reines and Cowan, 1956):

$$n^\circ \rightarrow p^+ + \beta^- + \bar{\nu} \text{ (antineutrino)} \quad \ldots\ldots (3.1)$$

$$p^+ \rightarrow n^\circ + \beta^+ + \nu \text{ (neutrino)} \quad \ldots\ldots (3.2)$$

where ν and $\bar{\nu}$ denote a neutrino and antineutrino respectively.

If we assume that in these processes electrical charge is conserved it follows from (3.1), (3.2), and (h_2) that the neutrino and antineutrino carry charges e_ν and $e_{\bar\nu}$ respectively where

$$e_\nu = e_n, \quad e_{\bar\nu} = -e_n.$$

Also, by hypotheses (H_1) and (h_1)

$$e_\nu = e_a$$

Hence,

$$e_n = e_a$$

and

$$e_{\bar\nu} = -e_a.$$

Thus the neutron carries a negative charge $-e_a$ and the neutrino and antineutrino carry the charges e_a and $-e_a$ respectively.

It will be noted that these hypotheses and deductions are entirely consistent with the following statements by D. Halliday (1950) and Reines and Cowan (1956) respectively :

" The neutron behaves like a spinning negative charge as far as the relation between its spin vector and its magnetic moment vector is concerned."

" The conclusion remains that the neutrino and anti-neutrino are distinct particles with an as yet undetected ' difference '." This conclusion was forced by the experimental evidence cited by Reines and Cowan.

Our hypotheses and deductions are also consistent with the current assumption that the principal thermonuclear process in the Sun is the proton-proton reaction in which two β^+ particles and two neutrinos (ν) are released for every four protons involved.

An alternative hypothesis on the source of the net electric charge on a star will be considered in Section 10.

3. The Charge $-Q_s$ Acquired by a Star

The f astrons generated per second by the thermonuclear processes in a star will mostly pass out of the star and so constitute an outwards current i_a where

$$i_a = f e_a.$$

As a result the star acquires a negative charge $-Q_s$, and so a surface potential $-V_s$ where

$$V_s = Q_s / R_s$$

and R_s is the star's radius.

Q_s remains constant if i_a is balanced by the currents due to electrically attracted nuclei and expelled electrons.

It is now convenient to relate the charge $-Q_s$ on a star to its mass M_s by the following formula :

$$Q_s = \beta_s G^{\frac{1}{2}} M_s, \quad \ldots\ldots\ldots (4)$$

where β_s is a pure number which is analogous to β_n in (2).

In order to estimate the value of β_s for an average star we shall determine its value for the Sun regarded as an average star. This can be done in two different ways, as shown in the next section.

4. Primary Cosmic Ray Particles Arising from Stellar Electric Fields

If W is the energy of a C.R. particle in electron volts it is known from experiments on C.R. extensive showers that $W \leqslant W_0$ where

$$W_0 \sim 5 \times 10^{18} \text{ eV.} \quad \ldots\ldots (5)$$

Hence, the electric potential of a point P_0 on the Earth's orbit, relative to a point in intergalactic space, is $-V$ e.s.u., where

$$V = 1{\cdot}7 \times 10^{16}/Z \quad \ldots\ldots (6)$$

and Ze is the charge on the nucleus concerned.

If we regard the Galaxy as an assembly of $N = 1{\cdot}6 \times 10^{11}$ stars like the Sun each carrying the charge $-Q_s$ then the potential at a point distant $r_s = 2{\cdot}7 \times 10^4$ light years from the galactic centre is given in order of magnitude by $-V_g$ where

$$V_g = N \beta_s G^{\frac{1}{2}} M_s / r_s \quad \text{e.s.u.}$$

For we may assume that nearly all the mass of the Galaxy lies within a sphere of radius r_s. Thus V_g is the potential, relative to a point in intergalactic space, at points P_s near the Solar System.

Also, if r_0 is the radius of the Earth's orbit and P_s is a point distant about 2 light years from the Sun* then the potential at any point P_0 of this orbit, relative to that at P_s, is given approximately by $-V_s$ where

$$\left.\begin{aligned} V_s &= \beta_s G^{\frac{1}{2}} M_s / r_0 \\ &= 3{\cdot}44 \times 10^{16} \beta_s \end{aligned}\right\} \text{e.s.u.} \quad \ldots. (7)$$

since

$$G^{\frac{1}{2}} = 2{\cdot}58 \times 10^{-4},$$
$$M_s = 2 \times 10^{33} \text{ g},$$
$$r_0 = 1{\cdot}5 \times 10^{13} \text{ cm}.$$

Then the potential at P_0, relative to intergalactic space, is given by $-V$ where

$$V = V_s (1 + N r_0 / r_s) = 95 V_s. \quad \ldots. (8)$$

From (7), (8) and (6) we then obtain

$$\beta_s = 5{\cdot}2 \times 10^{-3}/Z.$$

If we assume that the energy W_0 given in (5) relates to a proton attracted from intergalactic

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* i.e. a point also distant 2 l.y. from the nearest other star.

space up to the point P_0 (with negligible loss of energy by collisions on the way) then $Z=1$ and so

$$\beta_s=5\cdot 2\times 10^{-3}.$$

If, on the other hand, W_0 relates to an iron nucleus attracted from interstellar space in the Galaxy then $Z=26$ and (8) is replaced by

$$V=V_s. \qquad \ldots\ldots\ldots\ldots \quad (8.1)$$

We thus obtain

$$\beta_s=1\cdot 9\times 10^{-2}. \quad \ldots\ldots\ldots \quad (9)$$

This value agrees with the first estimate within a factor of 4 and is more reliable since the first estimate is subject to much greater errors.

In any event these calculations show that the C.R. particles of very high energy may arise from either one or both of two processes, namely:

I. The local electric field of the Sun acting on local nuclei, and

II. The electric field due to all the stars in our Galaxy acting on intergalactic protons.

If account is taken of losses of energy by collision of the attracted nuclei with other particles (H atoms) and with magnetic clouds of ionized hydrogen, it may be possible to explain in the same way the origin of C.R. particles of all energies.

Corresponding to β_s in (9) we find from (4) that the charge on the Sun is $-Q_s$ where

$$Q_s=10^{28} \text{ e.s.u.} \qquad \ldots\ldots \quad (9.1)$$

5. The General Magnetic Fields of the Sun and of the Galaxy Due to their Rotation

Since it is not possible to state how the charge $-Q_s$ is distributed in the Sun nor how the charge $-NQ_s$ is distributed in the Galaxy, we are compelled initially to adopt some simplifying assumption like the following one in order to determine the order of magnitude of the magnetic moment P of each of these bodies.

We shall therefore assume that the matter and motion are symmetrically distributed about an axis and that the net charge density $-\sigma$ at any point is in a constant ratio to the matter density ρ at that point, i.e.,

$$\sigma=\beta G^{\frac{1}{2}}\rho \qquad \ldots\ldots\ldots \quad (10)$$

where β is a constant of order 1 or less.

Chapman (1948) has proved that in these circumstances the magnetic field outside the rotating body is given approximately by that of an equivalent magnetic dipole of moment P where

$$P=\beta G^{\frac{1}{2}}U/2c \quad \ldots\ldots\ldots \quad (11)$$

and U is the angular momentum of the body. This formula had been previously used by Blackett (1949) in an interesting comparison of the fields of the Earth, the Sun and five other stars, but he had implicitly rejected its association with net electric charges on these bodies.

In his publication Chapman applied the relation (11) to a particular model of the Sun and computed the value of β corresponding to an assumed north polar magnetic field $\mathbf{H}_p=-10$ gauss, thus obtaining

$$\beta=0\cdot 04\,|\,H_p\,|.$$

On comparing this result with the value β given under (9) we obtain

$$H_p \sim -0\cdot 5 \text{ gauss}.$$

Other estimates of H_p can be made as follows.

A spherically symmetrical distribution of charge $-Q$ e.s.u. in a sphere of radius a which rotates with the angular velocity ω generates a polar field $\mathbf{H}'_p$ where

$$H'_p=-2f\omega Q/ca \text{ gauss}$$

and f is a numerical factor which depends on the distribution of Q. This result is also easily derived from (11) when Q and M are uniformly distributed in the star.

For the Sun we have $a=7\times 10^{10}$ cm, $\omega=2\cdot 9\times 10^{-6}$ radians/sec, $Q=10^{28}$ e.s.u., and therefore

$$H'_p=-27\cdot 6f.$$

For a uniform distribution $f=1/5$ and $H'_p=-5\cdot 5$ gauss, while for a distribution concentrated near the surface $f=1/3$ and $H'_p=-9\cdot 2$ gauss.

The two values of H'_p and the directions of $\mathbf{H}'_p$ at the two poles are in general agreement with the observations of Hale *et al.* made over many years.

The value of H_p for Chapman's model is in general agreement with recent observations of H. D. Babcock (1959). The directions of $\mathbf{H}_p$ also agree with his observations made since October 1958. But his observations between January 1956 and April 1957 indicate a reversal of $\mathbf{H}_p$ and so it is necessary to await the observations of the next ten years or so to confirm Hale's conclusion that the solar polar fields have constant components comparable with our estimates in magnitude and direction.

If our estimates are correct we can predict that the observed average magnitudes and directions will return to those published by Hale and Langer namely, about -4 gauss as reported (with approval) by H. W. Babcock (1953).

The alternating components of the polar fields may provisionally be attributed to secondary processes such as those responsible for the rapid local variations observed by the Babcocks and attributed by them to turbulence in a hydromagnetic medium.

By means of similar calculations we find that a rotating uniform, ellipsoidal model of the Galaxy conforming to the relation (11) with $U=\frac{2}{5}Ma^2\omega$, $M=NM_s=3\times10^{44}$ g, $a=4\times10^{22}$ cm, $\omega=10^{-15}$ radians/sec, $r_s=2{\cdot}6\times10^{22}$ cm, $\beta=1{\cdot}9\times10^{-2}$, yields, near the Solar System, a magnetic field of about 10^{-9} gauss. This is about ten times the minimum field which Alfven (1950) estimates is required to make even the extensive shower particles fairly isotropic.

6. Magnetic Stars, Novae and the Solar Corona

An immediate consequence of our fundamental hypothesis is that many rapidly rotating bright stars should possess general magnetic fields stronger than that of the Sun. This explains the existence of most of the known magnetic stars.

Also Blackett (1949) has shown that the value of the ratio P/U for the Sun and the mean value for five other stars are of the same order of magnitude within a factor of 10. H. W. Babcock had independently arrived at the same conclusion for the Sun and 78 Virginis. It follows from these results and equation (4) that the average value of β_s for the five other stars is of the order of β_s for the Sun, i.e., about $0{\cdot}02$.

For a variable star we may expect Q_s, and therefore also the stellar magnetic field to vary, too. Thus the Sun's charge may vary appreciably during a sunspot cycle. To account for periodic reversals of the field we may provisionally adopt Blackett's view that the star concerned also carries electric oscillations.

The fact that the values of β_s^2 for the Sun and five other stars are notably less than 1 suggests that one of the necessary conditions for a star to be stable is that the charge Q_s, if distributed in the same way as the mass M_s, must be less than that which would completely neutralize the gravitational forces by its electrostatic effects.

This in turn suggests that some novae may be stars for which $\beta<1$ in the deep interior and $\beta=\beta(r)$ increases monotonically with the distance r from the centre until at the surface $r=a$ we have

$$\int_0^a \rho r^2 dr \leqslant \beta(a) \int_0^a \beta(r)\rho r^2 dr, \quad \ldots . \quad (12)$$

i.e., β at the surface is equal to or greater than the reciprocal of the average value $\bar{\beta}$ throughout the star.

For when $\beta=1/\bar{\beta}$ the internal radiation pressure and centrifugal forces will be able to blow off a thin shell of the star and so release some radiation.

The bulk of the star then settles into a new state and may begin to increase its charge until the condition (12) recurs. This would explain qualitatively the behaviour of recurrent novae.

A similar, but more complicated, theory may explain the occurrence of a supernova. If such a star were initially a very hot, negatively charged and magnetic star with fast electrons trapped in its field then, the remnants would be associated with very fast electrons and appreciable magnetic fields. These would lead to visible and infra-red, polarized, synchrotron radiation and to strong radio noise. All this accounts in a simple way for the hitherto unexplained spectra of certain supernovae and in particular for the Crab Nebula and its known radiations.

The trapping of fast electrons in a star's magnetic field, described above, is apparently also occurring in the Sun's corona, for this process is adopted as a hypothesis by P. J. Kellogg and E. P. Ney (1959) in order to explain certain observed properties of the corona, such as the peculiar polarization of its light, the abnormal intensity of its infra-red radiation and its very strong radio noise.

7. A Star's Electric Field and Atmosphere. Increase and Decrease of C.R. Intensities Accompanying Strong Solar Flares

Besides the trapping of electrons and related phenomena mentioned in the last section the following other consequential phenomena may occur.

(1) Large increases of the atmospheric temperature with height above the star's surface.

(2) The acceleration and ejection from the star of fast magnetized and negatively charged clouds of ionized hydrogen which are generated along with stellar flares near local strongly magnetized regions analogous to sun-spots. The clouds may well be of the same character as the plasmoids and rings described by W. H. Bostick (1958).

An example of (1) is the high temperature of the gas in the solar corona.

Examples of (2) are the fast clouds which appear to reach the Earth's atmosphere after a strong solar flare has been observed and cause bright aurorae and magnetic storms.

These accelerated and ejected clouds could also serve to explain the solar radio phenomena associated with flares which have been observed by Wild *et al.* (1959) and interpreted by them and by McLean (1959) as indicating the early ejection of a fast stream of more than 3×10^{33} electrons with a mean velocity of about $\frac{1}{2}c$ and the later ejection of clouds of relativistic electrons at velocities of about $c/300$.

These facts suggest the following simple explanation of the transient large increase of primary cosmic ray intensities and the sudden increase of ionization below 100 km height in the dark ionosphere which occurred about 20 minutes after the start of the great flare of February 23, 1956. If we assume that such a fast stream of more than 3×10^{33} electrons and velocity about $\frac{1}{2}c$ was ejected within a solid angle of less than two octants (π steradians) then within 17 minutes more than 7×10^{25} electrons are intercepted by a sphere round the Earth of radius equal to that of the outer Van Allen belt. These would tend to become trapped in the Van Allen belt and so could lower the Earth's electric potential by more than $4 \cdot 5 \times 10^{9}$ volts. This would lead to a large transient increase in the intensity of the low-energy primary cosmic ray particles and to a large flux of low energy nuclei which can penetrate below the 100 km level of the dark ionosphere and considerably increase the ionization densities in the lower ionospheric regions in the manner discussed by D. K. Bailey (1959). The latter flux could continue for some hours during the period in which the Earth's potential is being restored to its normal value by the admission of the positively charged nuclei.

The electrical effects caused by such a fast stream would outweigh the effects due to any magnetic fields transported by it. On the other hand the electrical effects which may be caused in the Earth's atmosphere by the net electric charges on the much slower magnetic clouds could be expected to be less than the magnetic effects. This would explain the occurrence, after the lapse of two days, of a sudden commencement geomagnetic disturbance and characteristic auroral-zone effects; it would also explain the occurrence, after the lapse of about thirty hours from the start of the great flare of July 25, 1946, of a similar geomagnetic disturbance and a temporary decrease of the cosmic ray intensity.

It is important to note that the processes considered above make it unnecessary to assume that the additional primary cosmic rays which have been observed at the same time as certain solar flares are produced somewhere in the Sun.

8. The Magnetic Field near the Earth Generated by the Sun's Relative Motion of Translation. Origin of the Earth's Magnetization

In a non-rotating frame of reference accompanying the Earth in its orbital motion the Sun has a velocity of $v_s = -29 \cdot 8$ km/sec. Consequently the Sun's charge $-Q_s$ will set up in this frame a magnetic field $\mathbf{H}_r$ which is perpendicular to the Ecliptic, is directed from north to south, and has the intensity

$$H_r = v_s Q_s / c r_0^2 = 4 \cdot 6 \times 10^{-3} \text{ gauss}, \quad \dots . \ (13)$$

since

$$Q_s = 10^{28} \text{ e.s.u.}, \quad r_0 = 1 \cdot 5 \times 10^{13} \text{ cm}.$$

We thus see that $\mathbf{H}_r$ has the correct direction and the correct order of magnitude, about $0 \cdot 01$, required for it to serve as the " initially existing field " in Chatterjee's crustal theory of the Earth's state of magnetization (1956).

Moreover, the field $\mathbf{H}_r$ also neutralizes the resulting external terrestrial field in a narrow and approximately toroidal region of radius equal to about $4 \cdot 2$ earth radii which lies nearly in the Earth's magnetic equatorial plane. The magnetic field in and near this region is such that it could act as a " magnetic bottle " which is partly accessible to fast charged particles from regions much further out.

These facts indicate that the relative motion of the negatively charged Sun produces both the Earth's present state of magnetization and the outer Van Allen belt; for the latter has its maximum density at about $3 \cdot 6$ earth radii from the Earth's centre.

9. Cosmic Radio Noise

The view that strongly magnetized stars are the seat of large, net negative charges and the associated strong electrostatic fields leads to the conclusion that their high atmospheres should contain trapped electrons with relativistic energies; this in turn requires that these atmospheres should emit strong radio noise like that from the solar corona.

The noise produced by the remnants of a supernova like the Crab Nebula should therefore be exceptionally strong, as is found to be the case.

A negatively charged and rotationally magnetized galaxy may be expected to act similarly since its " halo " can be regarded as a galactic atmosphere in which electrons of relativistic energies are trapped. Consequently the halo should be a strong source of radio noise, as is actually observed. Another consequence of this argument is that the halo should emit polarized visible and infra-red radiation ; this consequence may be testable with existing observational equipment.

Similarly, two negatively charged and magnetic galaxies which approach close to one another with a high relative velocity will cause strong electromagnetic disturbances to occur in both their atmospheres and so generate strong noise on a vast scale.

10. An Alternative Fundamental Hypothesis (H_2) : Unification of the Theories of Gravitational, Electromagnetic and Quantum Fields and of Cosmology

In a note (Bailey, 1959) on the " Steady State Universe " of Bondi and Gold it was suggested that certain difficulties in Cosmology could be overcome by postulating with Kaluza, Klein and others that the space-time four-dimensional universe U_4 is a hyper-surface in a five-dimensional universe U_5, and that consequently the laws of conservation of energy, momentum and electric charge hold true exactly in U_5 rather than in U_4.

It follows from this hypothesis that there can exist streams or fluxes of electrically charged particles into (or out of) U_4 from (or into) U_5. The geometrical character of this hypothesis also requires that these fluxes be associated with the local metric of U_5 and that consequently they depend on the local physical conditions in U_4 ; for example, the fluxes inside a hot star will be very different from those outside it.

For our main purpose of discussing the effects of the net charge $-Q_s$ acquired by a star through these fluxes of particles it is not necessary to specify them in detail. We need therefore only mention the following possibilities without committing ourselves to any one of them at this stage :

(a) Unequal fluxes f_1, f_2 of electrons and protons respectively, with $f_1 > f_2$.

(b) Equal fluxes f of electrons with charges $-e$ and of protons with charges $e(1-y)$ where $y \sim 10^{-n}$ and $n \gg 1$.

(c) Unequal fluxes φ_1, φ_2 of charged neutrinos and antineutrinos carrying charges $\pm e_a$ respectively where $e_a/e \ll 1$.

The possibility (b) somewhat resembles the recently published hypothesis of Lyttleton and Bondi (1959) but differs from it by interchanging the roles of the electron and proton and including an explicit dependence of the flux f on the local physical conditions.

It should be noted that flow into or out of U_4 can be indicated by placing the signs + or — respectively before the symbols f_1, f_2, f, φ_1 and φ_2.

Since the conditions inside a hot star are favourable to thermonuclear processes it may be expected that the fluxes considered here are in some way related to these processes. This is equivalent to the expectation that the correct theory of nuclear forces can be unified with the theories of gravitational, electromagnetic and quantum fields by means of Kaluza's hypothesis of a five-dimensional universe U_5. This inference finds independent support from a publication by J. Rayski (1959) in which he gives " a six-dimensional interpretation of electrodynamics and nuclear interactions ".

One advantage of the present hypothesis is that it automatically provides the means of keeping a large charge $-Q_s$ constant against a possible large emission current of electrons from the star into space or a possible large current of nuclei from space into the star.

11. Some Requirements of the Theory

The number density of freely moving protons at the distance $r_0 = 1 \cdot 5 \times 10^{13}$ cm from the Sun may be taken to be nearly the same as the estimated number density $n = 0 \cdot 8 \times 10^{-10}$ particles/cm³ of primary C.R. particles near the Earth's orbit.

These move in all directions with velocities v near that of light and so a remote upper limit to the possible positive current i_p from space into the Sun is given by i_+ where

$$i_+ = 4\pi r_0^2 cne \text{ e.s.u.},$$

thus

$$i_p \ll 10^9 \text{ amp.}$$

The other (much more numerous) charged particles near the Earth's orbit may be assumed to be associated together in large ionized, magnetic clouds similar to plasmoids and carrying an excess of trapped electrons.

The energy carried away from the Sun per second by the escaping neutrinos is about 6 per cent of the total radiated by the Sun, i.e., about 2×10^{32} erg/sec. Also in the assumed proton-proton chain reaction the mean energy of each resulting neutrino is $\bar{W}=0\cdot25$ meV. Hence the total flux f of neutrinos out of the Sun is given by

$$f\sim5\times10^{38}\text{ neutrinos/sec.}$$

If we assume that the neutrino energies W have a Maxwellian distribution and that all those with an energy more than W_1 can escape from the charged Sun where

$$W_s\ll\bar{W}$$

then a necessary condition for the escape of most of the f neutrinos is

$$e_aV_s=eW_1.$$

Hence

$$e_a/e\ll\bar{W}/V_s$$

where V_s is the potential of the Sun's central regions. If we assume that the charge Q_s, given by (9.1), is mainly near the Sun's surface then

$$V_s=Q_s/a$$

where $a=7\times10^{10}$ cm is the Sun's radius, i.e.

$$V_s=4\times10^{19}\text{ volts.}$$

Hence,

$$\left.\begin{aligned}e_a/e&\ll6\times10^{-15},\\ e_a&\ll3\times10^{-24}\text{ e.s.u.}\end{aligned}\right\}\quad\ldots\ldots\quad(15)$$

The positive current carried by the f escaping neutrinos is i_a where

$$i_a=fe_a.$$

Hence

$$i_a\ll5\times10^5\text{ amp.}$$

The flux of electrons emitted by the Sun would then be much less than 3×10^{24} electrons/sec. This suggests that the solar magnetic fields exert a dominant control over the electron emission.

In Section 2 we found the neutron charge $-e_n$ to be equal to $-e_a$. Hence in the formula (2) we must have

$$\beta_n=e_a/G^{\frac{1}{2}}m_n$$

where $m_n=1\cdot67\times10^{-24}$ g. It then follows from (15) that

$$\beta_n\ll6900.\quad\ldots\ldots\ldots\quad(16)$$

Following a suggestion of Dr. M. J. Buckingham, possible lower limits for e_a/e and β_n can be found as follows.

We suppose that when the Sun was formed about $t_0=5\times10^9$ years ago the constant current $i_a=fe_a$ began to charge it negatively. Hence

$$\frac{dQ_s}{dt}=i_a-j$$

where j is the positive leakage current (at the time t) from space into the Sun. Therefore we have successively

$$i_at_0>Q_s,$$

$$e_a>Q_s/ft_0,$$

$$\left.\begin{aligned}e_a&>1\cdot3\times10^{-28}\text{ e.s.u.}\\ e_a/e&>2\cdot7\times10^{-19},\end{aligned}\right\}\quad\ldots\quad(17)$$

and so

$$\beta_n>0\cdot31.\quad\ldots\ldots\ldots\ldots\ldots\quad(18)$$

The limits (16) and (18) suggest the speculation that for the neutron β_n is of the order of 1, i.e., $e_a\sim4\cdot3\times10^{-28}=0\cdot9\times10^{-18}e$. It is remarkable that this charge is about one-half of the net charge which Lyttleton and Bondi (1959) have assumed to exist on a hydrogen atom in order to explain the recession of the galaxies. This fact suggests that with some elaboration our theory may also serve to explain galactic recession.

We have seen above that when the theory is based on the fundamental hypothesis H_1 of Section 2 it is necessary to conclude that nearly all the charged particles near the Earth's orbit form part of large magnetic clouds like plasmoids and that the solar electron emission is under the dominant control of the solar magnetic fields. Should these conclusions ever be *proved* wrong the hypothesis H_1 could simply be replaced by the alternative hypothesis H_2 considered in Section 10.

12. Possible Experimental Tests of the Theory

An experimental test can be applied by comparing the intensity and direction of the field $\mathbf{H}_r$, discussed in Section 8, with those of the magnetic fields determined by means of magnetometers carried on artificial satellites at distances between 1 and 20 earth radii from the Earth's centre.

A second experimental test is suggested by the following facts and calculations concerning a large fission reactor like the British "Pippa 2" which is at present under construction. The power generated is $4\cdot5\times10^8$ watts and, as a result, a total flux of about 10^{20} antineutrinos per second is generated. The current leaving the reactor is $-i$ where

$$i=10^{20}e_a,$$

and so, by (15) and (17),

$$4\cdot5\times10^{-18}<i\ll10^{-13}\text{ amp.}$$

This reactor approximates in size to a sphere of radius 10 metres, so if it were well insulated and the neutrons absorbed its potential would rise by v volts in 10 seconds where

$$4\times10^{-8}<v\leqslant10^{-3}\text{ volts.} \quad \ldots . \ (19)$$

If initially insulated at the same potential as the ground it would ultimately rise to a steady potential v_0 such that the natural conductivity of the surrounding gas would give rise to a current in the gas equal and opposite to $-i$.

Since the gas conductivity would depend partly on the presence of radioactive contaminants, it is not possible to estimate here the value of v_0. However, the limits to v indicated under (19) suggest that v may be measurable.

A third experimental test is suggested by the reference in Section 7 to plasmoids. For this implies that plasmoids carry an excess of negative charge and this possibility can be tested by firing them into or through a Faraday cage.

13. Summary

The fundamental hypothesis H_1 is proposed that the thermonuclear processes inside a star generate certain particles, here named " astrons ", which carry positive charges e_a very much smaller than the electronic charge e and which penetrate matter as freely as neutrinos. From this and two supplementary hypotheses it follows that a neutron carries the charge $-e_a$, a neutrino the charge e_a and an antineutrino the charge $-e_a$.

The flux f per second of astrons passes out of the star and as a result the star acquires a negative charge $-Q_s$. For convenience we introduce the pure number

$$\beta_s=Q_s/G^{\frac{1}{2}}M_s,$$

where M_s is the mass of the star.

From the fact that the most energetic known cosmic ray particle has an energy of 5×10^{18} electron volts the value of β_s for an average star like the Sun is found to be about $0{\cdot}02$. This leads to the conclusion that the Sun carries a charge of -10^{28} e.s.u. At the same time two different sources of cosmic rays are indicated, namely, the charged Sun and the charged Galaxy giving energy to protons and other nuclei.

From the charge -10^{28} and the angular velocity of the Sun it is deduced that the Sun has polar magnetic fields $\pm H_p$ where H_p has approximately the order of magnitude of the polar fields observed by Hale and the Babcocks and has the direction found by Hale and, more recently, by H. D. Babcock.

From the conclusions of Blackett and H. W. Babcock, that the ratio of the magnetic moment to the angular momentum of a star is roughly the same for the Sun and five other stars, it is deduced that the average value of β_s for the five stars is roughly the same as that of β_s for the Sun.

The fact that β_s^2 for the six stars is notably less than 1 suggests that a necessary condition for a star to be stable is that if Q_s were distributed in the same way as M_s the electric force of repulsion on the matter at a point would be less than the corresponding gravitational force of attraction.

This in turn suggests an origin for certain novae. A similar theory explains the occurrence and certain properties of supernovae including some of their unexplained spectra, polarized light and strong radio noise.

The associated trapping of energetic electrons in a star's magnetic field is in line with the theory of the solar corona recently published by Kellogg and Ney.

Other phenomena which may occur in a charged star's atmosphere are large increases of the atmospheric temperature with height and the ejection of fast, magnetized and negatively changed clouds of ionized hydrogen of the same character as plasmoids and generated by stellar flares near local strongly magnetized regions. Examples are respectively the very hot solar corona and the fast clouds which reach the Earth's atmosphere after a strong solar flare has been observed.

A detailed explanation is thus found for the principal phenomena which are observed to follow an exceptionally strong flare such as those of February 23, 1956 and July 25, 1946. This explanation makes it unnecessary to assume that at such times C.R. particles are produced in the Sun.

The magnetic field $\mathbf{H}_r$ generated near the Earth by the charged Sun's relative motion of translation is perpendicular to the Ecliptic, directed from north to south and has the intensity $4{\cdot}6\times10^{-3}$ gauss.

This field provides the correct initial field required to magnetize the Earth as it is now. It also neutralizes part of the external terrestrial field in such a way as to produce a " magnetic bottle " near the middle of the outer Van Allen belt, which bottle is partly accessible to energetic charged particles from further out.

The theory explains qualitatively, but very simply, the origin of strong cosmic radio noise in stellar atmospheres, in the Crab Nebula, in the Galactic "halo" and in colliding charged and magnetic galaxies.

An alternative fundamental hypothesis for the source of the net electric charges on stars is that the space-time universe U_4 is a hypersurface in a five-dimensional universe U_5 in which alone the laws of conservation of energy, momentum and charge strictly hold true; for it then follows that there can exist streams of electrically charged particles into (or out of) a star from (or into) U_5. Since it is likely that the star's internal thermonuclear processes are related to these streams it appears possible that a correct theory of nuclear forces can be unified with the theories of gravitational electromagnetic and quantum fields by means of the same fundamental hypothesis. The same hypothesis explains how it is possible to maintain a large charge $-Q_s$ on a star against any large currents of electrons into space or of nuclei from space into the star.

It is not possible at the present time to choose safely between this five-dimensional hypothesis and the earlier four-dimensional hypothesis. If the latter is chosen then certain requirements have to be met, namely:

(1) nearly all the charged particles near the Earth's orbit form part of large magnetic clouds like plasmoids;

(2) the Sun's electron emission is largely controlled by the solar magnetic fields;

(3) the charge e_a on an astron, neutron or neutrino is, in absolute value, much less than 3×10^{-24} e.s.u. and probably greater than $1 \cdot 3 \times 10^{-28}$ e.s.u. Also the speculation is suggested that this charge is of the order of $G^{\frac{1}{2}}m_n$ where m_n is the mass of a neutron, i.e., $e_a \sim 4 \cdot 3 \times 10^{-28}$ e.s.u. This is about half the excess charge on a hydrogen atom which is postulated by Lyttleton and Bondi in their theory of galactic recession, and this fact suggests that our present theory may be capable of explaining also galactic recession.

It is also pointed out that the present theory may be tested by means of (1) observations of magnetic fields taken with satellite-borne magnetometers, (2) observations of the electric potentials acquired by a large fission reactor which is well insulated and which has its neutrons absorbed, and (3) by observing the excess charges on plasmoids.

14. Conclusion

It is now clear that by means of the single hypothesis that a star like the Sun carries a net negative charge $-Q_s$ it has been found possible to account for the known orders of magnitude of five different astronomical phenomena and the directions relating to three of them and that the same hypothesis explains in simple qualitative or semi-quantitative ways at least thirteen other phenomena.

The first five phenomena are as follows:

(1) The maximum energy of about 5×10^{18} eV found for a primary cosmic ray particle.

(2) The Sun's polar magnetic field vectors $\pm\mathbf{H}_p$.

(3) The approximate equality of the ratios P/U for the Sun and for Blackett's group of five magnetic stars.

(4) The present state of magnetization of the Earth.

(5) The existence and position of the outer Van Allen belt.

In order to provide a source for the stellar charge $-Q_s$ we have considered alternative hypotheses H_1 and H_2. The first hypothesis may be associated with thermonuclear processes by means of supplementary hypotheses h_1 and h_2 and then leads to the interesting conclusion (among others) that a neutron carries a small *negative* charge $-e_a$ where e_a is of the order of 10^{-18} times the electronic charge e. This conclusion is consistent with the fact that the neutron's magnetic moment is like that of a spinning negative charge.

All these results of the present theory taken together constitute either a truly remarkable coincidence or strong evidence for our hypothesis that a star like the Sun carries a large negative charge $-Q_s$.

In either situation it seems highly desirable to subject this theory to the test of experiment and other observations such (for example) as those suggested above.

I wish to acknowledge the benefits which this work has received from the advice and criticisms of the following colleagues and friends: Professors S. T. Butler, H. Messel and C. N. Watson-Munro, Drs. M. J. Buckingham, R. G. Giovanelli, R. E. B. Makinson, H. D. Rathgeber and J. L. Pawsey and Mr. J. P. Wild.

Addendum, July 11, 1960

Since this paper was submitted for publication the planetoid Pioneer V (PV) has been launched into an orbit which initially lies close to that of the Earth and at perihelion approaches that of Venus. Some of its magnetometer's findings between March 11 and April 30 have now been published (Coleman *et al.*, 1960). These indicate the apparent existence in interplanetary space near the orbit of "a quiet time field perpendicular to the ecliptic" and of intensity about 2·5 gammas (10^{-5} gauss).

The perpendicular direction found confirms one of the predictions of our theory namely, the direction of the magnetic field $\mathbf{H}_r$ discussed in Section 8 above.

The observed intensity 2·5 gammas is about 180 times less than the value of $\mathbf{H}_r$ given under Equation (13); consequently the evidence on which this value was based has been re-examined with the result that the solar charge $-Q_s$ has now been located near the surface of the Sun and the C.R. nucleus of energy 5×10^{18} eV. has now been identified with one of atomic number about 90.

These modifications yield the new estimate $Q_s=3\times10^{27}$ e.s.u. and the resulting new value $H_p=-2\cdot8$ gauss for the Sun's north polar field; this value of H_p is close to the values observed by Hale and Langer and by H. D. Babcock (v. Section 5).

This estimate of Q_s yields the new estimate $H_r=140$ gammas. The fact that the observed quiet-time field is about 55 times smaller than H_r may be interpreted provisionally as evidence that PV is surrounded by a plasmoid of ionized hydrogen which largely screens its magnetometer from the field $\mathbf{H}_r$.

As soon as the *sense* of the quiet-time field observed by PV has been determined an important test of our main hypothesis will have been made. For if the Sun's charge is negative this field should be directed from the north to the south of the ecliptic.

Another possible test, suggested elsewhere (Bailey, in press), is that as PV moves along its orbit H_r will vary as $1/r^3$, where r is PV's distance from the Sun.

By means of measurements made with magnetometers moving near the Earth's orbit with different velocities $\mathbf{v}$ and the use of the corresponding Lorentz transformations it may be possible to determine the electric and magnetic vectors (and other physical quantities), near this orbit, which exist in an inertial frame attached to the Sun.

A number of such experiments with satellite-borne instruments would provide more convincing evidence for or against our hypothesis than any theoretical calculations, such as those about primary cosmic rays or about the Sun's electron emission, which depend on uncertain assumptions about the particles in interplanetary space or about the exact location of Q_s in the Sun's atmosphere.

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Annual Reports by the President and the Council

Presented at the Annual Meeting of the Society, April 6, 1960

The President's Report

It is customary and indeed I consider a duty for the retiring President to review for the members the past year's activities and to bring before them matters affecting the welfare of the Society and his suggestions for its future. The previous half dozen Presidential Addresses could with benefit be made compulsory reading for all incoming Presidents, for it is one of the weaknesses of the otherwise sound system of appointing a new President each year that twelve months is often not long enough for a President to see implemented the changes for the good of the Society he can envisage.

During the last few years the Society has undergone a major readjustment of its place in the scientific community. It has changed from a body one of whose major functions was the presentation of specialist papers to fellow specialists to one which devotes its meetings in the main to informing scientists of the developments in other fields than their own—and rightly so. The former function is adequately fulfilled in almost all the scientific disciplines by specialist societies, while there is no other society better able to fulfil the latter function.

I believe this readjustment is now virtually complete and is being reflected in a better support for our General Meetings. It should also be reflected in our membership if it is put clearly before both our senior and junior scientists that the Society is performing this function and merits and needs their support. A special drive to bring this before the many scientists who have not yet recognized membership of the Society to be a *duty* has just been instituted. That such a drive is overdue is clear when one compares our almost static membership over the past 40 years with the very great increase in the number of scientists in New South Wales over that time.

We have just seen that the present functions of the Society are very different from what they were, say, 50 years ago, and yet in one regard I consider the Society is failing to accept just such responsibilities as it carried 50 years ago. I refer to the fact that this is the Royal Society of *New South Wales*, not of Sydney, and that there are now several centres in N.S.W. remote from Sydney with scientific communities of about the same size as that of Sydney 50 years ago. The ideal Society for such a community would seem to be an all-purpose one such as a Section of our Society could provide. During the year the way has been cleared for this action by a suitable amendment to our Rules and I am hopeful that Regional Sections of the Society will soon be formed in both Armidale and Newcastle and perhaps later in Wollongong and Broken Hill.

Most of you will realize that the Society has been passing through difficult financial times. I think we can be reasonably confident that, thanks to the efforts of your officers during the last several years and the somewhat unpalatable sacrifices made, the Society will be able to balance its budget for the next few years. Without the augmented Government grant, of which we are very appreciative, this would not be so. One of the sacrifices reluctantly made was the vacation of the ground floor Reception Room. This room is still used by the Society in the same way as heretofore, but is only rented to the extent that we use it. In this way we are saved a heavy rental and receive our proportion of the income from lettings of the room. The retention of the room as a Reception Room has been assured and honour has been done to a great Past-President of the Society by naming it the Sir Edgeworth David Room.

Many more papers were submitted for publication in the Journal this year than last; whether this is a statistical fluctuation or represents an increase in the popularity of the Journal remains to be seen. During this year a number of changes designed to improve the format of the Journal were adopted. Sincere thanks are due to Dr. A. Day for his enthusiastic and conscientious work as Honorary Editorial Secretary and to the Donovan Trust for generous assistance with the publication of one paper.

I wish to extend the thanks of the Society to all those who have assisted its affairs during the year, particularly our lecturers, members of the sub-committees of Council, our Assistant Librarian Mrs. Huntley and our Assistant Secretary Miss Ogle. I would further like to tender my sincere personal thanks to Mr. Harley Wood for his unstinting work as Honorary Administration Secretary, to Vice-President J. Griffith who acted for him during Mr. Wood's absence overseas, to all the members of the Executive and Council for their support during the year, and to Miss Ogle for her ready assistance.

Report of the Council for the Year Ended 31st March, 1960

At the end of the period under review the composition of *the membership* was 316 ordinary members, 5 associate members, 8 honorary members; 20 new members were elected and 10 members resigned. Three names were removed from the list of members under Rule XVIII. It is with regret that we announce the loss by death of Mr. Frederick Lester Henriques and Dr. Roger Thorne.

Alterations to the Rules: At the General Monthly Meetings held on 1st July and 4th November, motions regarding alterations to the Rules were adopted. These motions were conformed at the meetings held 5th August and 2nd December. A full text of each of the alterations was contained in the Abstract of Proceedings of the meetings held 5th August and 2nd December.

Nine monthly *meetings* were held. The Proceedings of the 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 12 speakers who contributed to the addresses, symposia and commemoration, and also to the members who read papers at the November monthly meeting.

The meeting on 3rd June was held conjointly with the Linnean Society of New South Wales and was devoted to the Commemoration of the Centenary of the publication of " The Origin of Species ".

Two meetings were devoted to the screening of films :

7th October : " Desert Conquest ", by courtesy of A.M.P. Society Ltd. and Twentieth Century Fox Film Corporation.

2nd December : " Address Antarctica " and " Antarctic Crossing ", by courtesy of B.P. Australia, Ltd.

The *Annual Social Function* was held on 24th March and was attended by 47 members and guests.

The *Clarke Medal* for 1960 was awarded to Dr. A. B. Edwards, of the C.S.I.R.O., Division of Mineragraphic Investigations, for distinguished contributions in the field of geology.

The *Society's Medal* for service to science and to the Royal Society of New South Wales was awarded to Dr. Ida A. Browne.

The *James Cook Medal* for 1959 was awarded to Dr. Albert Schweitzer, of Lambaréné Republic, French Equatorial Africa, for outstanding contributions to science and human welfare.

The *Walter Burfitt Prize* for 1959 was awarded to Professor F. J. Fenner, M.B.E., M.D., F.R.S., F.A.A., of the John Curtin School of Medical Research at the Australian National University, for his outstanding contributions in the field of microbiology.

The *Edgeworth David Medal* was not awarded.

The *Archibald D. Olle Prize* was awarded to Professor G. Bosson for his paper entitled " Flexure of a Slab on an Elastic Foundation " published in volume 92 of the Society's " Journal and Proceedings ".

The *Clarke Memorial Lecture* for 1959, entitled " The Graptolite Faunas of Australia ", was delivered by Dr. D. E. Thomas, Chief Government Geologist of Victoria (see *Journal and Proceedings*, 94, pp. 1–58).

The *Pollock Memorial Lecture*, sponsored by the University of Sydney and the Society, was delivered by Professor Sir Harold Jeffreys, F.R.S., the title being " The Structure of the Earth " (see *Journal and Proceedings*, 93, pp. 137–139).

The Society has again received a *grant* from the Government of New South Wales, the amount being £750. The Government's interest in the work of the Society is much appreciated.

The Society's *financial statement* shows a deficit of £111 5s. 7d. As an economy measure the Reception Room was returned to the Management of Science House.

During the year four parts of the Journal were published.

The *Section of Geology* held five meetings during the year.

Council held eleven ordinary meetings. The attendance of members of Council was as follows : Mr. A. F. A. Harper 11, Mr. H. A. J. Donegan 4 (absent-on-leave for 5 meetings), Mr. J. L. Griffith 8, Mr. F. N. Hanlon 3, Mr. F. D. McCarthy 9, Mr. H. W. Wood 9, Dr. A. A. Day 8, Mr. C. L. Adamson 10, Dr. B. A. Bolt 5 (absent-on-leave for 3 meetings), Dr. F. W. Booker 0 (absent-on-leave for 3 meetings), Dr. C. M. Harris 0, Mr. C. T. McElroy 3, Mr. H. H. G. McKern 10, Mr. W. H. G. Poggendorff 7, Mrs. K. M. Sherrard 10, Mr. G. H. Slade 6, Mr. N. W. West 9, Mr. H. F. Whitworth 6.

The Society's representatives on *Science House Management Committee* were Mr. A. F. A. Harper and Mr. C. L. Adamson.

The President attended the Commemoration of the Landing of Captain Cook at Kurnell.

The President attended the meetings of the Board of Visitors of the Sydney Observatory and the meeting of the Donovan Astronomical Trust.

Soil Science Committee—At the request of the Australian Academy of Science the following Committee was appointed to discuss aspects of Soil Science in Australia : Prof. R. L. Crocker (Chairman), Mr. P. H. Walker (Hon. Secretary), Dr. W. R. Browne, Dr. J. A. Dulhunty, Mr. C. A. Hawkins, Dr. Alan Keast, Dr. T. Langford-Smith, Mr. F. D. McCarthy and Mr. S. Pels. Regular meetings have been held.

The Library—Periodicals were received by exchange from 384 societies and institutions. In addition, the amount of £106 was expended on the purchase of 12 periodicals.

Among the institutions which made use of the Library through the inter-library loan scheme were :

N.S.W. Govt. Depts.—Department of Agriculture, Department of Health, Department of Railways, Electricity Commission, Forestry Commission, M.W.S. & D. Board, Water Conservation and Irrigation Commission.

Commonwealth Govt. Depts.—C.S.I.R.O. (Division of Chemical Research, Melbourne ; Coal Research Section, Sydney ; Division of Fisheries and Oceanography, Cronulla ; National Standards Laboratory, Sydney ; Sheep Biology Laboratory, Parramatta ; Plant and Soils Laboratory, Brisbane ; Division of Food Preservation, Homebush) ; Australian Atomic Energy Commission ; Bureau of Mineral Resources, Canberra ; Commonwealth Department of Works ; Defence Standards Laboratory ; Snowy Mountains Hydro-Electric Authority.

Universities and Colleges—Sydney Technical College ; Wollongong Technical College ; University of Sydney ; University of New England ; University of New South Wales ; University College, Newcastle ; University of Queensland ; Australian National University, Canberra.

Companies—Amalgamated Wireless, Australian Cream of Tartar, Ltd. ; Australian Gaslight Co. ; Australian Paper Manufacturers ; Lewis Berger ; B.H.P. Co. Ltd. ; C.S.R. Co. Ltd. ; James Hardie Ltd. ; Johnson and Johnson ; Overseas Telecommunications ; Parke, Davis Ltd. ; Reichhold Chemicals, Inc. ; Standard Telephones and Cables.

Research Institutes—Bread Research Institute, Sydney ; Institute of Dental Research, Sydney ; N.S.W. Cancer Council.

Museums and Public Libraries—Botanic Museum, Brisbane ; National Museum of Victoria ; Public Library of South Australia.

HARLEY WOOD,
Hon. Secretary.

Financial Statement

BALANCE SHEET AS AT 29th FEBRUARY, 1960

LIABILITIES

1959 £		£	s.	d.	£	s.	d.
—	Accrued Expenses				200	0	0
15	Subscriptions Paid in Advance				36	4	6
186	Life Members' Subscriptions — Amount carried forward				176	11	0
	Trust and Monograph Capital Funds (detailed below)—						
	Clarke Memorial	1,842	0	2			
	Walter Burfitt Prize	1,167	8	9			
	Liversidge Bequest	706	8	3			
	Monograph Capital Fund	4,302	1	0			
	Ollé Bequest	144	16	1			
7,998					8,162	14	3
23,547	Accumulated Funds				23,423	10	6
	Contingent Liability (in connection with Perpetual Lease).						
£31,746					£31,999	0	3

ASSETS

1959 £		£	s.	d.	£	s.	d.
853	Cash at Bank and in Hand				1,224	2	4
	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			
8,460					8,460	0	0
	Debtors for Subscriptions	87	3	0			
	Less Reserve for Bad Debts	87	3	0			
—					—		
14,835	Science House—One-third Capital Cost				14,835	4	4
6,800	Library—At Valuation				6,800	0	0
780	Furniture and Office Equipment—At Cost, *less* Depreciation				662	7	7
17	Pictures—At Cost, *less* Depreciation				16	6	0
1	Lantern—At Cost, *less* Depreciation				1	0	0
£31,746					£31,999	0	3

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 29th February, 1960	1,800	0	0	1,000	0	0	700	0	0	3,000	0	0	—		
Revenue—															
Balance at 28th February, 1959	57	16	3	141	10	3	*19*	*8*	*11*	1,185	3	4	132	13	1
Income for twelve months	67	6	0	36	3	10	25	17	2	116	17	8	42	3	0
	125	2	3	177	14	1	6	8	3	1,302	1	0	174	16	1
Less Expenditure ..	83	2	1	10	5	4	—			—			30	0	0
Balance at 29th February, 1960	£42	0	2	£167	8	9	£6	8	3	£1,302	1	0	£144	16	1

ACCUMULATED FUNDS

	£	s.	d.	£	s.	d.
Balance at 28th February, 1959				23,547	8	1
Add Decrease in Reserve for Bad Debts ..				17	17	0
				23,565	5	1
Less—						
Bad Debts written off	30	9	0			
Deficit for twelve months	111	5	7			
				141	14	7
Balance at 29th February, 1960				£23,423	10	6

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 29th February, 1960, 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,
Registered under the Public Accountants
Registration Act 1945, as amended.

Prudential Building,
39 Martin Place, Sydney
18th March, 1960

(Sgd.) C. L. ADAMSON,
Honorary Treasurer.

INCOME AND EXPENDITURE ACCOUNT

1st March, 1959, to 29th February, 1960

1959 £			£	s.	d.
—	Advertising		1	12	3
—	Annual Social Function		6	6	6
31	Audit		31	10	0
117	Cleaning		104	0	0
42	Depreciation		35	14	0
50	Electricity		49	11	1
6	Entertainment		1	4	0
40	Insurance		40	14	8
151	Library Purchases		108	2	6
116	Miscellaneous		360	17	4
125	Postages and Telegrams		137	8	9
	Printing Journal—				
	Vol. 92, Parts 3–4	£878 1 6			
	Vol. 93, Parts 1–2	604 9 6			
	Vols. 91, 92—Binding	48 7 6			
929			1,530	18	6
102	Printing—General		93	3	10
140	Rent—Science House Management		26	9	10
4	Repairs		5	12	6
1,164	Salaries		1,217	9	6
29	Telephone		47	1	5
104	Surplus for twelve months		—		
£3,150			£3,797	16	8

1959 £			£	s.	d.
813	Membership Subscriptions		808	10	0
9	Proportion of Life Members' Subscriptions		9	9	0
222	Subscriptions to Journal		220	7	9
750	Government Subsidy		750	0	0
951	Science House Management—Share of Surplus		1,164	10	6
35	Rentals Received—Reception Room		—		
4	Annual Social Function		—		
100	Bequest		—		
74	Interest on General Investments		80	11	8
	Reprints—				
	Expenditure	£245 18 6			
	Receipts	283 5 4			
72			37	6	10
83	Sale of Back Numbers of the Journal		439	19	0
37	Sale of Periodicals *ex* the Library		145	16	4
—	Publication Grant		30	0	0
—	Deficit for twelve months		111	5	7
£3,150			£3,797	16	8

Obituary, 1959-1960

Frederick L. Henriques died on 18th November, 1959. He was elected to membership in 1919.

Dr. Roger Chapman Thorne, who became a member in 1958, died on 20th May, 1959, as a result of severe injuries received when he was struck by a car in Cooma, N.S.W. He was born on 30th April, 1929, a son of the late Harold Henry Thorne who himself was for long a member of the Society. Roger Thorne had an outstanding career at both Sydney Grammar School and the University of Sydney. He graduated B.Sc. in 1949 with First Class Honours in Mathematics, the University Medal in Mathematics and a Barker Travelling Scholarship. In 1950 he entered his father's old college, Trinity College, Cambridge, and in 1952 won a Distinction mark in Part III of the Mathematical Tripos. From 1952 to 1955 he was engaged on post-graduate work in Cambridge on the mathematics of water waves, and in 1955 received the Ph.D. degree for his thesis on this work. By invitation, he spent a post-doctoral year in the California Institute of Technology during 1955–56. Subsequently he was appointed Lecturer in Mathematics at Newcastle University College and, in 1957, to the equivalent post at the University of Sydney. He produced published work of high quality, initially on the theory of surface waves and later on asymptotic expansions.

Dr. Thorne had many outside interests. While at school he acquired, on his own initiative, an astonishing knowledge of Egyptology. An active member of the Church of England, he was at the time of his death a member of the Church Synod, the Council of St. Catherine's School, Waverley, and the management committee of the Church's Halls of Residence for university students. He was pleasant and companionable, as well as of unusual brilliance, and his death was a great loss to his family and all those who knew him.

Members of the Society, April 1960

A list of members of the Society up to 1st April, 1959, is included in volume 93.

During the year ended 31st March, 1960, the following were elected to membership of the Society.

BUNCH, Kenneth, Government Analyst, 1/17 Pacific Street, Manly.

BURROWS, Keith Meredith, B.Sc., Physics Department, University of N.S.W.

FYNN, Anthony Gerard, B.Sc., Director, Riverview College Observatory, Riverview, N.S.W.

GRAHAME, Mervyn Ernest, B.A., Schoolteacher, 161 Parry Street, Hamilton, N.S.W.

HOSKINS, Bernard Foster, B.Sc., 227 Waterloo Road, Greenacre.

HUMPHRIES, John William, B.Sc., Physicist, National Standards Laboratory, University Grounds, City Road, Chippendale.

JONES, James Rhys, 25 Boundary Road, Mortdale.

KRYSKO v. TRYST, Moiren, C.S.I.R.O. Division of Radiophysics, National Standards Laboratory, University Grounds, City Road, Chippendale.

LAWRENCE, Peter, Ph.D., Senior Lecturer in Anthropology, Australian School of Pacific Administration, Mosman.

LOWENTHAL, Gerhard, M.Sc., 43 Hinkler Street, Maroubra.

MEGGITT, Mervyn John, M.A., Lecturer, Department of Anthropology, University of Sydney.

MILLER, James, B.Sc., 35 Angus Avenue, Waratah West, N.S.W.

MUTTON, Ann Ruth, 8 Beta Road, Lane Cove.

PICKERING, William Frederick Joseph, M.Sc., Lecturer in Chemistry, Newcastle University College, Newcastle.

RAMM, Eric John, Experimental Officer, Australian Atomic Energy Commission, Research Establishment, Lucas Heights, N.S.W.

RYAN, D'Arcy James, B.A., B.Litt., Anthropologist, 3 Ormond Street, Bondi.

SHERWOOD, Arthur Alfred, B.Sc., Lecturer, University of Sydney.

SOMERVILLE, Jack Murielle, D.Sc., Department of Physics, University of New England, Armidale, N.S.W.

STEPHENS, James Norrington, M.A., 40 Pymble Avenue, Pymble.

WILSON, Peter Robert, M.Sc., Lecturer in Applied Mathematics, University of Sydney.

During the same period resignations were received from the following:

Baker, William Ernest
Baldick, Kenric James
Chapman, Dougan Wellesley
Darvall, Anthony Roger
Denton, Norma F.
McPhee, Stuart Duncan
McPherson, John Charters
Nordon, Peter
Phillips, June Rosa Pitt
Tugby, Elise Evelyn

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

Finch, Franklin Charles
May Albert
Ray, Reginald John.

Obituary, 1959-60

Frederick Lester HENRIQUES (1919)
Roger Chapman THORNE (1958)

Medals, Memorial Lectureships and Prizes

James Cook Medal

1959 Albert Schweitzer, D.Theol., Dr.Phil., Dr.Med.

Walter Burfitt Prize

1959 Frank J. Fenner, M.B.E., M.D., F.R.S., F.A.A. (Microbiology)

Clarke Medal

1960 Austin B. Edwards, D.Sc., Ph.D., D.I.C. (Geology)

The Society's Medal

1959 Ida A. Browne, D.Sc. (Geology)

Clarke Memorial Lectureship

1959 D. E. Thomas

Pollock Memorial Lectureship

1959 Sir Harold Jeffreys

Archibald D. Olle Prize

1959 G. Bosson

The Clarke Medal, 1960

Dr. Edwards has already been honoured by the Royal Society of N.S.W. by being asked to deliver the Clarke Memorial Lecture in 1951. He is well known for his prolific writings on various geological subjects, being a recognized authority on ore minerals and at present is Officer-in-Charge, C.S.I.R.O. Mineragraphic Investigations Section. It seems fitting that details of his academic and professional career should be placed on record.

Born in 1909, the youngest son of William Burton Edwards, I.S.O., he was educated at Caulfield Grammar School where, as both Captain and Dux, he completed his secondary education in 1926.

In 1930 he graduated from Melbourne University as B.Sc. with honours in Chemistry, Metallurgy and Geology, and for the next two years he was awarded an 1851 Overseas Exhibition and then pursued postgraduate research at Imperial College of Science and Technology, University of London, from 1932 to 1934. The result of this research was the award of Ph.D. (London), D.I.C.

In 1935 Dr. Edwards joined the C.S.I.R. as an Assistant Research Officer in Mineragraphic Investigations under Dr. F. L. Stillwell, whom he replaced as Officer-in-Charge in 1953. During this period (1935–53) he was awarded the David Syme Prize and Medal (1937) and D.Sc. (Melb.) (1942) for a thesis on Differentiation of the Dolerites of Tasmania and a number of supporting papers. From 1941 to 1953 he was part-time Lecturer in Mining Geology in the University of Melbourne.

Since 1955 he has been Geological Advisor at the State Electricity Commission of Victoria and during the period of 1958–61 is acting as Observer on the Commission of the International Union of Pure and Applied Chemistry.

Various professional and learned societies have benefited by his activities on their behalf. Since 1953 he has been Councillor of the Australasian Institute of Mining and Metallurgy and since 1955 has been editor of the Institute's Proceedings. In the Geological Society of Australia Dr. Edwards has served as President of the Victorian Division and Councillor representing Victoria and Western Australia. His interest in overseas societies is shown by his following positions: Fellow of the Mineralogical Society of America, Corresponding Fellow of the Edinburgh Geological Society, and Foreign Member of the Mineralogical Society of India.

Dr. Edwards has made many contributions to geological literature. His book entitled " Textures of Ore Minerals and their Significance " was first published by the Aust. Inst. of Min. and Met. in 1947, and a second edition was issued in 1954. Large numbers of his papers have appeared in Australian and overseas journals. These have been principally on mineralogy and allied subjects, but other papers illustrate much wider geological interests.

The Society's Medal, 1959

The award of the Society's medal to Ida Alison Brown (Mrs. W. R. Browne) is the first occasion on which a woman has been so honoured.

Ida Brown was awarded a Linnean Macleay Fellowship by the Linnean Society of N.S.W. after her graduation from the University of Sydney with the degree of Bachelor of Science with Honours in Mathematics and Geology and the University Medal in Geology. During her tenure of the fellowship, she published in the Proceedings of the Linnean Society a large number of papers on the geology of the South Coast of N.S.W., carrying out field work often under most arduous conditions. Her thesis on this work gained her the degree of D.Sc., the second time this degree was awarded to a woman by Sydney University.

She held the position of Lecturer and later Senior Lecturer in Palaeontology at the University of Sydney from 1934 to 1950 and during periods of study leave visited England, U.S.A. and Canada. In 1945, after a period as a Council member of the Linnean Society, she became the first woman to be its President.

In 1935 she was elected a member of the Royal Society of N.S.W., being its first woman member. She has contributed 12 papers to the Journal. In 1941 she was elected to the Council, again the first woman. She became Honorary Editorial Secretary in 1950. This was a time when the rising costs of publication of the journal by a Society with a fixed income called for the most devoted attention from its Editor. She served also as Vice-President, and the Society's appreciation of her services was shown by her election in 1953 as the first woman President.

She has been an official delegate from Australia to Pan-Pacific Congresses in Java (1929) and Canada (1933). She was a Fellow of the former Australian National Research Council.

Archibald D. Olle Prize, 1959

The Archibald D. Olle Prize is awarded to Professor G. Bosson for his paper entitled " Flexure of a Slab on an Elastic Foundation ", published in volume 92 of the Society's Journal and Proceedings.

Professor Bosson's paper deals with the bending of a loaded stratum resting on an elastic foundation. The problem is considered as a case of plane strain. The methods used are modern, involving considerable use of transform methods. The results are expressed in terms of rapidly convergent series.

However, the feature of the paper, which is most worthy of note, is the formulation of a new hypothesis for dealing with interface forces. Professor Bosson develops a hypothesis using a convolution formula which seems far more realistic than the classical Westergaard hypothesis.

Abstract of Proceedings, 1959

1st April, 1959

The ninety-second Annual and seven hundred and forty-sixth 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. Thirty-two members and visitors were present.

The death was announced of Charles A. Loney, a member since 1906.

Ann Ruth Mutton was elected a member of the Society.

The following awards of the Society were announced :

The Society's Medal for 1958 : Mr. F. R. Morrison.
The Edgeworth David Medal for 1958 : Dr. Paul I. Korner.
The Clarke Medal for 1959 : Mr. Tom Iredale.
The Archibald D. Olle Prize : Mr. Alex Reichel.

The Annual Report of the Council and the Financial Statement were presented and adopted.

Messrs. Horley and Horley were re-elected as Auditors to the Society for 1959–60.

The following papers were read by title only: " Distribution of Stress in the Neighbourhood of a Wedge Indenter ', by A. Reichel ; " Occultations Observed at Sydney Observatory during 1958 ", by K. P. Sims.

Office-bearers for 1950–60 were elected as follows :

President : A. F. A. Harper, M.Sc.
Vice-Presidents : H. A. J. Donegan, M.Sc. ; J. L. Griffith, B.A., M.Sc. ; F. N. Hanlon, B.Sc. ; F. D. McCarthy, Dip.Anthr.
Hon. Secretaries : A. A. Day, B.Sc. (Syd.), Ph.D. (Cantab.) ; Harley Wood, M.Sc.
Hon. Treasurer : C. L. Adamson, B.Sc.
Members of Council : B. A. Bolt, M.Sc. ; F. W. Booker, D.Sc., Ph.D. ; C. M. Harris, Ph.D., B.Sc. ; C. T. McElroy, B.Sc. ; H. H. G. McKern ; W. H. G. Poggendorff, B.Sc.Agr. ; Kathleen M. Sherrard, M.Sc. (Melb.) ; G. H. Slade, B.Sc. ; N. W. West, B.Sc. ; H. F. Whitworth, M.Sc.

The retiring President, Mr. J. L. Griffith, delivered his Presidential Address, entitled " Some Aspects of Integral Transforms ".

At the conclusion of the meeting the retiring President welcomed Mr. A. F. A. Harper to the Presidential Chair.

6th May, 1959

The seven hundred and forty-seventh General Monthly Meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. A. F. A. Harper, was in the chair. Forty members and visitors were present.

The Chairman announced that the Honorary Secretary, Mr. Harley Wood, was absent on leave, attending an Astrometric Conference at Cincinnati, to which he had been invited by the National Science Foundation of the U.S.A.

Kenneth Bunch, James Miller and William F. J. Pickering were elected members of the Society.

The Chairman announced that Professor V. A. Bailey and Mr. E. J. Kenny had now been elected to Life Membership.

The following papers were read by title only: " Palaeozoic Stratigraphy of the Area to the West of Borenore, N.S.W.", by D. B. Walker (communicated by G. H. Packham) ; " Minor Planets Observed at Sydney Observatory during 1958 ", by W. H. Robertson ; " Ronchi Test Charts for Parabolic Mirrors ", by A. A. Sherwood (communicated by Harley Wood).

The evening was devoted to a discussion on the Report of the Committee appointed to survey Secondary Education in New South Wales and the following speakers led the discussion : Mr. P. G. Price, Deputy Director-General of Education ; Professor J. L. Still, Dean of the Faculty of Science, University of Sydney ; Dr. W. G. Kett, Director, Mark Foy's Limited.

3rd June, 1959

The seven hundred and forty-eighth General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair. Sixty-five members and visitors were present.

The Chairman announced the death of Dr. Roger C. Thorne, 19th May, 1959, a member since 1958.

James Norrington Stephens was elected a member of the Society.

It was announced that the names of the following had been removed from the List of Members in accordance with Rule 18 : Franklin C. Finch and Albert May.

A notice of motion by the Council that the following alteration be made to the wording of Rule 8, paragraph 2 : " that three be replaced by two and two by one ".

The following papers were read by title only : " On Some Singularities of the Hankel Transform ", by J. L. Griffith ; " Petrology in Relation to Road Materials. Part 1. The Rocks Used to Produce ' Aggregate ' ", by E. J. Minty.

The evening was devoted, with the Linnean Society of New South Wales, to the commemoration of the centenary of the publication of " The Origin of Species ", and Professor P. D. F. Murray, of the Department of Zoology, University of Sydney, gave an address entitled " Charles Darwin ".

1st July, 1959

The seven hundred and forty-ninth General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair. Forty members and visitors were present.

Anthony Gerard Fynn and Mervyn Ernest Grahame were elected members of the Society.

The motion of the Council that the following alteration be made to Rule 8, paragraph 2, " that three be replaced by two and two by one " was carried.

The evening was devoted to a symposium on " The Anthropology of Central New Guinea " and addresses were delivered by Mr. M. Meggitt and Mr. D'Arcy Ryan, of the Department of Anthropology, University of Sydney.

5th August, 1959

The seven hundred and fiftieth General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair. Fifty-two members and visitors were present.

Arthur Alfred Sherwood and John William Humphries were elected members of the Society.

The motion of the Council carried at the General Monthly Meeting held on 1st July, 1959, that the following alterations be made to the wording of Rule 8, paragraph 2, " that three be replaced by two and two by one " was confirmed.

Professor J. M. Somerville, Department of Physics, University of New England, delivered the following address : " Attempts on Controlled Release of Thermonuclear Energy ".

2nd September, 1959

The seven hundred and fifty-first General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair. Thirty-three members and visitors were present.

Peter Lawrence and Jack Murielle Somerville were elected members of the Society.

A paper entitled " Variations in Physical Constitution of Quarried Sandstones from Gosford and Sydney ", by H. G. Golding, was read by title only.

The evening was devoted to a symposium on Ants. Professor G. W. K. Cavill, of the University of N.S.W., and Mr. G. Pasfield, of the N.S.W. Department of Agriculture, spoke on " Entomological and Chemical Aspects of their Control and Eradication, with Particular Reference to the Chemistry of Natural Insecticides ".

7th October, 1959

The seven hundred and fifty-second General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair. Forty-eight members and visitors were present.

Keith Meredith Burrows, Bernard Foster Hoskins, Gerhard Lowenthal and Mervyn John Meggitt were elected members of the Society.

A notice of motion by the Council that Rule XL be amended to read : " To allow fuller opportunities and facilities for meeting and working together to those members of the Society who devote attention to particular branches of science or who are resident in regions of New South Wales remote from Sydney, Sections or Committees may be established as the Council may decide."

The Australian Mutual Provident Society's film " Desert Conquest ", which was made available to us by courtesy of Twentieth Century Fox Films Corporation Pty. Ltd., was screened. Mr. R. O. Powys, of the A.M.P. Society, attended to discuss the film.

4th November, 1959

The seven hundred and fifty-third General Monthly Meeting was held in the Hall of Science House, Sydney.

The President, Mr. A. F. A. Harper, was in the chair.

Thirty-one members and visitors were present.

James Rhys Jones, D'Arcy James Ryan and Peter Robert Wilson were elected members of the Society.

A motion by the Council that Rule XL be amended to read : " To allow fuller opportunities and facilities for meeting and working together to those members of the Society who devote attention to particular branches of science or who are resident in regions of New South Wales remote from Sydney, Sections or Committees may be established as the Council may decide ", was carried unanimously.

The following papers were discussed : " Petrology in Relation to Road Materials. Part 1. The Rocks used to Produce Aggregate ", by E. J. Minty. Discussion was led by Professor D. F. Orchard, School of Highway Engineering, The University of New South Wales. " Ronchi Test Charts for Parabolic Mirrors ", by A. A. Sherwood. Discussion was led by Mr. Harley Wood, Government Astronomer, Sydney Observatory.

2nd December, 1959

The seven hundred and fifty-fourth General Monthly Meeting was held in the Hall of Science House, Gloucester Street, Sydney, at 7.45 p.m.

The President, Mr. A. F. A. Harper, was in the chair. Fifty-eight members and visitors were present.

The death was announced of Frederick L. Henriques, a member since 1919.

Moiren Krysko v. Tryst and Eric John Ramm were elected members of the Society.

A motion by the Council that Rule XL be amended to read " To allow fuller opportunities and facilities for meeting and working together to those members of the Society who devote attention to particular branches of science or who are resident in regions of New South Wales remote from Sydney, Sections or Committees may be established as the Council may decide " was confirmed.

The following papers were accepted for publication : " Tertiary Dykes in the Port Stephens District ", by B. Nashar and C. Catlin ; " Deuteric Alteration of Volcanic Rocks ", by H. G. Wilshire ; " Precise Observations of Minor Planets at Sydney Observatory during 1957 and 1958 ", by W. H. Robertson.

The following films were shown by courtesy of B.P. Aust. Ltd. : " Address Antarctica " and " Antarctic Crossing ".

Section of Geology

CHAIRMAN: T. G. VALLANCE, B.SC., PH.D.; HON. SECRETARY: L. E. KOCH, D.PHIL.HABIL.

Abstract of Proceedings, 1959

Five meetings were held during the year 1959, including the Annual Meeting held on 20th March, 1959, and a Jubilee Meeting to commemorate the fiftieth anniversary of continuous activities of the Section, held on 26th November. Average attendance was about 26 *members and visitors.*

March 20th (Annual meeting): *Election of Office bearers:* Dr. T. G. Vallance was elected chairman and Dr. L. E. Koch was re-elected Honorary Secretary of the Section.

Address: " Impressions from a Visit to famous Mineral Localities and Institutions Overseas ", Dr. L. J. Lawrence. Dr. Lawrence reported on his study periods at the Royal School of Mines, London, at the University of Cambridge, and at the University of Uppsala, Sweden, and Heidelberg, Germany. He carried out extensive travels to noted mineral localities and institutions in Great Britain (Cornwall, Gloucestershire), Sweden (Kiruuna), Hartz Mts., Mechernich, Siegerland, Germany. He also visited Switzerland, the Vulcanological Institute at Naples in Italy, and the graphite mines of Ceylon.

May 15th: (*1*) *Notes and Exhibits:*—Dr. Lawrence exhibited metalliferous minerals of colloidal origin: Schalenblende (Belgium), cassiterite (Stanley), jordanite, gratonite, schalenblende (Wiesloch, Baden), chalcopyrite (Redruth).

(*2*) *Address:* " The geology of the Cow Flat District, N.S.W." By R. A. Binns, B.Sc. An Ordovician-Silurian sequence of rocks in the Cow Flat area consists dominantly of volcanic and volcanically derived rocks with minor limestone. These rocks have been metamorphosed and subjected to two phases of folding and faulting, followed by the intrusion of the Bathurst granitic batholith. Ore deposits were formed probably n connection with the latter intrusion.

July 17th: (*1*) *Notes and Exhibits:*—Dr. Lawrence reported on observations of radioactivity in hematite from " Milestone " near Calvert Hills, N.T. Lantern slides furthermore illustrated autoradiographs of polished sections of titanite and epidote produced on specially sensitized photographic plates. Dr. Vallance exhibited large slabs of aplite containing euhedral quartz crystals several inches in diameter. (Location: 976 482 Oberon 1-mile sheet, E. of Fish River, N. of Duckmaloi, N.S.W.) Material was first collected by B. Guy (Geology IV, 1959). Dr. Vallance also exhibited various contact-metamorphic rocks, e.g., wollastonite hornfels formed from a limestone conglomerate (location: 941 718 Bathurst 1-mile sheet, between Meadow Flat and Portland). Dr. W. R. Browne reported on the observation of " tectonic ripples " of a remarkably recent age occurring directly W. of the headwaters of the Parramatta River, and running N.—S. Dr. Koch reported on an occurrence of epidote rock containing minor amounts of titanite, fibrous tremolite, quartz immediately adjacent to the chloritized shear zones in the granodiorite S.E. of Cobargo, South Coast, N.S.W.

(*2*) *Address* by Dr. L. E. Koch, " Diagrams representing Paragenetic and Reaction Relations of Ore and Other Minerals ". Paragenetic diagrams by Robertson and Vandeveer (1952) closely approach a new type of " standard diagrams " developed by the speaker, representing " composite wholes " and automatically permitting the application of the " Calculus of Composite Wholes " for their analysis and interpretation, i.e., set theory, imperfectly ordered sets, theory of relations, and combinatorics.

September 18th: (*1*) *Notes and Exhibits:*—Dr. Vallance exhibited two vols. of the " Theory of the Earth ", by James Hutton, a classic work in geological science reprinted as a facsimile edition in 1952. *Address:* " Some Observations on Tectonic Styles in New South Wales ", by B. Hobbs. Tectonic style is defined in terms of the geometry and overall fabric of a deformed belt and with reference to Sander's ideas of axial flow in B and transport ⊥B. Such concepts are then related to the two styles of folding, flexural slip (concentric) and pure slip (cleavage folding). The concepts are illustrated by the Peel Fault system in New England, N.S.W., as well as structures developed in the Central West of N.S.W. The depth and emplacement of granites occurring in connection with the above structures was given particular attention.

26th November: Jubilee Meeting to commemorate the fiftieth anniversary of continuous activities of the Section of Geology. (*1*) *Address:* " Recollections of the Early Days of the Section of Geology ", by Dr. W. R. Browne, F.A.A. Dr. Browne gave first a brief historical review of the foundation of nine specialized Sections of the Royal Society of N.S.W. in 1876. A Section of Geology operated with interruptions until 1893, when it lapsed. It was brought to new vigorous life again in 1909 by the initiative of Dr. Woolnough and other members of the Society. Dr. Browne gave a vivid account of the activities of the Section right to the Second World War, mentioning distinguished visitors and speakers from overseas, memorable exhibits, or discussions on fundamental geological problems of the day.

(*2*) *Address by Dr. Vallance:* The Chairman then reviewed the activities of the Section since 1946, with addresses and lecturettes as a new prominent feature of that activity. There has also been a marked increase since 1945 in the attendance figures which were maintained even after the formation of the fast-growing N.S.W. Division of the Geological Society of Australia.

L. E. KOCH,
Hon. Secretary, Section of Geology.

ADDENDUM TO REPORT OF SECTION FOR 1956

The following communication by Mr. H. G. Golding, duly recorded in the minutes of the meeting of 20th July, 1956, of the Section of Geology, but inadvertently omitted from the Abstracts of the Proceedings of the Section for that year, is given in abstract here:

Mr. Golding reported on the occurrence at Wheeler's Point, Penguin Head, South Coast, N.S.W., of an island stack developed in monoclinally folded Permian sandstones as a result of marine erosion acting along the meridional fold axis. Several types of concretions occur in these beds, at various levels, some of them packed with well preserved *Dielasma*, etc. Exhibits of specimens and photographs illustrated the communication.

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General. Manuscripts should be addressed to the Honorary Secretaries, Royal Society of New South Wales, Science House, 157 Gloucester Street, Sydney. Two copies of each manuscript are required: the original typescript and a carbon copy.

Papers should be prepared according to the general style adopted in this Journal. They should be as concise as possible, consistent with adequate presentation. Particular attention should be given to clarity of expression and good prose style.

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.

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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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IMPORTANT ANNOUNCEMENT

Commencing with the present volume the Journal and Proceedings of the Society will be issued in SIX parts per volume instead of four as previously.

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OF NEW SOUTH WALES

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Royal Society of New South Wales

OFFICERS FOR 1960-1961

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 N.S.W., Vol. 94, pp. 99–108, 1960

Kinetics of Chain Reactions

R. C. L. Bosworth and C. M. Groden

(*Received March* 17, 1960)

Abstract.—The concentration of active centres in the presence of branching and rupture in the volume and on the walls, due to diffusion, has been discussed and the differential equation obtained solved by means of Laplace Transforms in the case of cylindrical and spherical vessels.

1. Introduction

The propagation of a chain mechanism through a reacting system with only first order initiation and termination processes can, as first shown by Bursian and Sorokin (1931), be represented by the following differential equation

$$\frac{\partial n}{\partial t}=A+Bn+D\nabla^2 n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

where n is the number density of chain centres ;

A represents the total initial rate of formation of centres and is always positive ;

Bn is the net difference between linear branching and linear homogeneous termination. The factor B accordingly can be positive, negative, or in exceptional cases, zero ;

D is the mean coefficient of diffusion of the centres through the reaction mixture.

Many succeeding authors have given solutions for the case of one dimensional systems in which ∇^2 reduces to $\frac{d^2}{dx^2}$ (Semenoff, 1935). The following assays solutions in cylindrical and spherical polar co-ordinates approximating respectively to the conditions obtaining in long cylindrical reactors and to approximate spherical reactors such as ordinary chemical flasks. The solutions obtained show the development of the overall density and the distribution throughout the reactor during the whole of the transient stage of chain propagation.

2. Solution in Cylindrical Co-ordinates

Assuming circular symmetry we have in a cylindrical vessel (of radius R) that

$$\nabla^2 n=\frac{1}{r}\frac{\partial n}{\partial r}+\frac{\partial^2 n}{\partial r^2},$$

where r is the distance from the axis of the cylinder

$$0\leqslant r\leqslant R.$$

Thus, equation (1) becomes

$$\frac{\partial n}{\partial t}=A+Bn+D\left(\frac{\partial^2 n}{\partial r^2}+\frac{1}{r}\frac{\partial n}{\partial r}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

We put

$$A=a^2\,;\ D=d^2\,;\ B=\pm b^2 \text{ or } 0, \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

and consider the case when B is positive.
We then have

$$\frac{\partial n}{\partial t}=a^2+b^2n+d^2\left(\frac{\partial^2 n}{\partial r^2}+\frac{1}{r}\frac{\partial n}{\partial r}\right), \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

which we want to solve for $n=n(r,t)$ subject to the following initial and boundary conditions

$$\left.\begin{array}{lll}(a)\ n=0 & \text{when } t=0, & r>0\\ (b)\ n=0 & \text{when } r=R, & t>0\\ (c)\ n \text{ is finite} & \text{when } r=0 & \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

The most commonly used method for the solution of problems of this type involves the use of an infinite series of some orthogonal functions or an infinite integral to represent the unknown solution. However, in the following development the Laplace Transform methods are used as they represent a unified method, more rigorous than the usual series solution.

Putting

$$\rho=\frac{b}{d}r\,;\quad 0\leqslant\rho\leqslant\frac{b}{d}R \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

we obtain by substituting into (4) and dividing throughout by b^2

$$\frac{1}{b^2}\frac{\partial n}{\partial t}=\frac{a^2}{b^2}+n+\frac{1}{\rho}\frac{\partial n}{\partial \rho}+\frac{\partial^2 n}{\partial \rho^2} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Let the Laplace transform of $n(\rho,t)$ be denoted by $\bar{n}(p,\rho)$

$$\bar{n}(p,\rho)=\int_0^\infty \mathrm{e}^{-pt}n(\rho,t)dt \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Then the transformed equation, in which dashes denote differentiation with respect to ρ, reads

$$\frac{p}{b^2}\bar{n}=\frac{1}{p}\frac{a^2}{b^2}+\bar{n}+\frac{1}{\rho}\bar{n}'+\bar{n}''$$

or

$$\bar{n}''+\frac{1}{\rho}\bar{n}'+\bar{n}\left(1-\frac{p}{b^2}\right)=\frac{-a^2/b^2}{p} \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

This is a non-homogeneous differential equation of 2nd order whose general solution, finite at the origin, is given by

$$\bar{n}(p,\rho)=\frac{a^2}{p(p-b^2)}+\alpha I_0\left(\frac{\rho}{b}\sqrt{p-b^2}\right) \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

where α is a constant of integration and $I_0(r)$ is the modified Bessel function of first kind and order zero (Whittaker, 1946, page 372).

In view of (5*b*) and (6) we find that

$$\alpha=-\frac{a^2}{p(p-b^2)I_0\left(\frac{R}{d}\sqrt{p-b^2}\right)} \quad\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

and, therefore

$$\bar{n}(p,r)=\frac{a^2}{p(p-b^2)}\left[1-\frac{I_0\left(\frac{r}{d}\sqrt{p-b^2}\right)}{I_0\left(\frac{R}{d}\sqrt{p-b^2}\right)}\right]=\frac{a^2}{p(p-b^2)}\left[1-\frac{I_0(\sigma\sqrt{p-b^2})}{I_0(S\sqrt{p-b^2})}\right] \quad\ldots\ldots \quad (11a)$$

where $\sigma=\frac{r}{d}$ and $S=\frac{R}{d}$,

or, by using partial fractions

$$\bar{n}(p,r)=\frac{a^2}{b^2}\left\{\frac{1}{p-b^2}-\frac{1}{p}-\frac{I_0(\sigma\sqrt{p-b^2})}{(p-b^2)I_0(S\sqrt{p-b^2})}\right.$$

$$\left.+\frac{I_0(\sigma\sqrt{p-b^2})}{pI_0(S\sqrt{p-b^2})}\right\} \quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

Now, if $L^{-1}\{f(p)\}$ is the function $F(t)$ whose Laplace Transform is $f(p)$ then we have

$$\text{(I)} \quad L^{-1}\left\{\frac{1}{p-b^2}-\frac{1}{p}\right\}=e^{b^2t}-1; \qquad (13)$$

$$\text{(II)} \quad L^{-1}\left\{\frac{I_0(\sigma\sqrt{p-b^2})}{(p-b^2)I_0(S\sqrt{p-b^2})}\right\}=e^{b^2t}L^{-1}\left\{\frac{I_0(\sigma\sqrt{p})}{pI_0(S\sqrt{p})}\right\}$$

$$=e^{b^2t}\left[1-\frac{2}{R}\sum_{k=1}^{\infty}\mathrm{e}^{-d^2\lambda_k^2t}\frac{J_0(\lambda_k r)}{\lambda_k J_1(\lambda_k R)}\right]$$

$$=e^{b^2t}-\frac{2}{R}\sum_{k=1}^{\infty}e^{-(d^2\lambda_k^2-b^2)t}\frac{J_0(\lambda_k r)}{\lambda_k J_1(\lambda_k R)} \qquad (14)$$

where J_0, J_1 are Bessel functions of first kind and $\pm\lambda_k$ are roots of

$$J_0(\lambda_k R)=0 \qquad (15)$$

(Carslaw, 1948), pages 123/4) ;

$$\text{(III)} \quad L^{-1}\left\{\frac{1}{p}\,\frac{I_0(\sigma\sqrt{p-b^2})}{I_0(S\sqrt{p-b^2})}\right\}=\int_0^t L^{-1}\left\{\frac{I_0(\sigma\sqrt{p-b^2})}{I_0(S\sqrt{p-b^2})}\right\}dt$$

$$=\int_0^t e^{b^2t}L^{-1}\left\{\frac{I_0(\sigma\sqrt{p})}{I_0(S\sqrt{p})}\right\}dt \qquad (16)$$

Using the Inversion Theorem we find that

$$L^{-1}\left\{\frac{I_0(\sigma\sqrt{p})}{I_0(S\sqrt{p})}\right\}=\frac{2d^2}{R}\sum_{k=1}^{\infty}\frac{\lambda_k J_0(\lambda_k r)e^{-d^2\lambda_k^2t}}{J_1(\lambda_k R)} \qquad (17)$$

(Tranten, 1951, pages 27/8) ;

Thus

$$L^{-1}\left\{\frac{1}{p}\,\frac{I_0(\sigma\sqrt{p-b^2})}{I_0(S\sqrt{p-b^2})}\right\}=\int_0^t e^{b^2t}\sum_{k=1}^{\infty}\frac{2d^2\lambda_k J_0(\lambda_k r)}{RJ_1(\lambda_k R)}e^{-d^2\lambda_k^2t}dt$$

or, interchanging the operations of integration and summation

$$L^{-1}\left\{\frac{1}{p}\,\frac{I_0(\sigma\sqrt{p-b^2})}{I_0(S\sqrt{p-b^2})}\right\}=\frac{2d^2}{R}\sum_{k=1}^{\infty}\frac{\lambda_k}{(d^2\lambda_k^2-b^2)}\,\frac{J_0(\lambda_k r)}{J_1(\lambda_k R)}\left[1-e^{-(d^2\lambda_k^2-b^2)t}\right] \qquad (18)$$

Combining now (12), (13), (14) and (18) we obtain

$$n(r,t)=\frac{a^2}{b^2}\left\{e^{b^2t}-1-e^{b^2t}+\frac{2}{R}\sum_{k=1}^{\infty}e^{-(d^2\lambda_k^2-b^2)t}\frac{J_0(\lambda_k r)}{\lambda_k J_1(\lambda_k R)}\right.$$

$$\left.+\frac{2d^2}{R}\sum_{k=1}^{\infty}\frac{\lambda_k}{(d^2\lambda_k^2-b^2)}\,\frac{J_0(\lambda_k r)}{J_1(\lambda_k R)}\left[1-e^{-(d^2\lambda_k^2-b^2)t}\right]\right\}$$

which on simplifying yields the final result

$$n(r,t)=\frac{2a^2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)\left[1-e^{-(d^2\lambda_k^2-b^2)t}\right]}{\lambda_k(d^2\lambda_k^2-b^2)J_1(\lambda_k R)} \qquad (19)$$

$$=\frac{a^2}{b^2}\left[\frac{J_0\left(\frac{b}{d}r\right)}{J_0\left(\frac{b}{d}R\right)}-1\right]-\frac{2a^2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)e^{-(d^2\lambda_k^2-b^2)t}}{\lambda_k J_1(\lambda_k R)(d^2\lambda_k^2-b^2)} \qquad (19a)$$

(see Appendix (*c*)).

3. Analysis of Results

(a) When $t \rightarrow \infty$ we have from (19*a*)

$$n(r) \rightarrow \frac{a^2}{b^2}\left[\frac{J_0\left(\frac{b}{d}r\right)}{J_0\left(\frac{b}{d}R\right)}-1\right] \quad \ldots\ldots\ldots\ldots \quad (20)$$

which is the obvious solution of the steady state equation $\left(\frac{\partial n}{\partial t}=0\right)$, and represents a distribution of the active centres over a radial section under final steady state conditions. The distribution represents a peak in the density of active centres along the cylindrical axis with a vanishing of the density of centres at the walls.

At the other extreme stage in process of setting up a distribution of active centres, namely when $t \rightarrow 0$, the exponential in equation (19) may be replaced by its first order terms in a Taylor expansion and the equation as a whole reduces to

$$n(r,t)=\frac{2a^2}{R}t\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)}{\lambda_k J_1(\lambda_k R)}=At$$

(see Appendix (a)).

(b) When B is negative, i.e., the original equation reads

$$\frac{\partial n}{\partial t}=a^2-b^2n+d^2\nabla^2 n$$

then we get directly from (19) the solution

$$n(r,t)=\frac{2a^2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)\left[1-e^{-(d^2\lambda_k^2+b^2)t}\right]}{\lambda_k(d^2\lambda_k^2+b^2)J_1(\lambda_k R)} \quad \ldots\ldots\ldots\ldots \quad (21)$$

which for steady state yields the result

$$n(r) \rightarrow \frac{2a^2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)}{\lambda_k\left(\lambda_k^2+\frac{b^2}{d^2}\right)J_1(\lambda_k R)}=\frac{a^2}{b^2}\left[1-\frac{I_0\left(\frac{b}{d}r\right)}{I_0\left(\frac{b}{d}R\right)}\right] \quad \ldots\ldots \quad (21a)$$

(c) When B is zero $\therefore$ $b=0$ we have from (19)

$$n(r,t)=\frac{2a^2}{d^2R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)}{J_1(\lambda_k R)\lambda_k^3}\left[1-e^{-d^2\lambda_k^2 t}\right]; \quad \ldots\ldots\ldots\ldots \quad (22)$$

This result can be obtained directly from the equation

$$\frac{\partial n}{\partial t}=A+D\nabla^2 n.$$

When $t \rightarrow \infty$ we get in this case

$$n(r) \rightarrow \frac{2a^2}{d^2R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k r)}{J_1(\lambda_k R)\lambda_k^3} \quad \ldots\ldots\ldots\ldots \quad (23)$$

$$=\frac{a^2}{d^2}\left(\frac{R^2-r^2}{4}\right) \quad \ldots\ldots\ldots\ldots \quad (23a)$$

(see Appendix (b)).

(d) Differentiating (19) with respect to r we obtain

$$\frac{\partial n}{\partial r}=-\frac{2a^2}{R}\sum_{k=1}^{\infty}\frac{J_1(\lambda_k r)}{J_1(\lambda_k R)}\,\frac{\left[1-e^{-(d^2\lambda_k^2-b^2)t}\right]}{d^2\lambda_k^2-b^2} \quad \ldots\ldots\ldots\ldots \quad (24)$$

which for $r=0$ becomes zero since $J_1(0)=0$. Thus, the function $n(r,t)$ has a peak value in the centre.

4. Solution in Spherical Co-ordinates

Assuming radial symmetry we have in a spherical vessel (of radius R) that

$$\nabla^2 n=\frac{2}{r}\frac{\partial n}{\partial r}+\frac{\partial^2 n}{\partial r^2},$$

where r is the distance from the centre of the sphere. Then equation (1) takes the form

$$\frac{\partial n}{\partial t}=A+Bn+D\left(\frac{\partial^2 n}{\partial r^2}+\frac{2}{r}\frac{\partial n}{\partial r}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (25)$$

As before we consider the case when B is positive ($B=b^2$) and introduce a function $m(r,t)$ defined by the equation

$$m(r,t)=rn(r,t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (26)$$

or

$$n(r,t)=\frac{m(r,t)}{r}$$

Using equations (3), (25) and (26) we find that $m(r,t)$ satisfies the differential equation

$$\frac{\partial m}{\partial t}=a^2r+b^2m+d^2\frac{\partial^2 m}{\partial r^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (27)$$

with the initial and boundary conditions

$$\left.\begin{array}{llll} (a) & m=0 & \text{when } t=0, & r>0 \\ (b) & m=0 & \text{when } r=R, & t>0 \\ (c) & m=0 & \text{when } r=0, & t>0 \end{array}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (28)$$

If $\bar{m}(r,p)$ represents the Laplace Transform of $m(r,t)$

$$\bar{m}(r,p)=\int_0^\infty e^{-pt}m(r,t)dt$$

the transformed equation (27) now reads

$$\bar{m}''(r)-\frac{(p-b^2)}{d^2}\bar{m}=-\frac{a^2r}{d^2p},\quad p-b^2>0, \quad \ldots\ldots\ldots\ldots\ldots \quad (29)$$

where dashes denote differentiation with respect to r.

Putting

$$\frac{r}{d}=\rho\,;\ \frac{R}{d}=P \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (30)$$

we find that differential equation (29) has the general solution

$$\bar{m}(\rho,p)=\alpha e^{-\rho\sqrt{p-b^2}}+\beta e^{\rho\sqrt{p-b^2}}+\frac{da^2\rho}{p(p-b^2)} \quad \ldots\ldots\ldots\ldots\ldots \quad (31)$$

The constants of integration α and β are determined by conditions (28*b*, *c*); in fact

$$\alpha=-\beta=\frac{da^2P}{2p(p-b^2)\sinh\left(P\sqrt{p-b^2}\right)} \quad \ldots\ldots\ldots\ldots\ldots \quad (32)$$

so that

$$\bar{m}(p,\rho)=\frac{da^2\rho}{p(p-b^2)}-da^2P\left[\frac{\sinh\left(\rho\sqrt{p-b^2}\right)}{p(p-b^2)\sinh\left(P\sqrt{p-b^2}\right)}\right] \quad \ldots\ldots \quad (33)$$

or, using partial fractions

$$\bar{m}(p,\rho)=\left\{\frac{da^2\rho}{b^2}\left(\frac{1}{p-b^2}-\frac{1}{p}\right)\right.$$

$$\left.-\frac{da^2R}{b^2}\left[\frac{\sinh(\rho\sqrt{p-b^2})}{(p-b^2)\sinh(P\sqrt{p-b^2})}-\frac{\sinh(\rho\sqrt{p-b^2})}{p\sinh(P\sqrt{p-b^2})}\right]\right\}\quad\ldots\ldots\ldots\ldots\ldots\ldots\ (34)$$

Now

$$\text{(I)}\qquad L^{-1}\left\{\frac{\sinh(\rho\sqrt{p-b^2})}{(p-b^2)\sinh(P\sqrt{p-b^2})}\right\}=e^{b^2t}L^{-1}\left\{\frac{1}{p}\,\frac{\sinh(\rho\sqrt{p})}{\sinh(P\sqrt{p})}\right\}$$

$$=e^{b^2t}\int_0^t L^{-1}\left\{\frac{\sinh(\rho\sqrt{p})}{\sinh(P\sqrt{p})}\right\}dt\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (35)$$

and

$$L^{-1}\left\{\frac{\sinh(\rho\sqrt{p})}{\sinh(P\sqrt{p})}\right\}=\frac{1}{P}\,\frac{\partial}{\partial\rho}\left[\theta_4\left(\frac{\rho}{2P};\ e^{-\frac{\pi^2t}{p^2}}\right)\right]\quad\ldots\ldots\ldots\ldots\ldots\ldots\ (36)$$

(Bateman, 1953, Tables, Vol. I, page 258).
Where θ_4 is Jacobi's Theta function defined as follows

$$\theta_4(v;q)=1+2\sum_{k=1}^{\infty}(-1)^kq^{k^2}\cos(2k\pi v)\quad\ldots\ldots\ldots\ldots\ldots\ldots\ (37)$$

(Bateman, 1953, Functions, Vol. II, pages 354/60).
In our case

$$\theta_4(\rho;t)=1+2\sum_{k=1}^{\infty}(-1)^ke^{-\frac{\pi^2}{p^2}k^2t}\cos\left(k\pi\frac{\rho}{P}\right)$$

$$=1+2\sum_{k=1}^{\infty}(-1)^ke^{-\delta^2k^2t}\cos(k\delta\rho)\quad\ldots\ldots\ldots\ldots\ldots\ldots\ (38)$$

if

$$\delta=\frac{\pi}{P}=\frac{\pi d}{R}\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (39)$$

As a function of $(\delta\rho)$ θ_4 is continuous in the interval $(-\pi,\pi)$, $t>0$, and also

$$\theta_4(-\pi)=\theta_4(\pi).\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (40)$$

Hence the derivative $\frac{\partial\theta_4}{\partial\rho}$ can be obtained by termwise differentiation (Churchill, 1941, pages 78/9) :

$$\frac{\partial\theta_4}{\partial\rho}=2\delta\sum_{k=1}^{\infty}(-1)^{k+1}ke^{-\delta^2k^2t}\sin(k\delta\rho)\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (41)$$

and therefore

$$\int_0^t\frac{\partial\theta_4}{\partial\rho}dt=\lim_{\varepsilon\to0}\int_\varepsilon^t 2\delta\sum_{k=1}^{\infty}(-1)^{k+1}ke^{-\delta^2k^2t}\sin(k\delta\rho)dt$$

$$=\lim_{\varepsilon\to0}\frac{2}{\delta}\left[\sum_{k=1}^{\infty}(-1)^ke^{-\delta^2k^2t}\frac{\sin(k\delta\rho)}{k}\right]_\varepsilon^t$$

$$=\frac{2}{\delta}\left[\sum_{k=1}^{\infty}(-1)^ke^{-\delta^2k^2t}\frac{\sin(k\delta\rho)}{k}-\sum_{k=1}^{\infty}(-1)^k\frac{\sin(k\delta\rho)}{k}\right]\quad\ldots\ldots\ (42)$$

The last sum represents the half range sine Fourier series of $(-\frac{1}{2}\delta\rho)$ so that

$$\int_0^t \frac{\partial\theta_4}{\partial\rho}dt = \frac{2}{\delta}\left[\frac{\delta\rho}{2} + \sum_{k=1}^{\infty}(-1)^k e^{-\delta^2k^2t}\frac{\sin(k\delta\rho)}{k}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (42a)$$

and therefore

$$L^{-1}\left\{\frac{\sinh(\rho\sqrt{p-b^2})}{(p-b^2)\sinh(P\sqrt{p-b^2})}\right\} =$$

$$= \frac{e^{b^2t}}{P}\rho + \frac{2}{\delta P}\sum_{k=1}^{\infty}(-1)^k e^{-(\delta^2k^2-b^2)t}\ \frac{\sin(k\delta\rho)}{k} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (43)$$

(II)

$$L^{-1}\left\{\frac{\sinh(\rho\sqrt{p-b^2})}{p\sinh(P\sqrt{p-b^2})}\right\} = e^{b^2t}L^{-1}\left\{\frac{\sinh(\rho\sqrt{p})}{(p+b^2)\sinh(P\sqrt{p})}\right\} \quad \ldots\ldots\ldots\ldots \quad (44)$$

and since

$$L^{-1}\left\{\frac{1}{p-i\omega}\ \frac{\sinh(\rho\sqrt{p})}{\sinh(P\sqrt{p})}\right\} =$$

$$= \frac{\sinh(\rho\sqrt{i\omega})}{\sinh(P\sqrt{i\omega})}e^{i\omega t} + 2\pi\sum_{k=1}^{\infty}(-1)^k\ \frac{k\sin(k\delta\rho)}{k^2\pi^2+P^2i\omega}e^{-\delta^2k^2t} \quad \ldots\ldots\ldots\ldots \quad (45)$$

(Bateman, 1953, Tables, Vol. I, page 259),
and in our case

$$b^2 = -i\omega \text{ or } \sqrt{i\omega} = \pm bi,$$

we have that

$$L^{-1}\left\{\frac{\sinh(\rho\sqrt{p})}{(p-b^2)\sinh(P\sqrt{p})}\right\} = \frac{\sin(\rho b)}{\sin(Pb)}e^{-b^2t} + \frac{2}{\pi}\sum_{k=1}^{\infty}\ (-1)^k\frac{k\sin(k\delta\rho)}{k^2-\frac{b^2}{\delta^2}}e^{-\delta^2k^2t}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (46)$$

or

$$L^{-1}\left\{\frac{\sinh(\rho\sqrt{p-b^2})}{p\sinh(P\sqrt{p-b^2})}\right\} = \frac{\sin(\rho b)}{\sin(Pb)} + \frac{2}{\pi}\sum_{k=1}^{\infty}\ (-1)^k\ \frac{k\sin(k\delta\rho)}{k^2-\frac{b^2}{\delta^2}}e^{-(\delta^2k^2-b^2)t}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (47)$$

Combining now (34), (13), (43) and (47) we obtain $m(\rho,t)$ in the form

$$m(\rho,t) = \frac{a^2d}{b^2}\left[P\frac{\sin(b\rho)}{\sin(Pb)} - \rho\right] + \frac{2a^2d}{\delta^3}\sum_{k=1}^{\infty}\ (-1)^k\ \frac{\sin(k\delta\rho)}{k\left(k^2-\frac{b^2}{\delta^2}\right)}e^{-(\delta^2k^2-b^2)t}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (48)$$

or

$$n(\rho,t) = \frac{a^2}{b^2}\left[\frac{P}{\rho}\ \frac{\sin(b\rho)}{\sin(bP)} - 1\right] + \frac{2a^2d}{\delta^3\rho}\sum_{k=1}^{\infty}\ (-1)^k\ \frac{\sin(k\delta\rho)}{k\left(k^2-\frac{b^2}{\delta^2}\right)}e^{-(\delta^2k^2-b^2)t}$$

$$\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (49)$$

By expanding the expression $\frac{a^2}{b^2}\left[\frac{P}{\rho}\,\frac{\sin\,(b\rho)}{\sin\,(bP)}-1\right]$ in a half range sine Fourier series we finally have

$$n(\rho,t)=\frac{2a^2}{\delta^3}\,\frac{1}{\rho}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin\,(k\delta\rho)}{k\left(k^2-\frac{b^2}{\delta^2}\right)}\left[e^{-(\delta^2k^2-b^2)t}-1\right] \quad\dots\dots\dots\dots\dots \quad (50)$$

5. Analysis of the Results

(a) When $t\to\infty$ we get from (49)

$$n(\rho)\to\frac{a^2}{b^2}\left[\frac{P}{\rho}\,\frac{\sin\,(b\rho)}{\sin\,(bP)}-1\right] \quad\dots\dots\dots\dots\dots \quad (51)$$

which is the steady state solution $\left(\frac{\partial n}{\partial t}=0\right)$.

On using (3) and (30) equation (51) becomes

$$n(r)\to\frac{A}{B}\left[\frac{R}{r}\,\frac{\sin\sqrt{B/D}\;r}{\sin\sqrt{B/D}\;R}-1\right] \quad\dots\dots\dots\dots\dots \quad (51a)$$

The final distribution of active centres about the centre thus corresponds approximately to a paraboloid about the centre, the approximation being the better the lower the value of $\frac{BR^2}{D}$.

In the initial stages of development the exponential in equation (50) may be expanded and the equation becomes

$$\begin{aligned} n(\rho,t)&\to\frac{2a^2t}{\delta}\,\frac{1}{\delta}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin k\delta\rho}{k} \quad\dots\dots\dots\dots\dots \quad (51b)\\ &=\frac{a^2t}{\delta\rho}\delta\rho\\ &=a^2t \end{aligned}$$

or

$$n(r,t)\to At, \quad\dots\dots\dots\dots\dots \quad (51c)$$

which represents an initial homogeneous distribution throughout the cylindrical vessel completely different from the paraboloidal distribution in the fully developed system.

(b) When B is negative, then replacing b^2 by $(-b^2)$ or b by (ib) we have from (49)

$$n(\rho,t)=\frac{a^2}{b^2}\left[1-\frac{P}{\rho}\,\frac{\sinh\,(b\rho)}{\sinh\,(bP)}\right]+\frac{2a^2d}{\delta^3\rho}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin\,(k\delta\rho)}{k\left(k^2+\frac{b^2}{\delta^2}\right)}e^{-(\delta^2k^2-b^2)t} \quad\dots\dots \quad (52)$$

or from (50)

$$n(\rho,t)=\frac{2a^2}{\delta^3}\,\frac{1}{\rho}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin\,(k\delta\rho)}{k\left(k^2+\frac{b^2}{\delta^2}\right)}\left[e^{-(\delta^2k^2+b^2)t}-1\right] \quad\dots\dots\dots\dots\dots \quad (53)$$

The last two equations are equivalent. The steady state solution is given in this case by

$$n(\rho)\to\frac{a^2}{b^2}\left[1-\frac{P}{\rho}\,\frac{\sinh\,(b\rho)}{\sinh\,(bP)}\right] \quad\dots\dots\dots\dots\dots \quad (54)$$

(c) When B is zero $\therefore$ $b=0$, we have from (50)

$$n(\rho,t)=\frac{2a^2}{\delta^3}\,\frac{1}{\rho}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin(k\delta\rho)}{k^3}[e^{-\delta^2k^2t}-1] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (55)$$

and since $\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin(k\delta\rho)}{k^3}$ represents the half range sine Fourier series of $\frac{a^2}{6}(P^2-\rho^2)$, equation (55) takes the form

$$n(\rho,t)=\frac{a^2}{6}(P^2-\rho^2)+\frac{2a^2}{\delta^3}\,\frac{1}{\rho}\sum_{k=1}^{\infty}(-1)^k\,\frac{\sin(k\delta\rho)}{k^3}e^{-\delta^2k^2t} \quad \ldots\ldots\ldots\ldots\ldots \quad (56)$$

This is the expression which is obtained directly as the solution of the equation.

$$\frac{\partial n}{\partial t}=A+D\nabla^2 n\,;$$

when $t\to\infty$, (56) yields the steady state solution

$$n(\rho)\to\frac{a^2}{6}(P^2-\rho^2) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (57)$$

(d) Differentiating (50) with respect to ρ we find that for $\rho=0$ $\frac{\partial n}{\partial \rho}=0$ since for each k

$$\frac{d}{d\rho}\left[\frac{\sin(k\delta\rho)}{\rho}\right]_{\rho=0}=\left[\frac{k\delta\rho\cos(k\delta\rho)-\sin(k\delta\rho)}{\rho^2}\right]_{\rho=0}$$

$$=\lim_{\rho\to 0}\left[\frac{-\rho k^2\delta^2\sin(k\delta\rho)}{2\rho}\right]=0.$$

Thus, the function $n(\rho,t)$ has a peak value at the centre of the vessel.

6. Appendix

(Expansion of functions in Fourier Bessel series)

An arbitrary function $f(\rho)$, $0\leqslant\rho\leqslant R$, can be expressed as a series of Bessel functions of order 0 in the form

$$f(\rho)=\sum_{k=1}^{\infty}A_kJ_0(\lambda_k\rho)$$

where λ_k are roots of the equation $J_0(\lambda R)=0$ and the coefficients A_k are given by

$$A_k=\frac{2}{R^2J_1^2(\lambda_kR)}\int_0^R\rho J_0(\lambda_k\rho)f(\rho)d\rho$$

(Churchill, 1941, page 163).

Using recurrence formulae

$$(1)\ \frac{2n}{\rho}J_n(\rho)=J_{n-1}(\rho)=J_{n+1}(\rho),$$

$$(2)\ \frac{d}{d\rho}[\rho^nJ_n(\rho)]=\rho^nJ_{n-1}(\rho)\,;\qquad n=0,\ 1,\ 2,\ldots$$

and the formula

$$(3)\ \int_0^R\rho J_0(\alpha\rho)J_0(\beta\rho)d\rho=$$

$$=\frac{1}{\alpha^2-\beta^2}\Big[\rho\{\alpha J_1(\alpha\rho)J_0(\beta\rho)-\beta J_1(\beta\rho)J_0(\alpha\rho)\}\Big]_0^R$$

(Churchill, 1945, page 148; Whittaker, 1946, page 381), the following results have been obtained:

$$\text{(a)}\quad 1=\frac{2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k\rho)}{\lambda_k J_1(\lambda_k R)};$$

$$\text{(b)}\quad \rho^2=\frac{2}{R}\sum_{k=1}^{\infty}\frac{R^2\lambda_k^2-4}{\lambda_k^3}\,\frac{J_0(\lambda_k\rho)}{J_1(\lambda_k R)}$$

and hence

$$\tfrac{1}{4}(R^2-\rho^2)=\frac{2}{R}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k\rho)}{\lambda_k^3 J_1(\lambda_k R)};$$

$$\text{(c)}\quad J_0\left(\frac{b}{d}\rho\right)=\frac{2J_0\left(\frac{b}{d}R\right)}{R}\sum_{k=1}^{\infty}\frac{\lambda_k J_0(\lambda_k\rho)}{\left(\lambda_k^2-\frac{b^2}{d^2}\right)J_1(\lambda_k R)}$$

and hence

$$\frac{a^2}{b^2}\left[\frac{J_0\left(\frac{b}{d}\rho\right)}{J_0\left(\frac{b}{d}R\right)}-1\right]=\frac{2a^2}{Rd^2}\sum_{k=1}^{\infty}\frac{J_0(\lambda_k\rho)}{\lambda_k\left(\lambda_k^2-\frac{b^2}{d^2}\right)J_1(\lambda_k R)}$$

The approach to the subject in this paper has been purely mathematical, but since this paper has been prepared mainly for those with an interest in Chemistry rather than in Mathematics, the treatment has avoided the use of Inversion Theorem as much as possible although this method might appear mathematically more elegant and compact.

No attempt has been made to develop expressions suitable for test against experimental data. It is clear, however, that a number of significant points are already emerging. The development of a stationary system of active centres following from the equation of Bursian and Sorokin involves, not only an induction period in the chemical reaction depending to some extent on the geometry of the system, but also a progressive change in the distribution of the active centres depending not only on the geometry of the system but also on the ratio of the parameters in the Bursian and Sorokin equation. These matters, together with the computation of experimental factors, will be taken up in a subsequent paper.

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An Interpretation of the Lorentz Transformation Co-ordinates

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Abstract.—It has been shown in a previous paper that Einstein's principles and definitions are consistent with a new interpretation regarding the measurement of time in Special Relativity. An extension of the argument to space-interval measurements leads to a fully consistent interpretation of the Lorentz transformation and the co-ordinates involved therein. The approach gives physical meaning to the reciprocity property of the transformation and suggests a criterion of simultaneity for observers in relative motion.

It is suggested that the transformation may have a previously unsuspected bearing on a number of practical and theoretical issues including radar measurements and the nature of light transmission.

1. Introduction

The Lorentz transformation co-ordinates are based on Einstein's measurement conventions for synchronizing clocks and timing a distant event, the displacement co-ordinates of the event being also defined in terms of these measurements. A consequence of these conventions is that observers with similar clocks previously synchronized but stationary in different inertial systems, obtain different measures of the co-ordinates of a given event. These two sets of measures are related according to the Lorentz transformations and this was first demonstrated by Einstein (1905).

Unfortunately this demonstration and also all subsequent derivations of the Lorentz transformations concealed the purely conventional nature of the measurements. Most of the derivations given (e.g. Møller, 1952; McCrea, 1947) are based on obtaining transformations which satisfy uniquely the invariance relation,

$$x^2+y^2+z^2-c^2t^2=x'^2+y'^2+z'^2-c^2t'^2.$$

Such derivations are independent of the meaning of the symbols, and their interpretation has been the subject of much controversy.

It will be shown that a rigorous interpretation of Einstein's conventions, in the light of his principles of relativity and light velocity constancy, leads to a new but fully consistent interpretation of the Lorentz transformations and the co-ordinates involved therein. There are some interesting and possibly verifiable consequences of this approach involving both practical and theoretical issues. Some of these will be briefly considered.

2. The Measurement of Time

In a previous communication (Prokhovnik, 1960) it was suggested that Einstein's principles and definitions (i) to (iv) were consistent with an assumption referred to as the "light-signal hypothesis", viz.

> 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.

On the basis of this assumption, a definition (v) of synchronism for relatively moving clocks was also proposed.

We then considered 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 A's conventionally measured time of the event is according to the definition (ii)*

$$t_A^m=\tfrac{1}{2}(t_A^1+t_A^3) \quad \ldots\ldots\ldots\ldots \quad (1)$$

---

* Wherever reference is made to Einstein's principles I, II or to the definitions (i) to (v), these refer to the assumptions outlined in the author's previous paper (Prokhovnik, 1960). In brief these are

I Equivalence of inertial systems.
II Universal constancy of light-velocity.
(i) Definition of synchronism.
(ii) Definition of "time" of an event.
(iii) Definition of space interval.
(iv) Definition of relative velocity.
(v) Synchronism of clocks in relative motion.

The time of reflection, t^r_A, on A's time-scale was then related to t^1_A and t^3_A by a consistent application of the light-signal hypothesis and it was shown that

$$(t^r_A)^2 = t^1_A t^3_A \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

whence

$$t^r_A = t^m_A \sqrt{1 - \frac{v^2}{c^2}} \quad \ldots\ldots\ldots\ldots \quad (3)$$

It was suggested therefore that if A's light signal reflects the clock reading t^r_B from B's clock, such that

$$t^r_B = t^m_A \sqrt{1 - \frac{v^2}{c^2}},$$

then the clocks must be synchronous in the sense of the definition (v)*; and it was further shown that if the clocks synchronize in this sense according to the observer A, they would be similarly synchronous according to the observer B. Such observers were then said to have a common time-scale.

Combining (1, (2) and (3), we also obtain

$$t^r_A = t^1_A \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}} \quad \ldots\ldots\ldots \quad (4)$$

and

$$t^3_A = t^r_A \sqrt{\frac{1 + \frac{v}{c}}{1 - \frac{v}{c}}} \quad \ldots\ldots\ldots \quad (5)$$

3. Derivation of Transformations

We now deduce the relations between the two sets of co-ordinates of an event at E, obtained by two observers A and B in relative uniform motion.

It will be sufficient and instructive for our present purpose to consider a number of cases where A, B and E are collinear.

As usual we will consider that the two observers are using similar clocks previously synchronized at the instant of their spatial coincidence, and that their respective co-ordinates of any particular event are obtained according to Einstein's conventions (i)* to (iv)*.

We will take the observer A's location as the origin of his inertial reference frame and similarly B's location as his origin. We will refer to the line joining A and B† and its extension in either direction as the common x-axis of A and B where the direction A to B is taken as the positive direction of this axis.

The co-ordinates of a point along this axis according to A will be denoted by x_A, and according to B by x_B.

In accordance with the direction of the common axis, the velocity of B relative to A will be denoted by v, and of A relative to B by $-v$.

3.1. *Case where* E *is collinear with* A *and* B *and stationary relative to* B

Consider an event at E reflected by two light rays, one transmitted by observer A at time t^1_A and returning to him at t^3_A, and the second transmitted by observer B at t^1_B and returning to him at t^3_B.

Then the x and t co-ordinates of the event according to observer B are given by definition according to (ii)* and (iii)*:

$$t^m_B = \tfrac{1}{2}(t^3_B + t^1_B) \quad \ldots\ldots\ldots\ldots \quad (6)$$

and

$$x^m_B = \frac{c}{2}(t^3_B - t^1_B) \quad \ldots\ldots\ldots\ldots \quad (7)$$

Since B and E are relatively stationary, t^m_B is simultaneous (according to Einstein) with the event at E and x^m_B is a constant independent of the time.

According to observer A we have correspondingly

$$t^m_A = \tfrac{1}{2}(t^3_A + t^1_A) \quad \ldots\ldots\ldots\ldots \quad (8)$$

and

$$x^m_A = \frac{c}{2}(t^3_A - t^1_A) \quad \ldots\ldots\ldots\ldots \quad (9)$$

Now the light ray from observer A will reach B at $t^1_A \sqrt{\dfrac{1 + \frac{v}{c}}{1 - \frac{v}{c}}}$, using (4), and, in accordance with Einstein's light velocity principle, will take an additional time $\dfrac{x^m_B}{c}$ to reach E, since B and E are separated by a fixed space interval, x^m_B.

---

† This line may be considered as lying along the path of a light ray transmitted from A to B or vice versa.

Hence, on A's time scale, the event at E is reflected at t^r_A, where

$$t^r_A = t^1_A \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} + \frac{x^m_B}{c} \quad \ldots (10)$$

Similarly on reflection the ray returns to B at $t^r_A + \frac{x^m_B}{c}$, and thereafter behaves like a light signal from B to A; so that, using (5), the ray returns to A at t^3_A, where

$$t^3_A = \left(t^r_A + \frac{x^m_B}{c}\right) \sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} \quad \ldots (11)$$

(10) may be written

$$t^1_A = \left(t^r_A - \frac{x^m_B}{c}\right) \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}} \quad (12)$$

Therefore, using (11), (12) in (8)

$$t^m_A = \frac{t^r_A}{2}\left(\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} + \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}\right) + \frac{x^m_B}{2c}\left(\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} - \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}\right) = \frac{t^r_A + \frac{vx^m_B}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} \quad \ldots\ldots\ldots (13)$$

And in (9)

$$x^m_A = \frac{ct^r_A}{2}\left(\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} - \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}\right) + \frac{x^m_B}{2}\left(\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}} + \sqrt{\frac{1-\frac{v}{c}}{1+\frac{v}{c}}}\right) = \frac{vt^r_A + x^m_B}{\sqrt{1-\frac{v^2}{c^2}}} \quad \ldots\ldots\ldots (14)$$

Now if the clocks at A and B have remained synchronous such that the time of reflection of the event at E is given by the same clock reading according to either time scale, that is

$$t^r_A = t^m_B,$$

then (13), (14) become the familiar relations of the Lorentz transformation, viz.:

$$t^m_A = \frac{t^m_B + \frac{vx^m_B}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}} \quad \ldots\ldots\ldots\ldots (15)$$

$$x^m_A = \frac{x^m_B + vt^m_B}{\sqrt{1-\frac{v^2}{c^2}}} \quad \ldots\ldots\ldots\ldots (16)$$

By eliminating x^m_B and t^m_B, in turn, from (15) and (16) we obtain also the reciprocal relationships.

3.2. *Case where* E, A *and* B *are collinear and have a common time-scale*

We will assume that E moves with velocity u_A relative to A and with velocity u_B relative to B, and that A, B and E were simultaneously spatially coincident at zero time according to the similar clocks carried by A and B. We might also imagine a similar clock associated with E similarly synchronized with those at A and B.

Now consider an event at E simultaneous with the reading t_E on the clock at E. The event is reflected by a light-ray from A whence A's conventional time, t^m_A, of the event is related to his " geometric mean time " t^r_A by

$$t^r_A = t^m_A \sqrt{1-\frac{u_A^2}{c^2}} = t_E \quad \ldots\ldots (17)$$

since A and E have a common time-scale.

Similarly B's conventional time of the event t^m_B is related to his t^r_B by

$$t^r_B = t^m_B \sqrt{1-\frac{u_B^2}{c^2}} = t_E, \quad \ldots\ldots (18)$$

B and E also having a common time-scale.

Hence from (17) and (18),

$$t^m_A = \frac{\sqrt{1-\frac{u_B^2}{c^2}}}{\sqrt{1-\frac{u_A^2}{c^2}}}\, t^m_B \quad \ldots\ldots\ldots (19)$$

$$= \frac{t^m_B + \frac{Ux^m_B}{c^2}}{\sqrt{1-\frac{U^2}{c^2}}}, \quad \ldots\ldots\ldots\ldots (20)$$

where

$$U=\frac{u_A-u_B}{1-\frac{u_Au_B}{c^2}}, \quad \ldots\ldots\ldots\ldots \text{(21)}$$

and using $x^m_B=u_Bt^m_B$ in accordance with (iv)*. Using also $x^m_A=u_At^m_A$, (19) becomes

$$x^m_A=\frac{\sqrt{1-\frac{u_B^2}{c^2}}}{\sqrt{1-\frac{u_A^2}{c^2}}}u_At^m_B$$

$$=\frac{x^m_B+Ut^m_B}{\sqrt{1-\frac{U^2}{c^2}}} \quad \ldots\ldots\ldots\ldots \text{(22)}$$

with U as before.

In order that a common transformation should apply to the cases of 3.1 and 3.2 it is necessary that U should be equivalent to v, the velocity of B relative to A. This is easily verified since from (15) and (16) we obtain

$$\frac{dx^m_A}{dt^m_A}=\frac{\frac{dx^m_B}{dt^m_B}+v}{1+\frac{v}{c^2}\frac{dx^m_B}{dt^m_B}},$$

that is

$$u_A=\frac{u_B+v}{1+\frac{vu_B}{c^2}}$$

and hence

$$v=\frac{u_A-u_B}{1-\frac{u_Au_B}{c^2}} \quad \ldots\ldots\ldots \text{(23)}$$

which compares with (21). Thus the identity of U and v is entirely consistent with the rest of the argument.

3.3. *General case for* E, A *and* B *collinear*

As in 3.2 we will denote the velocity of E relative to A by u_A and relative to B by u_B. We assume here that the observers A and B only, have a common time scale.

However, there must exist a location C, along the line ABE, in E's inertial system, such that A, B and C were simultaneously spatially co-incident. We can therefore imagine an observer at this point C who shares a common time-scale with A and B, is stationary relative to E and hence has a velocity of u_A relative to A and u_B relative to B.

Then, according to (15) and (16), the co-ordinates of an event on E, as measured by A and C, are related by

$$x^m_A=\frac{x^m_C+u_At^m_C}{\sqrt{1-\frac{u_A^2}{c^2}}}$$

and

$$t^m_A=\frac{t^m_C+\frac{u_Ax^m_C}{c^2}}{\sqrt{1-\frac{u_A^2}{c^2}}};$$

and the co-ordinates of the same event, as measured by B and C, are related by

$$x^m_B=\frac{x^m_C+u_Bt^m_C}{\sqrt{1-\frac{u_B^2}{c^2}}}$$

and

$$t^m_B=\frac{t^m_C+\frac{u_Bx^m_C}{c^2}}{\sqrt{1-\frac{u_B^2}{c^2}}}.$$

Eliminating x^m_C and t^m_C from these four equations we obtain

$$x^m_A=\frac{x^m_B+vt^m_B}{\sqrt{1-\frac{v^2}{c^2}}}$$

and

$$t^m_A=\frac{t^m_B+\frac{vx^m_B}{c^2}}{\sqrt{1-\frac{v^2}{c^2}}}$$

where v is the velocity of B relative to A and as in 3.2

$$v=\frac{u_A-u_B}{1-\frac{u_Au_B}{c^2}}.$$

The combining of the results of 3.1 and 3.2, in this way, to obtain the more general result demonstrates incidentally that a succession of two Lorentz transformations is itself a Lorentz transformation. This reflects an important feature of the Lorentz transformations, namely, that they form a group.

4. Discussion

The above derivation of the Lorentz transformations is both cumbersome and limited. However, it serves to demonstrate that the light signal hypothesis together with the definition relating to synchronism, are entirely consistent with the interpretation of the Lorentz transformations as linking two sets of specific measurements of an event. It is seen that the light signal hypothesis enables us to apply a criterion of simultaneity for observers in relative motion and this criterion is applied in the derivations, particularly in cases 3.1 and 3.2, to yield the expected results.

The criterion depends on distinguishing between the time of reflection of the event and the conventionally measured time. In the simple circumstances considered in Part 2 the relation between these two times is that between the geometric and arithmetic means of the initial and final readings of the signalling process reflecting an event. In more general circumstances this difference provides the different measurements of the co-ordinates of an event by observers in relative motion, and the relation between these two sets of co-ordinates is given by the Lorentz transformation, precisely if the observers' clocks have remained synchronous.

The reciprocity of the observers' measurements can now no longer suggest paradoxes ; it can be considered as a consequence of the equivalence of all inertial systems with regard to time, where for each observer the conventional measure of time and space intervals in the inertial system of his opposite number will be less than the corresponding proper intervals.

The correction of these measurements is effected precisely by the Lorentz transformation which can thus be seen as having more than merely theoretical significance.

Thus if our interpretation is correct, radar measurements should be corrected in this way if relatively moving bodies are involved. These measurements are based on the arithmetic mean of the times of transmitting a beam and receiving its echo. However, in his definition of synchronism Einstein himself emphasized that this arithmetic mean time will coincide with the time of reflection only if the reflected object is stationary relative to the observer. We have shown that if such is not the case then the time of reflection t_A^r is related to the arithmetic mean time t_A^m by (3), viz.

$$t_A^r = t_A^m \sqrt{1 - \frac{v^2}{c^2}}.$$

This correction would require the determination of the body's relative velocity from a sequence of radar contacts. For relative velocities small compared to that of light, the necessary correction would of course be negligible. However, for radar contacts with heavenly bodies the correction may have significance.

Our approach implies that the synchronism of two clocks is not affected by their relative motion. It also suggests (definition (v)*) a method of synchronizing clocks in relative motion even when these are not spatially coincident. This should make it possible to investigate experimentally the nature of light propagation between observers in relative motion. It may also lead to a better understanding of the relation between the " clocked " velocity‡ and its corresponding value when determined by Einstein's definition (iv)*.

If the proposed approach to Special Relativity is valid, then its consequences (including the above) will require much deeper consideration. Meanwhile we have attempted to show that our approach is not only a consistent alternative to the conventional view of Special Relativity, but also that it permits of positive physical interpretations of interest and importance.

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‡ This involves clocking a body at two different points of a given inertial system.

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An Occurrence of Buried Soils at Prospect, N.S.W.

C. A. Hawkins and P. H. Walker

(*Received February* 2, 1960)

Abstract.—Examination of a cutting at the base of the Prospect Hill dolerite intrusion, N.S.W., showed a vertical sequence of five soil layers or their remnants. Each of the four upper layers, formed on dolerite detritus, represents a phase of landscape instability and erosion when fresh parent materials were laid down followed by a phase of landscape stability when soil formation took place. The fifth or deepest soil was formed on Wianamatta shale country rock and was truncated at the onset of the unstable phase which gave rise to layer four.

This record extends the finding of periodicity in soil formation to the coastal environment.

Introduction

An excavation made by the Metropolitan Water, Sewerage and Drainage Board on the west side of the basic igneous intrusion at Prospect Hill was examined by the authors in October, 1957. The exposure, see Plate I, revealed a considerable depth of soil material in which there was evidence of five separate soil systems arranged in a well-defined stratigraphic sequence. In this paper a description of the soil materials in the excavation is presented and the significance of the data discussed.

Prospect Hill was formed by the localized intrusion of a Pliocene dolerite (essexite) into the extensive Triassic, Wianamatta shales. The intrusion is still partially overlain by the shale, see Figure 1; however, that part of the intrusion which is of interest to this investigation has been exposed and forms the upper slope of the hill in which the excavation was made.

The mineralogy of the dolerite has been described in detail by Jevons, Jensen, Taylor and Sussmilch (1911). The percentage silica lies between 40 and 50 and the minerals are predominantly feldspars (plagioclase), augite, olivine and biotite.

Soils on the Prospect Intrusion

The lower slope soils have been previously described by Brewer (1947) and the soils of the catenary sequence have been compared with adjacent catenas on shale (Walker, unpublished data*).

Soils on the dolerite catena range from reddish chocolate soils in the upper slope to prairie soils in the mid-slopes, then to black earths. Shale catenas consist of red podzolic soils in the upper and mid-slopes with yellow podzolic soils as the end number.

Brewer (1948) found that the boundary between the shale and dolerite was characterized by a zone of soils developed on a mixture of weathered shale and dolerite. He suggested, as the causal process, soil creep in which base-rich material moved downhill and became

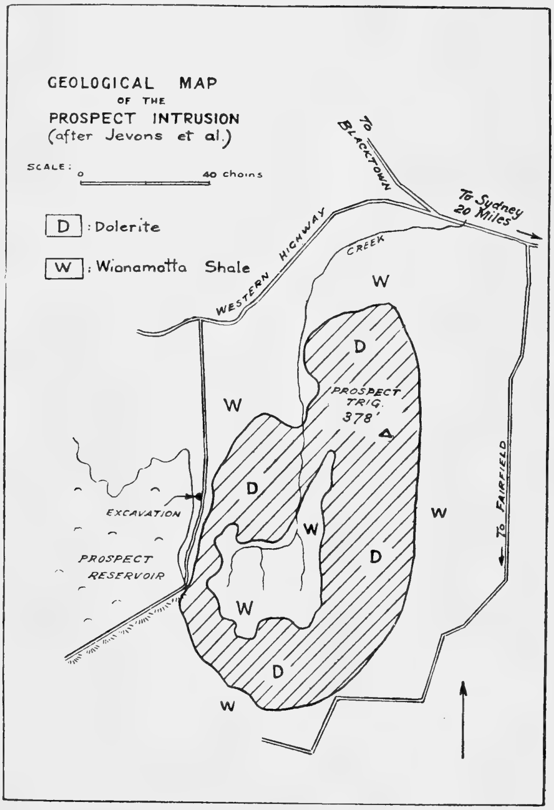

Fig. 1

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* Soil survey of the County of Cumberland, N.S.W.—Report, N.S.W. Department Agriculture.

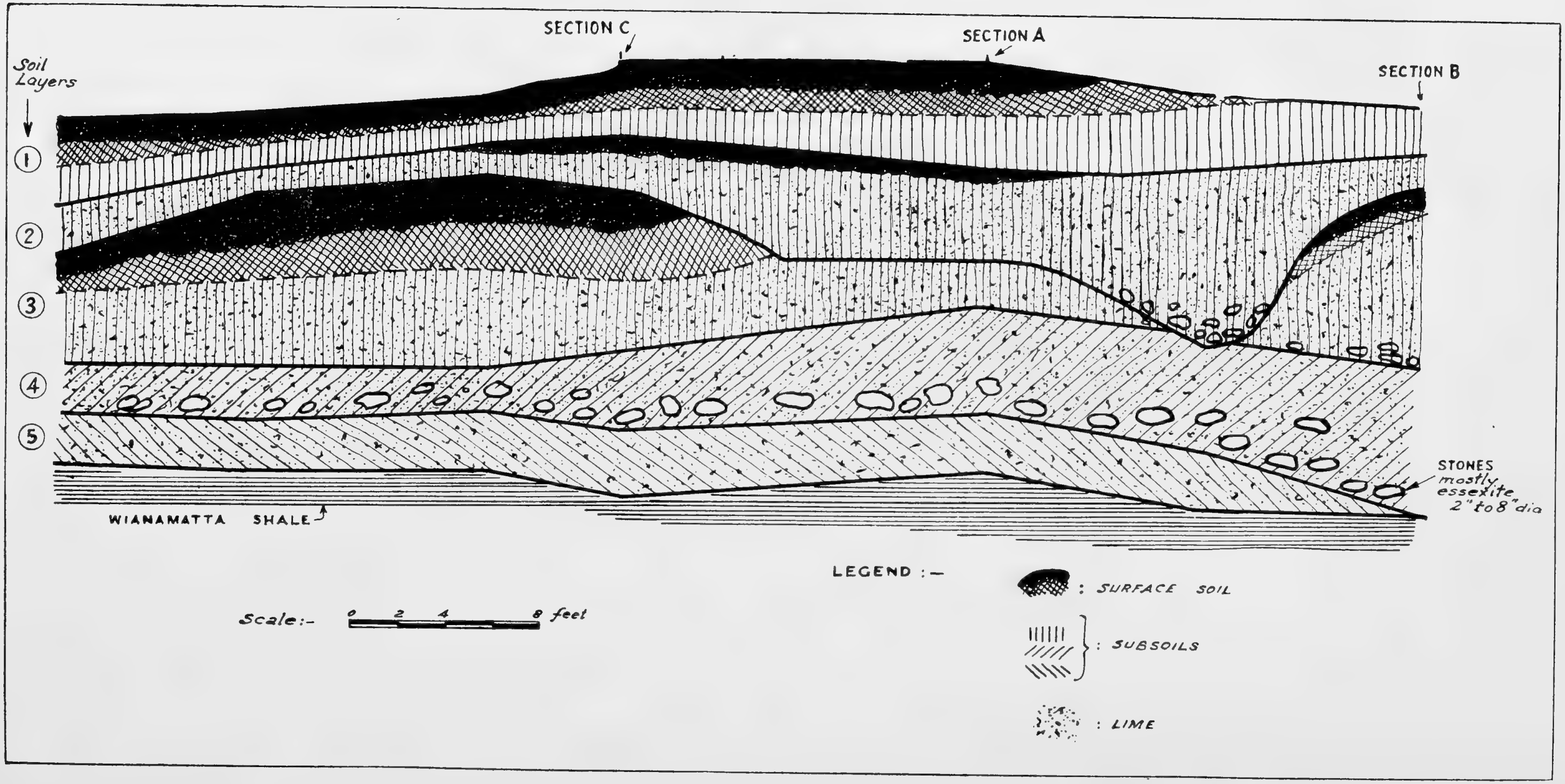

FIG. 2
Scale diagram of Prospect cutting.

intimately mixed with shale on the lower slopes. Brewer's evidence of soil creep, involving the downslope movement of soil materials, is interesting in view of the periodic erosion and deposition proposed herein.

Layered Soils in the Excavation

The location of the excavation is shown in Figure 1. It is situated at the base of a long slope of maximum angle 17–20°. The foot of the cutting penetrates several feet into unaltered shale and is below the present water level of the reservoir.

Preliminary observations of the excavation indicated five separate soil layers above the shale bedrock. The main soil layers can be seen in the photograph of Plate I, and the whole soil layer sequence has been drawn to scale in Figure 2. The top three of these were separated because of darkened zones of organic matter accumulation presumed to be the result of surface exposure. Each of the three soil layers had horizons similar to those of the Black Earth great soil group (Stephens, 1956) and each was formed largely from dolerite material with a slight admixture of hardened shale fragments. The fourth layer was also developed from doleritic material, copious rounded stones up to 8 inches in diameter occurring throughout. These dolerite stones appeared to be water worn and had a marked white, weathered rind which was absent in the rock fragments of overlying layers. Layer 4 did not have a dark organic surface, due it was thought, to truncation of its upper profile during the erosion and deposition associated with layer 3. Layer 4 was lime-rich and in this respect resembled the lower horizons of overlying materials; it is probable therefore that the soil of layer 4 was also a black earth. Layer 5 was typically a shale-derived material and again only a stump of the original profile remained. In this case, however, the soil material passed gradually into bedrock, suggesting *in situ* weathering from shale.

It is important in studies of buried soils that evidence be presented confirming the proposition that the layers are in fact separate soils. In this study the clarity of the boundaries between layers and the kind and trends in soil properties were used as evidence. These properties are organic matter, clay and lime, pedality, oriented clay coatings and segregations of iron etc. The distribution of soil properties with depth indicates accumulations or depletions with respect to a particular surface and distinguishes a soil from a fresh, pedologically unmodified deposit.

Generally the boundaries separating soil layers were sharp and easily observed by eye. With all the soil materials it was possible to find immediate transitions (over 2–3 inches) from a state of unorganized and unweathered C horizon material to underlying soil in which weathering and segregation of constituents was considerably greater, e.g. a B-horizon. Compared with the abrupt changes when passing from one layer to another, the rate of change of soil characteristics within each layer was gradual.

A number of observable profile trends were followed throughout all layers. These were colour (in the moist state), particularly as it indicated surface organic accumulation, texture, structure, clay surfaces, lime and the state of alteration of C horizon minerals.

Layers 1, 2 and 3 each had clearly defined, dark coloured, upper horizons although these were not entire across the cutting. The dark colours graded to browns and yellow browns in the B-horizons. For example, layer 3 at section B in Figure 2 was 10YR 2/2 in its A horizon and graded through 10YR 3/3 and 10YR 4/3 to 10YR6/8 in the lower B horizon. Layers 1 and 2 had similar colour trends. Layers 4 and 5, without A horizon remnants, had B horizon features and in layer 4, the colours were mottles of 10YR 4/4 and 10YR7/1 while in layer 5 (on shale) they were 7·5YR6/8 and 7·5YR7/0.

All soil materials were in the clay texture range, the usual profile trend being from medium clay in the A and upper B horizon to light clay, often with coarse sand and gravel in the lower B and C horizon.

Structure was strongly developed in the upper horizons of layers 2 and 3 and to a less extent in the surface of soil 1. A strong grade of lenticular or fine blocky structure gradually gave place to a weak grade of 2 × 4 inch prismatic structure in the lower B-horizon, and where there was sufficient depth of profile (layers 2 and 4), the original depositional laminations were observed in the C horizon. Generally, the layers 4 and 5 showed variable, weak structure.

The degree of segregation and eluviation of clays within a layer was estimated by the ultimate fineness of peds (natural aggregates) about which glossy surfaces were entire. In layers 3 and 4, such peds were $\frac{1}{32}$–$\frac{1}{16}$ inch incross the zones of maximum clay, indicating a high degree of organization. The size of peds increased to $\frac{1}{2}$–1 inch in the lower horizons of

TABLE 1

Analytical data for the layered soils on Prospect Hill taken from the sampled sections A, B and C of Figure 2

Section	Soil Number	Depth (inches)	Horizon	pH 1 : 5	Organic Carbon %	Lime %
A	Soil 1	0–10	A	7·1	1·15	0·10
		20–25	B	7·9	0·37	0·13
	Soil 2	(?) 51–56	A–B	8·3	0·09	2·5
		80–86	BC	8·5	0·13	0·50
	Soil 3	116–120	B	8·8	0·07	9·1
		127–130	BC	8·8	0·07	3·0
	Soil 4	135–138	B	8·6	0·05	7·8
		155–157	C	8·8	0·04	4·7
	Soil 5	182–186	C	9·1	0·01	2·1
B	Soil 1	14–18	B	8·2	0·11	6·1
	Soil 2	(?) 36–39	BC	8·2	0·09	0·63
	Soil 3	48–52	A	8·6	0·23	4·1
		72–75	B	9·1	0·13	6·5
		116–120	C	8·6	0·06	12·8
C	Soil 1	9–12	A	6·8	1·76	0·18
		36–39	B	6·5	0·45	0·40
	Soil 2	(?) 40–50	A	8·0	0·11	0·36
		55–59	B	7·9	0·02	0·65
	Transition	72–76		8·5	0·02	4·1
	Soil 3	103–106	A	8·7	0·26	6·0
	Soil 4	150–156	B	8·9	0·03	10·0

these layers. Ped size in layers 2 and 5 was coarser (¼ inch) than in 3 and 4, whilst in layer 1 clay surfaces were more widely spaced again and sporadic. It would appear from these data that there are zones within layers 3 and 4 which are more highly organized than layers 2 and 5 and that layer 1 has the least segregation of all the layers.

Lime distribution (see Table 1) was variable within each layer laterally but where sufficient depth of a layer occurred, definite trends were evident in vertical section within each layer. Where some of the layers were thin and more lime-rich, secondary accumulations continued into the underlying layer, so that in places, buried organic-rich A-horizons became the BCa. horizon for the layer above. Layer 1 had least lime, layers 2 and 3 had considerable lime in the powdery and concretionary form, and layer 4 had the heaviest accumulations. Layer 5 had lime which appeared to be derived from layer 4; the accumulations were not found in the general soil mass but in soil cracks and rock bedding planes.

Some of the morphological features have been plotted as depth functions to test the reality of the proposed five-fold subdivision of the excavation.

Munsell colour values from profile section B have been plotted in Figure 3. Colour value indicates darkness of soil colour in relation to grey and decreases as the effect of surface organic additions becomes greater. Apart from the darkened zone of soil layer 1, the sudden reversal of profile trends at 5 feet and 10 feet shows the presence of buried surfaces belonging to soil 3 and soil 4 respectively. There is no evidence of soil 2 as a distinct layer.

In Figure 4, the ultimate ped size is plotted against depth at section A, Figure 2. Ultimate

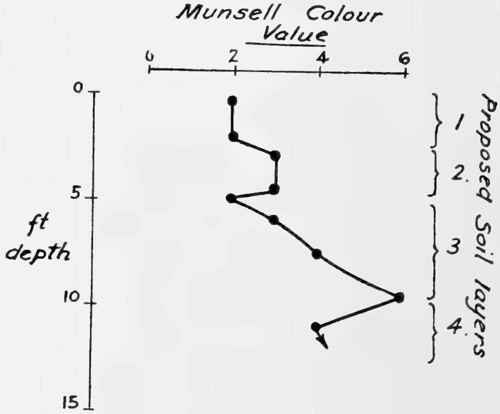

FIG. 3

Munsell colour values plotted against depth for Section B (Fig. 2) at Prospect

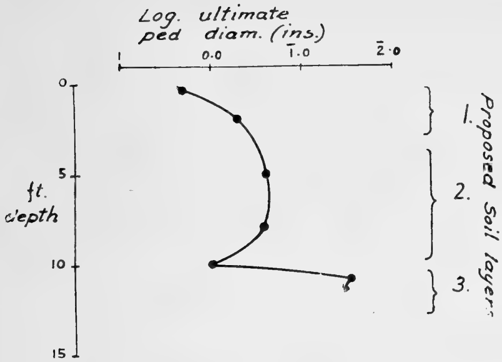

FIG. 4

Changes in ped diameter with depth at Section A (Fig. 2)

peds are the minimum size of ped about which an entire coating of colloid occurs. The diameter of ultimate peds indicates the degree of organization of soil colloids ; the greater the organization the smaller the diameter. The upper 10 feet of soil in Figure 4 shows a typical plot for a single profile with a colloid maximum at 6–7 feet. There is no evidence of a maximum in the colloid of soil 2 in this section. At 10 feet there is an abrupt change to a more highly organized state of soil layer 3.

Percentage $CaCO_3$ data in section A have been taken direct from Table I and plotted in Figure 5. The three maxima correspond to the proposed BCa horizons of soil layers 2, 3 and 4 and indicate that at least three separate dolerite-derived soil layers are present above the weathered shale. Once again there is no evidence of a double soil profile within the zone proposed for soils 1 and 2.

The depth function graphs give reasonable support to the proposal that buried soils occur in the Prospect excavation. Soil layers 1, 3, 4 and 5 are readily distinguishable, however it is difficult to establish the separateness of soil 2 by depth function graphs. Its inclusion in Tables 1 and 2 and in the diagrams is based on field observations only.

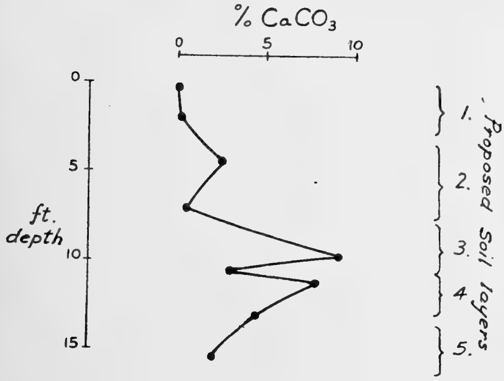

FIG. 5

Depth functions for $CaCO_3$ in Section **A** (Fig. 2)

Soil pH, organic carbon (Walkley-Black) and lime data for each of the soils is recorded in Table 1, with a note of the genetic horizon from which each soil sample was taken.

Discussion

It is evident that the layered soil sequence at Prospect represents successive periods of soil formation on erosional materials, since the oldest soil system was developed on shale, while the four younger systems were developed on dolerite detritus. The truncation of the buried layers, together with the gravelly nature of their lower horizons, is evidence that between the periods of soil development there were periods of erosion and deposition. The deep

TABLE 2

Soil and hillslope history at Prospect, starting from the oldest events

Surface history	Soil layer number
Deep weathering of the Wianamatta shale country rock to a profile with a red and grey deep subsoil	5
Erosion and truncation of soil layer No. 5 and superposition of doleritic detritus containing rounded boulders.	
Stabilization and deep weathering of the dolerite detritus with the mobilization and deposition of abundant lime which percolated into the relic shale soil below	4
Erosion and truncation of soil layer No. 4 and superposition of an even veneer of doleritic detritus containing gravels.	
Stabilization with deep and intense weathering of the dolerite detritus, with deep movement of secondary lime, and great mobilization of colloid weathered from primary minerals. Black earth profile developed	3
Partial erosion and truncation of soil layer No. 3 with deep gullying and deep deposition of a gravelly dolerite detritus in some places and a thin veneer in others.	
Stabilization with relatively shallow weathering and slight mobilization of colloid and secondary lime (?). Black earth profile developed (?)	2
Mild truncation of soil layer No. 2 and deposition of a relatively even veneer of clayey detritus (?).	
Stabilization with shallow weathering and very slight mobilization of colloid and secondary lime. Black earth profile developed as the present surface . .	1

incision of layers at several places in the excavation, together with the gravels, indicates hill-wash and channel cutting as the removal processes, with perhaps some form of soil creep (see Brewer, 1948) filling in with finer materials and smoothing off the hillslope surface.

The soil history of Prospect Hill is one of periodic soil development within layers of erosional origin. Each of the four younger soil systems originated with deposition which resulted from erosional instability. For each deposit soil development became the dominant process, necessarily under conditions of erosional stability. This soil development ceased as erosion again became predominant and the soil was truncated and/or buried as a new layer and soil system came into being. The sequence of events is summarized in Table 2. Butler (1959) has outlined the principles of periodic soil development as evidenced by buried soil surfaces. Van Dijk (1959) has described the periodic, or " cyclic ", soil surfaces in the Canberra area. It is clear that the sequence of soils at Prospect can be likened in principle to the Canberra situation, even though the soils are different and the age of the sequences could be of a different order. It is significant that the Prospect data extend the observed erosional origin and periodic development of soils in south-eastern Australia to the coastal environment.

Acknowledgments

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Explanation of Plate I

Photograph of the excavation at Prospect, showing a sequence of layered soils developed on dolerite detritus over shale bedrock. The soil layers are numbered from 1, the youngest, to 5, the oldest.

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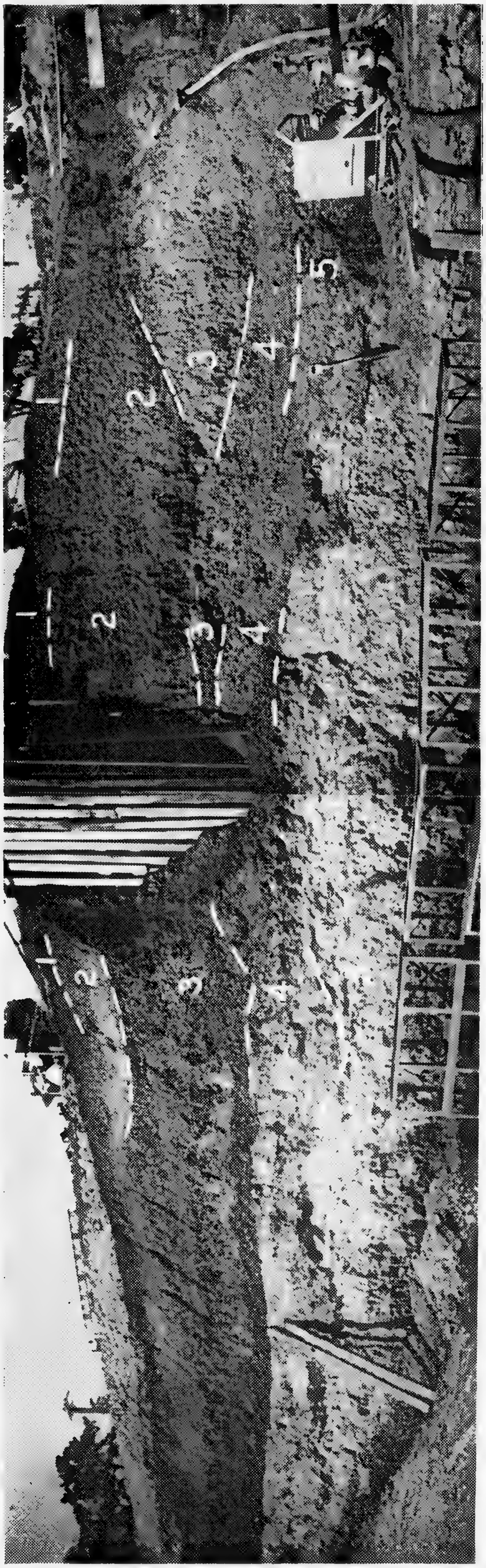
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Coking Characteristics of Selected Australian and Japanese Coals

C. E. Marshall and D. K. Tompkins

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Abstract—A laboratory-scale investigation of the coking characteristics of Australian and Japanese coals, both individually and in blends, has indicated their relative suitability for blending in the production of metallurgical coke.

The value of small-scale coking tests is discussed briefly and the importance of inherent seam characteristics, methods of charge preparation, controlling size and maceral distribution, and the specific conditions of carbonization, are emphasized. Also of critical significance is the temperature at which charges are introduced to the furnace ; despite substantial chemical and physical differences in the coals studied it was possible to accept a uniform " standard " charging temperature which appeared suitable for the majority of coals in the production of optimum quality coke in small-scale studies.

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Introduction

In the majority of heavy industrial communities, diminishing resources of premium grade coal and intensifying competition from other sources of fuel and power have emphasized the need for the greatest possible efficiency in production, preparation and utilization of the solid fuels. Furthermore, increased efficiency, leading to greater production capacity in the mines, has intensified both local and international competition for more critical markets which are generally either waning, or expanding at a rate relatively slower than the coal producing industries.

Depletion of reserves of the most suitable premium grade coals has been generally and most severely felt in the carbonization industries, more particularly those concerned with the production of metallurgical coke. The more exacting demands of modern blast furnace and foundry practice, often stimulated by the enforced utilization of inferior ores and other raw materials, require continuous scientific and technological development of methods for the production of metallurgical cokes from coals formerly considered unsuitable for this purpose.

The situation of the Japanese heavy industries in relation to coal supplies is particularly difficult. The domestic seams are of Tertiary age and vary widely in rank and quality, frequently in response to a particular or complex geological environment, which may also adversely condition both the efficiency and economy of extraction.

Coals suitable for the production of metallurgical coke are in particularly short supply and a considerable proportion of the annual requirements must be imported. Economic, social and technological factors, however, determine the national policy which requires that a proportion of " local " coal must be used in the production of metallurgical coke ; consequently the " compatibility " or " blending characteristics " of the domestic Japanese coals and the imported fuels are of considerable importance.

In New South Wales, efficient and economic coal production capacity has exceeded the requirements of local industry, thus making successful entry into overseas markets essential to the welfare of the coal mining industry and the balanced development of the national economy.

It was largely in response to this mutually important and " complementary " situation of the Australian and Japanese coal producing and consuming industries that the present introductory laboratory-scale investigation was proposed, and undertaken with the co-operation and part financial assistance of the Joint Coal Board.

Previous and current experience (e.g. Marshall, **1958** ; Tompkins, **1959** ; Branagan, **1959** ; Marshall, Tompkins, Branagan and Sanderson, **1960**) has demonstrated that carefully controlled laboratory-scale methods of coke production and testing are reliable and capable of critical discrimination ; combined with the results of fundamental petrographic, physical and chemical research they permit evaluation and interpretation of current and projected industrial practice. The quantitative results of the small-scale investigation cannot be integrated directly with those of the industrial operation but they do permit rapid and economic study of important factors in coke production, and help to establish trends which may be used as guides to improved industrial practice.

It is unfortunate that the Permian (bituminous) coal seams of Australia are generally (but not invariably) characterized by relatively higher proportions of inherent or dispersed sedimentary mineral matter than are the high-grade products of other industrialized communities with which they must compete. As the character and proportions of mineral matter are important factors in determining the value of a coal intended for the production of metallurgical coke, this situation emphasizes the need to strengthen other technological and economic claims to an adequate share of the available international markets, and re-emphasizes the importance of fundamental and applied research for the future of the Australian coal industry.

Objectives of the Investigation

The primary purposes of this study were to determine with the least possible delay which of the more " eligible " coal seams of New South Wales would be most suitable for blending with typical Japanese coals used in the production of metallurgical coke, and what improvement might be expected in the physical quality of the resultant coke over that produced from the Japanese coal when coked alone.

For this purpose, the Japanese authorities supplied four bulk representative samples from the Akahira, Ohyubari, Futase and Takashima mines, the first two situated in Hokkaido Province and the others in Kyushu. As representative of the potentially more interesting seams of New South Wales, the Joint Coal

Board submitted bulk samples of washed coal from the Bulli seam of the South Coast and Burragorang Valley, as well as from the Victoria Tunnel, Young Wallsend, Borehole and Greta seams of the Northern Coalfield. For purposes of comparison, the University Coal Research Group included in the series a sample of the middle section of the Liddell seam (excluding stone bands) from the Foybrook open cut of the Singleton-Muswellbrook coalfield, upon which detailed carbonization studies were already well advanced. The Liddell seam is a representative of the Tomago (lower) Stage seams of the New South Wales Upper Coal Measures.

Previous experience gained through detailed, laboratory-scale carbonization studies of individual coal seams has demonstrated that coking characteristics are affected by many related and often mutually sympathetic factors, including the inherent petrological, physical and chemical characteristics of the seam; induced modification of these characteristics as a result of preparation for the coke oven; and the specific conditions of carbonization (Marshall, 1958). Both individual and sympathetic variation in these factors induces changes in the physical properties of the coke produced, including the " hardness " or " toughness " of the actual coke substance, the size and distribution of gas cavities in relation to " wall " thickness, and breakage characteristics resulting from the nature and distribution of joint and fracture planes.

For the most satisfactory evaluation of the blending properties of the Australian and Japanese coals, it would have been desirable to complete first, a comprehensive and progressive study of the individual character and coking potential of all seams concerned, as revealed by controlled and progressive variation in each of the factors likely to affect coke quality. The results of these individual seam studies would have been of great value for the necessarily much more extensive and much more critical development of two- and three-component blend studies. Unfortunately, to complete in any reasonable time a project of such scale was much beyond the material resources and time available. Consequently, certain limitations of study were imposed, greatest attention being directed to those aspects and conditions which previous experience has indicated as being of greatest potential importance. The same limitations largely confined the study to blend systems involving two components; one three-component blend series was investigated for each of the four Japanese coals available, the two Australian coals being selected on the basis of previous study.

Range and Limitations of Study

The physical characteristics of a coke may be greatly affected by the particle size consist and distribution in the oven charge, factors which in turn may be significantly related to overall petrographic composition, coal type and maceral distribution (Burstlein, 1955; Marshall *et al*, 1958; Tompkins, 1959; Branagan, 1959). For medium and high volatile bituminous coals in particular, the proportions and distribution of both the coking constituents (essentially vitrinite, resinite and exinite) and the " inerts " (dominantly fusinite, micrinite and in some circumstances mineral matter) in the oven charge are of very considerable importance. Consequently in fully critical and comprehensive coking studies, there should be determined not only the overall petrographic composition, but also both coal type and maceral proportions in relation to coal-particle size distribution in the oven charge.

Detailed investigation of these important and related factors requires carefully controlled preparation of very many individual oven charges, in which both the size consist and petrographic character of each size fraction are varied and accurately determined; investigation of the products of coking individual and progressively cumulative size fractions can also be very informative. However, previous experience has indicated that when coked under the conditions of the present laboratory study, the majority of medium and high volatile coals yield most satisfactory cokes from oven charges in which the coal has been reduced by controlled breakage to pass a 3 mm mesh ($\frac{1}{8}''$) with minimum production of finer sizes. For urgent reasons of time economy, this size-condition of the oven charge was adopted as standard in all the blend studies. Under these circumstances the petrographic phase of the investigation was limited to the overall micrometric (maceral) analysis of representative samples of the broken coal as prepared for carbonization. More detailed studies of the important petrographic-size consist characteristics will be undertaken later, as they appear to be of considerable importance in certain of the coals of contrasted coal types.

Factors in the thermal cycle of coking are often related and mutually disturbing. For convenience, those which appear to be most significant in determining coke quality may be referred to oven temperature at charging and rate of heating (potentially closely related in the initial stages of heating) as well as final temperature and period of coking (total and " soaking " time). From previous detailed study results referred to above, temperature of charging (especially in relation to plastic range and properties of the coal) appears to be of considerable significance to the quality of the coke produced from medium- and high-volatile bituminous coals. Consequently, this relationship was investigated for each of the individual seams, with the two-fold objective of deriving a " standard " charging temperature for the blend studies proper, and evaluating the possible effects upon coke quality, of any departure from either the general " standard " or the individual " optimum ".

Also based upon previous and current study results, standards were adopted for the apparently rather less significant final rate of heating, coking temperature and " soaking " period, individual investigation of the influence of these factors upon the quality of coke produced from each coal not being practicable in the time available.

Study Procedures

With the exception of the Liddell coal each of the samples for investigation was submitted in bulk after plant preparation. Consequently, no direct relationship can be established between study results and the character and coking potential of the raw coal and all comment upon characteristics of the seams must be considered as subject to possible qualification. More especially does this bear upon coal " strength " and fracture characteristics as indicated by the results of the " standard " laboratory preparation and the possible effects upon coke quality (both beneficial and maleficial) of material rejected in the course of cleaning.

Preparation of the Coal for Coking

Each coal submitted was prepared for carbonization by identical " standard " procedures. After preliminary screening to secure material already less than 3 mm ($\frac{1}{8}''$) mesh, the bulk sample was broken progressively by roll crusher, roll separation being successively reduced between passes to a final spacing of 3 mm ; all material less than 3 mm was screened out after each crushing and reserved for the final sample. In this way, each of the bulk samples was reduced entirely to $-\frac{1}{8}''$ with the minimum production of fine material (Table 1,

Table 1

Size Consist of all Coals as used in Blend Studies after Standard Preparation

Size Range Tyler Mesh	Australian Coals														Japanese Coals							
	Greta		Liddell		Borehole		Young Wallsend		Victoria Tunnel		Bulli Wollondilly		Bulli Coalcliff		Akabira		Ohyubari		Futase		Takashima	
	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum	%	% cum
− 6+ 10 . .	51·5	51·5	61·7	61·7	44·1	44·1	58·6	58·6	59·6	59·6	54·2	54·2	39·4	39·4	33·9	33·9	49·9	49·9	57·5	57·5	43·7	43·7
−10+ 20 . .	26·6	78·1	19·5	81·2	25·8	69·9	22·0	80·6	20·9	80·5	23·6	77·8	24·2	63·6	26·5	60·4	24·9	74·8	24·3	81·8	25·8	69·5
−20+ 35 . .	11·9	90·0	10·9	92·1	17·5	87·4	10·4	91·0	17·4	97·9	17·9	95·7	19·6	83·2	22·6	83·0	13·7	88·5	10·4	92·2	16·4	85·9
−35+ 65 . .	5·1	95·1	4·5	96·6	10·8	98·2	4·4	95·4	1·3	99·2	3·1	98·8	8·8	92·0	9·1	92·1	5·6	94·1	4·1	96·3	8·3	94·2
−65+150 . .	3·0	98·1	2·5	99·1	1·5	99·7	2·8	98·2	0·6	99·8	1·0	99·8	5·8	97·8	4·7	96·8	3·5	97·6	2·4	98·7	3·3	97·5
− 150 . .	1·9	100·0	0·9	100·0	0·4	100·1	1·8	100·0	0·2	100·0	0·2	100·0	2·2	100·0	3·2	100·0	2·4	100·0	1·4	100·1	2·5	100·0

Fig. 1). After final crushing the coal sample was carefully mixed to ensure uniform distribution of particle sizes and coal constituents.

Petrographic Analysis

For the purposes of this investigation, petrographic analysis was limited to the estimation of overall proportions of the major significant constituents (macerals) in micro-preparations representative of the bulk samples. Micrometric analyses were made upon polished sections of representative samples of broken coal as prepared for carbonization mounted in Polylite Resin, aggregate and mean linear intercepts indicating maceral proportions and dimensions. The results of these analyses are summarized in Table 2.

Coke Production

As needed for immediate study purposes, coal charges of approximately seven hundred grams were prepared so as to be properly representative, either of the individual coals, or of their blends in the required, thoroughly mixed proportions. Each charge was coked in a standard covered retort, eight of which could be accommodated in the special oven without significant disturbance of uniform heating conditions. Each specific coke required for study was prepared in quadruplicate. A silit-rod (Globar) type electrical furnace with accurate thermostatic and programme control was used to heat eight charged retorts at a maximum uniform rate of temperature increase of 3·3 C° per minute to a final coking temperature of 1200° C, which in each case was maintained for a period of two hours; adoption of these standards was based upon the results of previous detailed studies. At the termination of each particular coking cycle, the cokes were quenched individually in water, recovered with a minimum of disturbance and oven dried to constant weight at 105° C before testing.

However, as the mechanical quality of coke produced from the majority of bituminous coals appears to be particularly sensitive to charging temperature, initial coking studies of each seam were concerned with an evaluation of this relationship and the possible determination of an acceptable standard charging temperature. In this study series individual charges of each coal were introduced into the oven, which was already raised to a predetermined temperature, the heating rate thereafter being controlled to the standard temperature increase of 3·3 C° per minute up to the final coking temperature of 1200° C, maintained for two hours. The coking cycle was repeated with fresh charges of each coal introduced into the oven preheated to successively higher temperatures up to the final coking temperature of 1200° C.

Discussion of the results of the above study series is reserved for later, but it is appropriate to record here that a " standard " charging temperature of 800° C was adopted for all charges comprising blends of the Australian and Japanese coals.

Coke Testing

After oven drying at 105° C to constant weight, each of the coke samples was weighed so as to provide an estimate of the yield, great care being exercised to avoid breakage of the individual coke fragments.

For the convenient evaluation of the physical or mechanical properties of cokes, a number of simple, quantitative tests have been evolved and are in common use by industry. Laboratory scale modifications of these methods have been developed so as to accommodate the much smaller coke bulk available for testing, and in practice have proved to be very successful in quality discrimination.

Broadly, these tests define the " bulk " mechanical quality of coke by its resistance to degradation by impact (shatter and tumbler stability indices) and by abrasion (resistance to abrasion and tumbler stability indices); the mechanical qualities of the actual coke substance are largely defined by its resistance to impact under special conditions (micro-strength or micro-mechanical indices) and to a qualified extent, by the resistance to abrasion as determined on the bulk sample.

After weighing, each of the carefully dried, individual coke samples was sized, so as to permit estimation of the overall progressive breakage induced by each particular method and then re-combined for actual testing. One complete sample was used for each of the macro- or bulk tests; all tests were run at least in duplicate, and in the few cases where significant differences emerged, the entire study run was repeated. The detailed methods of mechanical evaluation developed for these studies are as follows:

Shatter Index

After preliminary sizing, the entire, re-combined sample was dropped once through a height of six feet on to a thick steel plate and again sized. The reconstituted entire sample was then allowed to fall twice through the same height and again sized. As the final stage of the test the reconstituted sample was allowed to fall three times through a height of six feet and the final coke size distribution determined.

The shatter index adopted for these laboratory scale studies is represented by the percentage of +1″ coke remaining in the sample after the sixth drop. The initial and intermediate sizing permitted estimation of the progressive degradation.

The equipment designed for this test is particularly simple, consisting of a spring-operated trap which ensures uniform conditions of release for the sample, at the top of a 12″ diameter, six-foot long metal tube which effectively prevented scattering of coke fragments during fall or after impact ; the steel impact plate is in the form of a large, flat-based scoop to facilitate handling of the broken coke.

Stability Index

The sample, recombined after preliminary sizing, was rotated end-over-end at 40 revolutions per minute in a standard drum of one gallon capacity, for two periods each of twenty minutes ; the sample was sized at the end of each period.

For the purposes of the present study, the stability index is represented by the percentage of +1″ coke remaining at the end of the test ; an estimate of the progressive degradation was obtained from the preliminary, intermediate and final size consists.

Resistance to Abrasion

This estimate was obtained concurrently with the stability index, the resistance to abrasion being gauged by the percentage of $+\frac{1}{4}$″ coke disclosed in the final size analysis of the drum stability test.

Micro-Mechanical Indices

The technique developed and described by Blayden, Noble and Riley (1937) for the small scale estimation of coke strength has proved particularly useful, the conditions of test providing results which are related more to the physical properties of the coke substance than those of the coke bulk.

The equipment comprises essentially a stainless steel tube of effective internal length of 12 inches, and internal diameter of 1 inch, burnished on the inside and closed by two dust-proof, screw-on caps. Twelve stainless steel balls, each of $\frac{5}{16}$″ diameter, are included with the coke charge in the tube. Coke for examination is sized between 14 and 28 mesh Tyler screens, two grams being required for each test.

The stainless steel tube containing the two-gram sample and the twelve steel balls was rotated end-over-end at 25 revolutions per minute for 32 minutes. At the end of this period, the sample was again sized, the percentage remaining +65-mesh, and the ratio of the proportions +28/+65, being recorded as " micro-strength 65 " and " micro-strength 28/65 " respectively.

As indicated by the consistency obtained in multiple runs, as well as by the discriminatory and progressive character of the results obtained, the laboratory-scale methods developed for both controlled production and evaluation of coke have proved to be very satisfactory. In the majority of the graphs which convey the essential study results, the strength indices are logged independently in relation to the factors under investigation.

It is perhaps unfortunate that these indices, although revealing individually consistent trends, often vary quite independently of each other, and but seldom correspond in the circumstances of their maximum development.

Consequently, virtually every coke of " optimum " quality represents a compromise in physical or mechanical properties. The nature of the industrial processes concerned, the properties of other materials with which it is to be used, the type of plant and conditions of operation, personal experience and preference, will all be concerned in the determination of the particular characteristics required in any industrial coke. Consequently, specific and detailed consideration of all physical properties is normally required in the selection of coke most suitable for a particular purpose. However, for general guidance and ease of comparison, " summary " indices have also been derived by taking the arithmetic mean of all strength indices (" overall strength index ") and the arithmetic mean of all strength indices and coke yield (" overall strength-yield index "). It is recognized that these indices are open to criticism in that the " overall " figures have not been weighted to compensate either for scale differences in the individual indices, or for particular considerations as to their relative significance, such adjustments again being largely matters of personal experience and preference.

RESULTS

The Australian Coal Seams

Micrometric and chemical analyses of the coals of New South Wales included in the blend studies are summarized in Tables 2 and 3. Variation in petrographic composition is substantial (Table 2), the dominant coking constituent vitrinite ranging in content from 50·1% in the Bulli seam of the South Coast to 84·7% in the Young Wallsend seam from Boston Washery; the inerts vary sympathetically.

The chemical analyses confirm the majority of the samples as being of high volatile bituminous coal. According to the A.S.T.M. rank classification the Greta coal is emphatically high-volatile "A" bituminous, the Young Wallsend and Victoria Tunnel coals high-volatile "B" bituminous, while the Liddell and Borehole lie at the boundary of the two classes. Both of the Bulli samples are of appreciably higher rank, the South Coast coal approaching low-volatile bituminous, while the Valley (Wollondilly) sample is best described as medium to high volatile bituminous.

Subject to the qualification already discussed (p. 124), the size consists of the standard prepared samples of these coals generally follow a normal pattern, the Victoria Tunnel and "Valley" Bulli being outstanding, however, in their particularly low proportion of fines. Most susceptible to mechanical disintegration (as evidenced by low proportions of the coarser sizes) were the South Coast Bulli and Borehole seams (Fig. 1).

Charging Temperature and Coke Quality

General

With the exception of the Liddell, all study series employed 200° C increments; it is appreciated that a greater number of smaller increments may have given a somewhat different picture in some cases.

Without exception, the effects of increased charging temperature upon quality of coke produced from the Australian coals were found to be systematic and frequently severe, especially as reflected in the macro-strength indices (shatter, tumbler stability and resistance to abrasion). For these indices, two main "patterns" of variation emerge, each however subject to adjustment and qualification in particular cases.

(a) Progressive and general improvement in the macro-strength characteristics of the coke with successive increments in the charging temperature up to 600° or 800° C; with higher initial temperatures, both shatter index and tumbler stability decline rapidly but resistance to abrasion tends to increase further, but at a slower rate. These trends were exhibited by the coals from the Liddell, Borehole and Victoria Tunnel seams (Figs. 3, 4 and 6).

(b) Initial 200° C increment of oven temperature above that of the laboratory is generally accompanied by deterioration in the macro-strength indices, followed immediately by progressive improvement with charging temperatures up to 600 or 800° C; higher initial temperatures are associated with precipitate decline in shatter index and tumbler stability, while the resistance to abrasion again improved quite significantly. These trends are evident in the coal from the Greta, Young Wallsend, Valley and Coastal Bulli seams (Figs. 2, 5, 7 and 8).

The micro-strength indices may exhibit equally systematic and sometimes sympathetic variation; in other cases these indices vary in an apparently irregular manner, which however, like the macro-strength indices, may be affected by charging temperature in relation to the plastic range.

For ease of study and comparison, all coke strength indices are graphed against the temperature of the oven at which the corresponding coal charge was introduced. The study results of the Australian coals are represented in Figures 2–8 inclusive.

Greta Coal (Fig. 2)

The Greta Coal as supplied from Aberdare Colliery, washed to an ash content of approximately 5%, yielded after standard preparation, a size consist in which the larger material (+20 mesh) was well represented. Micrometric analysis reveals the overall character of the coal as a fine duroclarain (almost a durain) with fairly uniform micro-banding.

As indicated by the properties of the resultant cokes the coal proved to be very sensitive to variations in the temperature of charging. After pronounced minima associated with an initial temperature of 200° C, all three macro-strength indices improved sympathetically with charging temperatures up to 600° C. Charging temperatures above 600° C brought about a progressive and very rapid decline in shatter strength and stability, whilst resistance to abrasion improved gradually to an extremely high value for cokes produced from coals introduced to the oven at

TABLE 2

Petrographic Constitution

Coal	Maceral Proportions—%				Maceral Mean Dimensions—Microns			
	Vitrinite	Exinite	Inertinite	Mineral Matter	Vitrinite	Exinite	Inertinite	Mineral Matter
Greta	54·0	5·4	39·2	1·4	31·0	3·9	36·9	12·9
Liddell	80·9	1·3	16·9	0·9	83·6	3·3	19·1	14·9
Borehole	79·3	1·1	15·5	4·1	90·9	3·5	30·4	11·3
Young Wallsend	84·7	0·7	13·2	1·4	93·9	3·5	34·3	9·0
Victoria Tunnel	62·8	1·3	33·0	2·9	37·8	3·7	21·6	12·5
Bulli Wollondilly	58·4	0·8	40·4	0·4	39·0	3·7	35·5	7·0
Bulli Coalcliff	50·1	0·9	48·5	0·5	30·0	3·7	34·3	7·0
Akahira	90·9	2·1	5·1	1·9	78·3	2·7	15·2	6·4
Ohyubari	84·8	0·9	13·2	1·0	72·8	2·9	30·1	6·8
Futase	91·6	1·6	5·9	1·0	87·0	3·1	14·4	10·9
Takashima	90·1	2·1	5·5	2·3	81·5	3·1	13·7	10·9

TABLE 3

	Australian Coals							Japanese Coals			
	Greta	Liddell	Borehole	Young Wallsend	Victoria Tunnel	Bulli Wollondilly	Bulli Coalcliff	Akahira	Ohyubari	Futase	Takashima
Proximate Analysis (a.d.)											
Moisture	2·5	3·0	3·0	3·2	3·5	2·5	1·1	2·8	1·4	3·0	2·2
Volatile Matter	40·9	36·8	34·2	34·3	32·7	29·2	22·2	41·7	40·2	38·2	43·6
Fixed Carbon	52·3	52·2	52·3	55·0	51·4	62·9	69·5	50·0	51·6	50·4	48·3
Ash	4·3	8·0	10·5	7·5	12·4	5·4	7·2	5·5	6·8	8·4	5·9
Ultimate Analysis (d.a.f.)											
Carbon	82·9	82·4	81·0	83·0	82·8	85·2	89·0	82·3	85·3	82·3	83·8
Hydrogen	5·7	5·8	6·1	5·7	6·0	5·0	5·0	6·2	6·3	6·0	6·3
Oxygen	9·4	9·1	11·0	9·3	9·1	8·1	3·8	8·6	6·0	9·9	7·9
Nitrogen	2·0	2·3	1·9	2·0	2·1	1·7	1·9	2·3	2·0	1·5	1·4
Calorific Value (gross uncorr.)	13,940	12,850	12,580	12,900	12,130	13,830	14,170	13,480	14,290	12,950	13,920
Swelling Index (B.S.)	4	2½	5	5	3	7½	8	5	8	1½	7
Coke Type (G.K.)	G	C	G	G	D	G2	G2	G	G7	D	G4
Total Sulphur	0·70	0·42	0·49	0·36	0·47	0·42	0·38	0·68	0·43	0·32	0·65
Pyritic Sulphur	0·05	0·05	0·02	0·01	0·02	0·01	nil	0·07	0·08	0·01	0·06
Sulphate Sulphur	0·02	0·02	nil	nil	0·02	nil	nil	0·03	0·03	nil	0·03
Phosphorus	0·022	0·066	0·092	0·030	0·097	0·073	0·064	0·048	0·031	0·005	0·032
Ash Analysis											
SiO_2		51·2					50·5	40·6	45·1	57·0	42·5
Al_2O_3		38·9					35·9	22·9	23·3	28·7	26·5
Fe_2O_3		4·4					4·8	6·8	8·1	4·4	5·0
TiO_2		1·0					1·0	1·0	0·8	0·8	1·0
CaO		6·3					2·9	11·3	10·8	4·1	10·9
MgO		0·7					1·0	4·4	2·3	0·3	2·4
P_2O_5		1·90					2·04	2·02	1·04	0·14	1·25
SO_3		3·6					1·2	7·9	6·1	2·0	7·0
K_2O+Na_2O		0·7					0·7	3·0	2·5	2·5	3·1

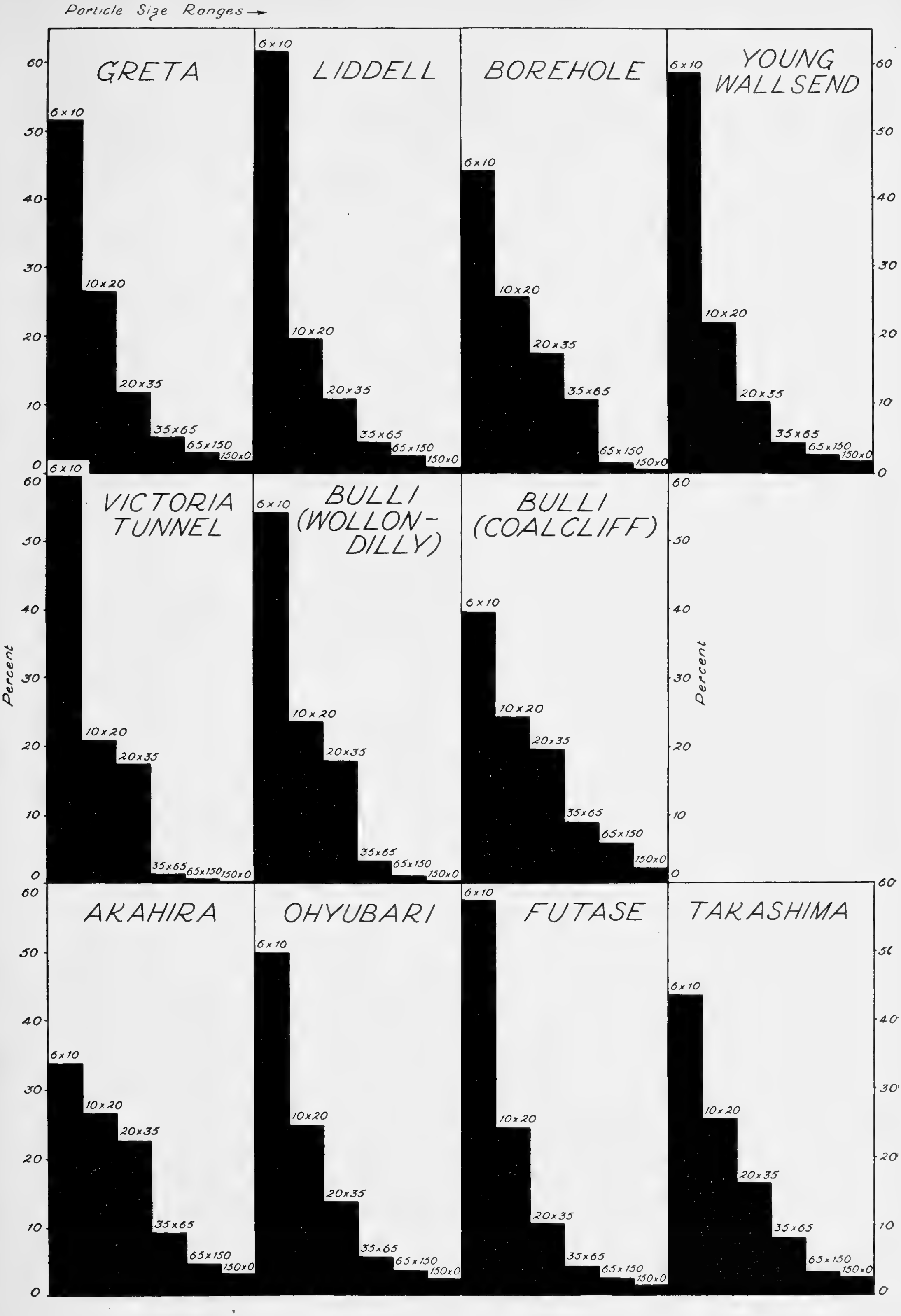
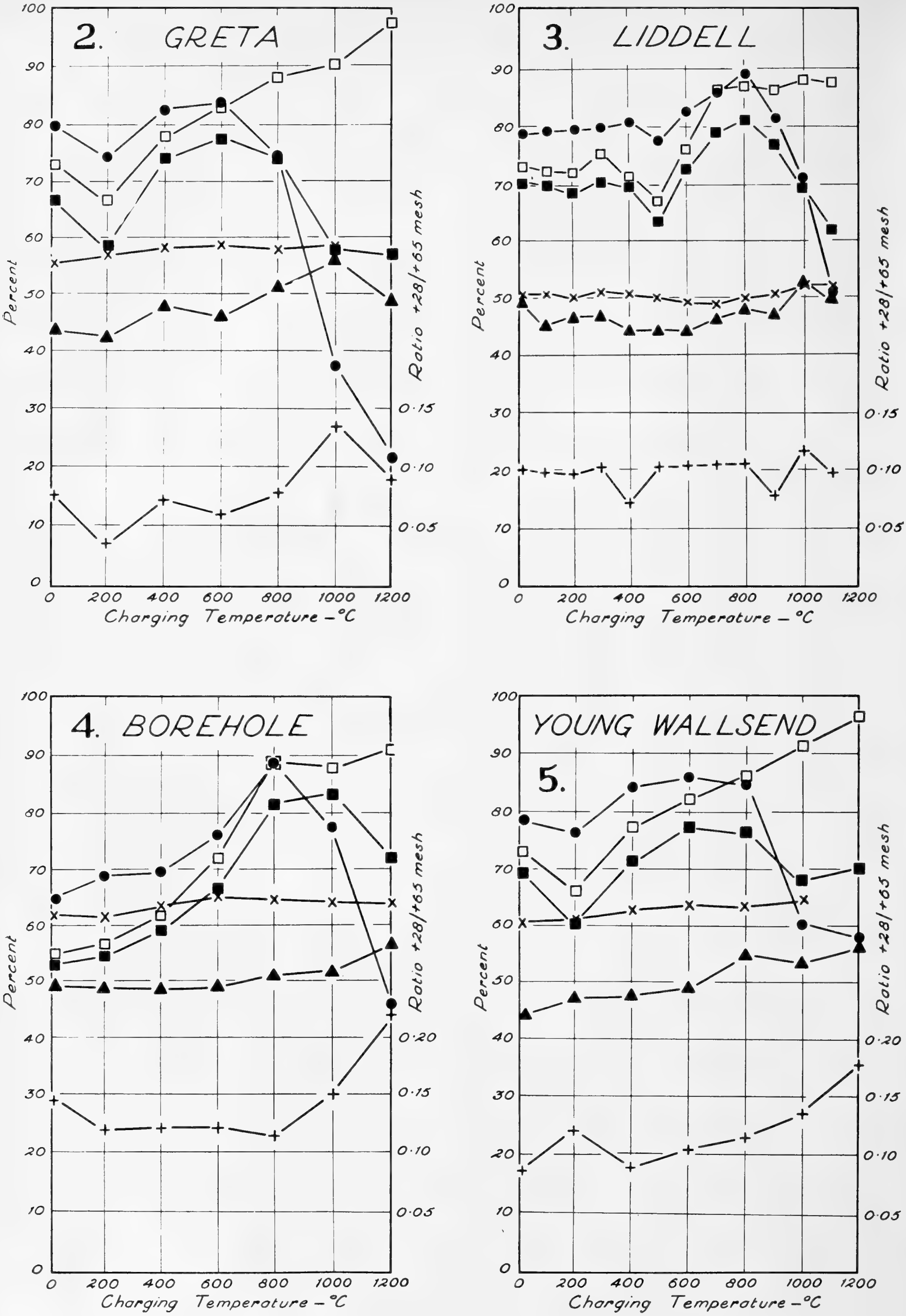


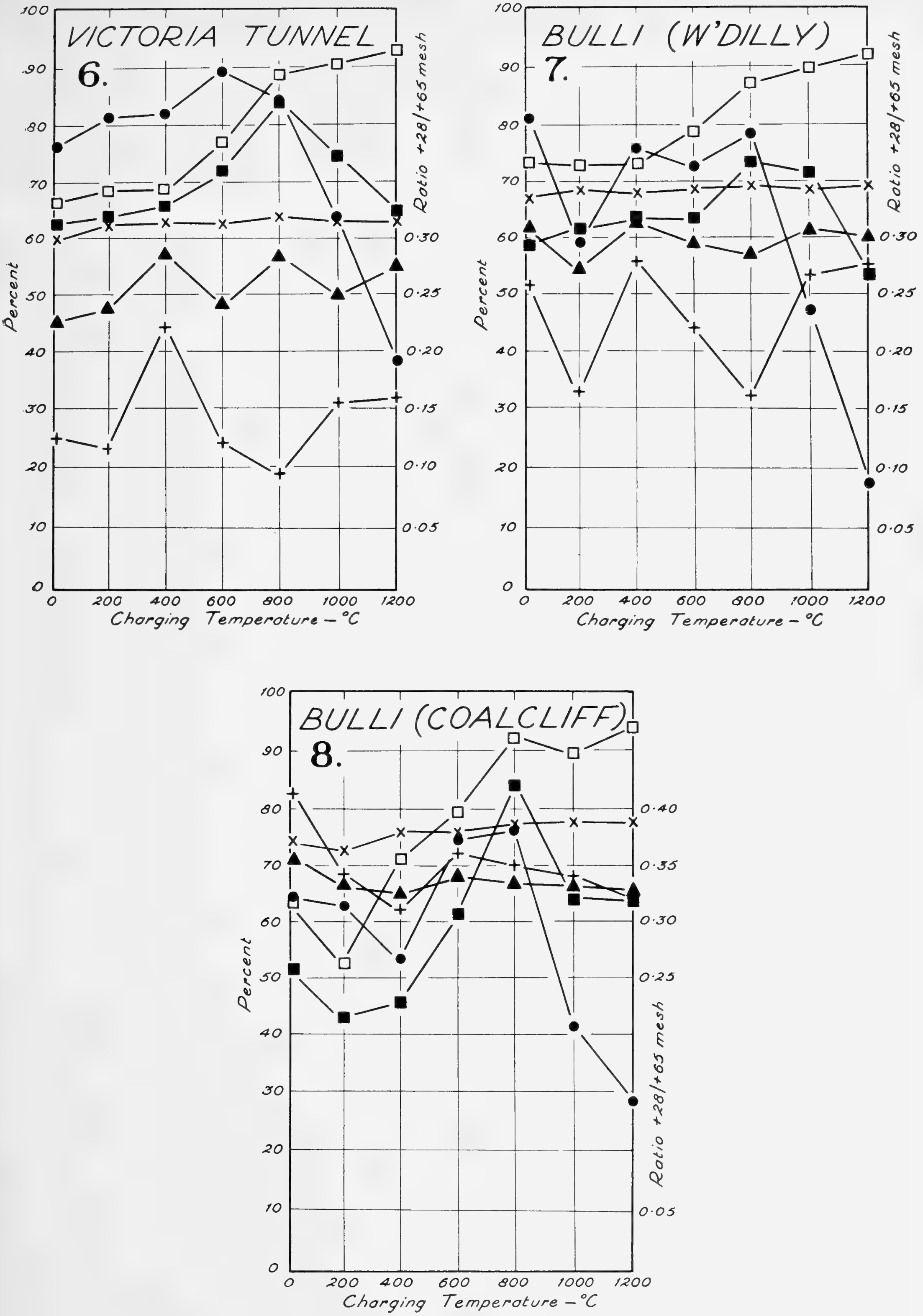
FIG. 1
Size consist analysis of the individual blend components



FIGS. 2–5

Effects of charging temperature on strength of cokes produced from four Australian coal.

Legend : ●——● Shatter Index ; ■——■ Stability Index ;
□——□ Resistance to Abrasion ; ▲——▲ Micro-strength 65 ;
+——+ Micro-strength 28/65 ; ×——× Coke Yield



FIGS. 6–8
Effects of charging temperature on strength of cokes produced from three Australian coals
Legend : (see Figs. 2–5)

the final coking temperature of 1200° C. The micro-mechanical strength indices varied in mutual sympathy throughout, recording definite minima and maxima at 200° C and 1000° C respectively. Coke yield showed a very slight tendency to improve with increased charging temperature.

In the case of this Greta coal, charging temperature assumed particular and critical significance in relation to coke shatter and tumbler stability indices; unlike the American coals discussed in previous papers (Marshall *et al.*, 1958, 1960) there was no serious and continuing decline in macro-strength of the coke produced with charging temperatures immediately above the plastic range of the coal. The minima recorded for macro-strength with an initial temperature of 200° C may however be related to the plasticity and gas evolution characteristics of the coal in the vicinity of its plastic range.

On the basis of " overall " coke quality (Fig. 46) there is little to choose between charging temperatures of 400° C, 600° C and 800° C; selection of an optimum would depend upon particular consumer requirements.

Liddell Coal (*Fig. 3*)

" Standard " laboratory preparation of the Liddell sample provided a coal charge with a particularly high content of +10 mesh material and a particle size distribution indicative of a particularly " strong " coal; overall micrometric analysis indicated the coal bulk to be a medium to coarse clarain in which the average dimensions of the vitrinite intercepts greatly exceeded those of the " inerts ".

With progressive increase of charging temperature to 400° C, the shatter index of the coke produced improved slowly, while with the exception of small but definite improvement in the " 300° C coke ", both tumbler stability and resistance to abrasion declined at a similar rate. All three macro-indices are significantly reduced for the coke produced from coal charged at 500° C, but thereafter progressive increase in charging temperature to 800 °C is accompanied by substantial overall improvement. With further elevation of initial oven temperature, deterioration in shatter index and tumbler stability was precipitate, while resistance to abrasion continued to improve but at a much reduced rate. The micro-strength indices vary fairly sympathetically and in very broad correspondence with the tumbler abrasion indices. Coke yield improved generally but slightly with increased charging temperature. It is possibly of considerable significance that the disturbance of the initial trends exhibited in each of the strength-index curves, occurs in cokes which were formed from samples charged to the oven at temperatures within, or just above the plastic range of the coal. Further, it is important to note that charging to an oven the temperature of which is 300° or 400° C higher than the plastic range yields substantially improved cokes.

On the basis of " overall " quality in the coke produced, a charging temperature of 800° C emerges as by far the most acceptable for the Liddell coal in all cases where greatest resistances to macro-fracture are decisive qualities.

Borehole Coal (*Fig. 4*)

After standard preparation the Borehole seam coal supplied from Stockrington Colliery via Hexham Washery yielded a size consist possibly indicative of only moderate strength as compared with others examined in this study (Table 1). As usual, this observation is subject to qualification as extraction and preparation methods may greatly influence the sample breakage properties. Micrometric analysis reveals this to be an overall clarain in which durain bands are quite well represented; preparation control is likely to be very important in determining coke quality.

The strength of the coke produced from this coal reacted in an extremely regular fashion to variations in the oven charging temperature. The macro-strength indices behaved fairly sympathetically, showing a progressive and marked improvement with increasing charging temperature up to 800° C or 1000° C, after which both shatter and stability indices fell rapidly and resistance to abrasion remained fairly constant. Micro-strength indices were largely unaffected by charging temperatures in the range up to 800° C, after which they improved significantly. Coke yield varied but little, achieving a very modest maxima with a charging temperature of 600 °C.

Fracture characteristics of the coke " bulk " were again more susceptible to variations in charging temperature than the mechanical strength of the actual coke substance. In general, this coal followed the " normal " trend of progressive strength improvement with increasing initial temperature, each index reaching its maximum value in the higher charging temperature range. There were no apparent deteriorations in the vicinity of the plastic range (360–430° C) but shatter index declined rapidly with temperatures in excess of

800° C and stability index above 1000° C; in this range coke micro-strength showed accelerated improvement.

On the basis of these studies, a charging temperature of 800° C is considered to produce coke of best " overall " quality (Fig. 46). The higher charging temperature of 1000° C resulted in a coke of slightly improved micro-strength and stability index, but one in which shatter strength was severely impaired.

Young Wallsend Coal (*Fig. 5*)

The Young Wallsend coal as supplied from the Boston Colliery washery provided, after standard preparation, a size consist in which the larger fractions are well represented, possibly indicative of slightly better-than-average strength. Micrometric analyses reveal the overall character of the coal to be clarain; it is well banded, with individual intercepts of the dominant coking maceral vitrinite much greater than those of the inerts.

This coal proved to be quite sensitive to variations in the temperature of charging. Minimal values for both macro-tumbler test indices were recorded for cokes obtained from coals charged at a temperature of 200° C; with progressively higher initial temperatures, the stability index improved to a modest maximum at 600° C and then fell, whilst resistance to abrasion increased with considerable regularity to 1200° C. Shatter index was similarly depressed in association with a charging temperature of 200° C, then rose to an inconspicuous maximum at 600° C; with initial temperature above 800° C it fell rapidly. Micro-strength indices improved significantly with increase in the charging temperature; coke yield also rose slightly.

The general pattern of variation of coke strength with charging temperature follows closely the pattern established by the Greta coal (p. 132). The depression of macro-indices with a charging temperature of 200° C is slightly less marked in the case of Young Wallsend coal, but it is also thought to be related to the plasticity and gas evolution characteristics of the coal in the vicinity of the plastic range. Further, in the charging temperature range 200° to 800° C the progressive improvement of overall strength is significantly greater, so that at this " optimum " charging temperature it is considerably higher than that of Greta coal. While shatter and stability indices, in common with all other Australian coals, fall quite substantially for charging temperatures in excess of 800° C, there is not the usual continuing deterioration. This factor, together with the accelerated improvement in hardness and micro-strength in the higher temperature range, results in a coke of acceptably high overall strength being formed when the coal charge is introduced to the furnace preheated to the actual coking temperature (1200° C).

On the basis of " overall " quality (Fig. 46) a charging temperature of 800° C clearly emerged as producing a superior coke. Where maximum coke size is not a dominant consideration, however, higher charging temperatures will yield a coke substance of significantly greater strength.

Victoria Tunnel Coal (*Fig. 6*)

As provided for this study, the Victoria Tunnel coal from Waratah Colliery yielded, after standard preparation, a size consist in which the 6×10-mesh fraction was well represented and finer sizes were present in remarkably low proportions, possibly indicative of a " very strong " coal (Table 1, Fig. 1). " Bulk " micrometric analysis indicated the coal to be a normal duroclarain type, the average dimensions of the dominant vitrinite and inertinite macerals being reasonably similar; the microtype (and maceral) distribution in the various particle size fractions varied considerably.

Progressive increases in the furnace charging temperature up to 600° C and 800° C respectively brought about systematic and regular improvements in coke shatter and tumbler strength indices; with successively higher temperatures both the shatter and the stability indices fell rapidly, while resistance to abrasion continued to improve but at a much reduced rate. Micro-strength properties were very irregular, recording a series of high and low figures (not always coincident) but showing a general very slight overall improvement with increasing charging temperature. Coke yield varied but little after initial improvement.

Cokes produced from Victoria Tunnel coal followed broadly the trends established by the Borehole study—a gradual improvement in overall strength to a maximum at the " optimum " charging temperature, and thereafter a precipitate decline.

Despite very considerable fluctuations in micro-strength, the " overall " quality of the coke from Victoria Tunnel coal improves in a regular and progressive fashion with increases in charging temperature up to 800° C and then deteriorates with similar regularity as it is raised further (Fig. 46).

The coke produced with the " standard " charging temperature is significantly superior to any other in macro-mechanical properties, but selection of an " optimum " for full-scale practice should be decided on consumer requirements for particular characteristics as at 800° C, the shatter index is somewhat depressed from its maximum and micro-strength 28/65 is at a pronounced minimum.

Bulli Coal (Wollondilly) (Fig. 7)

The Bulli seam coal from Wollondilly Extended Colliery provided, after standard preparation, a size consist in which the fines were present in rather less than " average " proportions, possibly indicative of a moderately strong coal (Table 1).

As indicated by micropetrological studies the overall character of the coal is that of a fine duroclarain of very uniform character. The character of the coke produced from this coal was particularly susceptible to variation as a result of changes in the temperature of oven charging, especially in respect of shatter strength and micro-strength 28/65. Both of these indices were high for " cold " charging and deteriorated very markedly when the oven charging temperature was raised to 200° C. Micro-strength 65 also deteriorated at 200° C, but to a less marked degree, while other indices remained almost constant. As charging temperature was progressively increased up to 800 °C the coke shatter index fluctuated and then fell precipitately with further temperature increases. The stability index achieved a maximum at 800° C before deteriorating, and resistance to abrasion increased progressively throughout the range to 1200° C. The micro-strength indices fluctuated sympathetically with " minima " at 200° and 800° C charging temperature, the variation in the 28/65 index being particularly severe. Coke yield was little affected by variations in the charging temperature.

On the basis of " overall " coke quality (Fig. 46) there appears to be little to recommend any particular charging temperature between 400° C and 1000° C other than consumer requirements for particular strength characteristics ; the choice lies principally between high micro-strength (for which consideration a charging temperature of 400° C would be the most acceptable) and high tumbler strength (achieved with a charging temperature of 800° C) ; resistance to shatter is generally poor to moderate.

For the Bulli coal from Wollondilly, temperature of charging assumed its most critical significance in relation to the shatter and micro-strength 28/65 indices of the resultant cokes.

Bulli Coal (Coalcliff) (Fig. 8)

As indicated by the size consist after " standard " preparation of the material originally provided, this Bulli sample was possibly the most " tender " of the Australian coals examined to date (Table 1, Fig. 1), the progressive degradation and proportions of fines being pronounced. In petrographic constitution this coal closely resembled that of the Bulli seam from Burragorang Valley, being a fine duroclarain of particularly uniform character.

The reaction of this coal to variations in charging temperature was emphatic. All coke strength indices displayed marked initial minima for charging temperatures in the range 200° C to 400° C. All macro-strength indices achieved their maximum value when introduced to the oven already at 800° C ; with higher charging temperatures, resistance to abrasion was not affected significantly whilst stability and shatter indices declined precipitately. The micro-strength of the coke is generally very good. Both micro-strength indices were very high for the cokes produced when the charge was introduced to a cold furnace ; after distinct minima at 400° C, they improved slightly to 600° C and then declined again progressively but gently. Coke yield increased slightly with increasing temperature of charging.

On the basis of " overall " quality as assessed by all strength indices and coke yield, the " standard " 800° C charging temperature was significantly best ; this is largely as a result of the very pronounced maximum for the stability index recorded at this temperature, all other indices also being at or near their respective maxima under these same conditions. " Overall " strength and quality/quantity indices of the cokes produced from this South Coast Bulli coal are appreciably higher than for those of any other coal examined in the course of the present study. Factors contributing to this are the exceptionally good micro-strength indices, excellent stability index, and high coke yields ; throughout the series the shatter index is poor to moderate.

The Japanese Coals

The overall petrographic constitutions of the Japanese coals are remarkably similar. Vitrinite content ranges from 84·8% for the Ohyubari seam to 91·6% for the Futase (Table 2). All are emphatically of high-volatile bituminous rank, type " A " (A.S.T.M. Classification), their hydrogen contents being significantly higher than those of the majority of bituminous coals of Carboniferous or Permian age. The two coals from Hokkaido have appreciably higher contents of nitrogen than those of Kyushu and in this respect are more closely akin to the majority of other bituminous coals studied. Both swelling index and Gray King Coke Type vary widely in these otherwise reasonably similar coals.

As indicated by the size consist induced by the standard laboratory-scale methods of sample preparation, in general physical character these coals are reasonably comparable with the majority of the Australian coals also studied; they are in general not quite so resistant to breakage as any of the Australian coals with the exception of the South Coast Bulli sample (Fig. 1) and when broken by the standard procedures yield a significantly higher proportion of the finer sizes.

Charging Temperature and Coke Quality

General

As revealed by the range and character of variation made evident in the strength indices of the associated cokes, the four Japanese coals submitted for study are particularly sensitive to differences in the temperature of the oven on charging. Two of the coals (Akahira and Futase, Figs. 9 and 11) exhibit trends which conform broadly with the simple progressive variation in strength pattern characteristic of the Australian coals from the Victoria Tunnel, Borehole and Liddell seams. The remaining two Japanese coals (Ohyubari and Takashima) differ markedly in degree and type of strength variation revealed by the laboratory cokes. The main features of the strength variation patterns may be summarized as follows:

(a) Progressive and general increase in macro-strength indices of the resultant coke with increase of charging temperature (Figs. 9 and 11), the improvement being either maintained throughout the full range (resistance to abrasion) or terminated by maxima which need not be achieved under similar conditions (shatter and tumbler stability).

(b) Immediate and rapid deterioration in macro-strength indices of the cokes formed from coals charged at successively higher temperatures, ranging up to 600 or 800° C. Charging at higher temperatures may provide improvement and subordinate maxima in these qualities, possibly followed by renewed improvement in the final ranges (Figs. 10 and 12).

Throughout the range of increasing charging temperature, with either subordinate or significant variations, the micro-strength indices may either improve generally but irregularly, improve to maxima in the vicinity of 1000° C, fluctuate about a general level, or progressively deteriorate.

For ease of reference and comparison the coke strength indices are graphed against the temperature of the oven at which the corresponding coal charge was introduced; the study results obtained for the individual Japanese coals appear in Figs. 9–12.

Akahira Coal (*Fig. 9*)

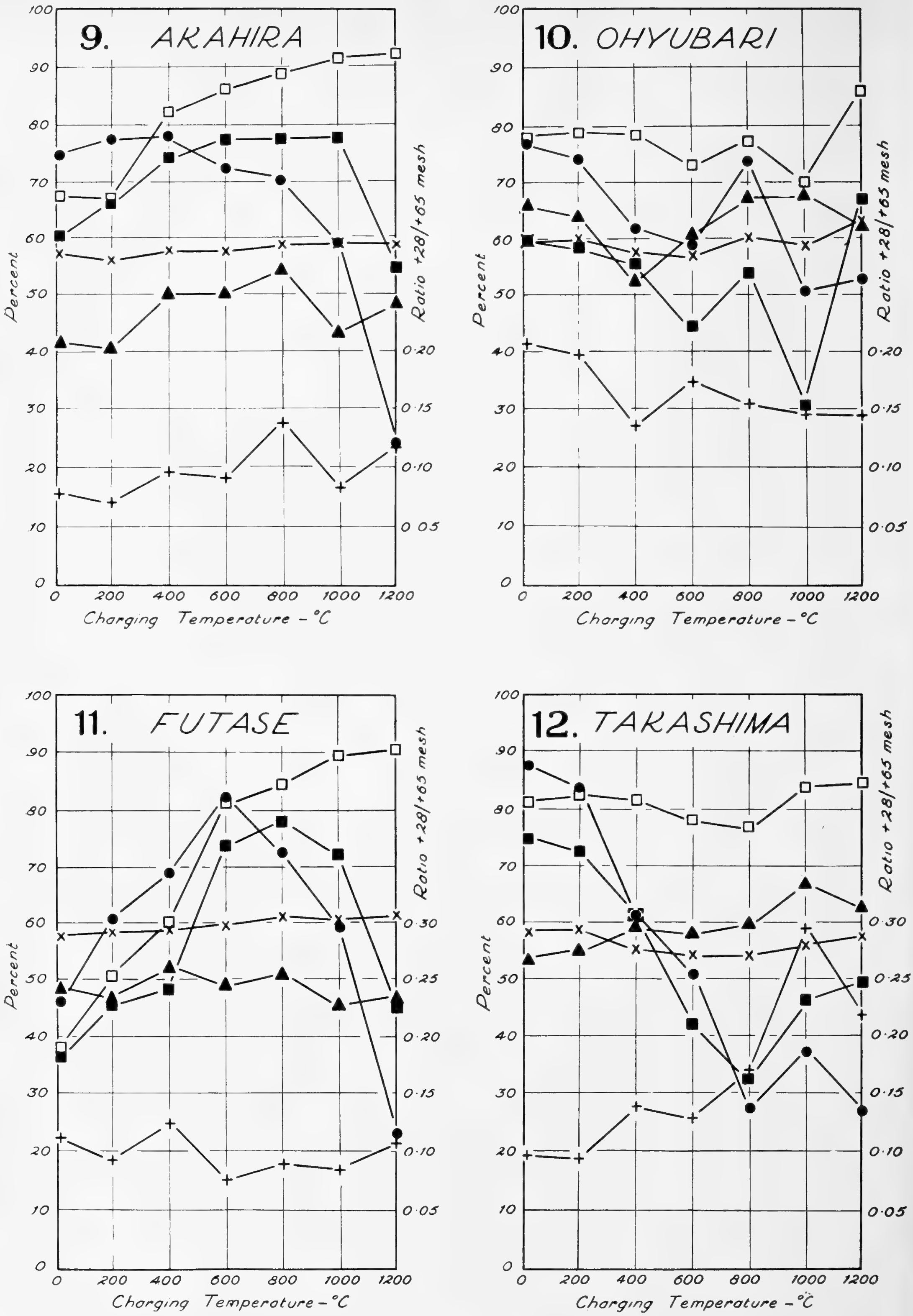
Standard laboratory preparation indicated the Akahira coal as supplied to be possibly the most tender of the four submitted; the size characteristics exhibited by this sample (Table 1) compare quite closely with those of the Coalcliff Bulli. Micropetrographic analysis indicates the overall character of the coal to be high vitrain clarain, in which the average dimensions of the dominant coking constituent vitrinite greatly exceeded those of the inerts.

Increase in charging temperature up to 600° C was accompanied by a progressive improvement in coke stability which then maintained a consistent level before declining for temperatures above 1000° C; resistance to abrasion continued to improve up to 1200° C. Slight initial improvement in shatter strength with increasing charging temperature was followed by a significant decline which became severe for temperatures above 800° C. Micromechanical strength indices exhibited a general but irregular improvement with increasing temperature of charging; both achieved pronounced maxima at 800° C. Coke yield increased very modestly throughout the range.

Although the corresponding shatter index was somewhat depressed, the "standard" charging temperature of 800° C was found to produce coke of best "overall" quality (Fig. 46). The mechanical characteristics of the coke produced from the Akahira coal alone under these conditions are reasonably comparable with those of the cokes of a number of northern coalfield seams prepared under similar conditions.

Ohyubari Coal (*Fig. 10*)

As revealed by the size consist after standard laboratory preparation, the Ohyubari coal as supplied is apparently of moderate to good "strength" (Table 1). According to the results of micrometric analysis, the overall character



Figs. 9–12

Effects of charging temperature on strength of cokes produced from four Japanese coals

Legend : (see Figs. 2–5)

of the coal may be described as a clarain, with approximately 85% vitrinite. The difference between the mean dimensions of coking and non-coking constituents was the least marked of all the Japanese samples.

In respect of strength of the resultant cokes, this coal was found to be particularly sensitive to variations in charging temperature. All coke strength indices were at or near their respective maximum values for charges introduced to a cold furnace. With increase in charging temperature, all coke macro-strength indices declined considerably to initial minima at 600° C. With a charging temperature of 800° C, all three macro-indices recovered to almost their original values, only to fall again to even more pronounced minima at 1000° C. A charging temperature of 1200° C induced considerable improvement in all macro-strength indices, particularly that of tumbler stability. The coke micro-strength indices declined rapidly and sympathetically in cokes produced from coals charged at temperatures up to 400° C. With higher charging temperatures micro-strength 65 improved considerably, high values being recorded for cokes of 800° C and 1000° C charging temperature. Coke yield was variable, but exhibited a tendency to a general increase with higher temperatures of charging.

On the basis of " overall " quality of the resultant coke (Fig. 46), charging at laboratory temperature, 200° C, 800° C and 1200° C all have closely similar effects. Once again " optimum " quality may only be determined by specific consumer preference for certain characteristics. Under the " standard " conditions of the present test series the Ohyubari coal yields a coke significantly inferior to the majority of those obtained from seams of the northern and southern coalfields of New South Wales which have been studied under the same conditions. It is probable that in conditions of normal industrial practice, Ohyubari coal alone would yield a coke of very inferior quality.

Although beyond the scope of this present investigation, it is considered that this coal would repay particular study for the production of coke of metallurgical quality from blends charged to beehive type ovens at relatively low temperatures.

Futase Coal (*Fig. 11*)

As indicated by the size consist after standard preparation, the Futase coal appeared to be the most resistant to mechanical disintegration (Table 1) ; it corresponds most closely with the Young Wallsend sample from the Boston Washery. Constituent maceral proportions indicate the overall character of the broken coal to be high-vitrain clarain.

Increase in the oven charging temperature from that of the laboratory to 600° C, induced a progressive and very rapid increase in all macro-mechanical strength indices of the resultant cokes. Thereafter shatter index decreased precipitately while the stability index increased slightly to a maximum at 800° C ; resistance to abrasion showed further progressive but less marked improvements to 1200° C. Although varying sympathetically, micro-strength indices were rather irregular ; both achieved modest maxima at 400° C although the general range of variation was small. Coke yield increased gently but progressively throughout the range.

On the basis of overall coke quality, the " standard " 800° C charging temperature proved again to be the most effective compromise, although for cokes produced from coals charged at this temperature the shatter index was appreciably depressed from its maximum achieved at 600° C. The mechanical characteristics of the cokes produced from Futase coal charged at either 600° C or 800° C are reasonably comparable with those of the cokes of some northern coalfield seams produced under the same conditions.

Takashima Coal (*Fig. 12*)

The size consist after standard preparation of the sample submitted indicates the Takashima coal to be of moderate strength (Table 1). According to the results of micrometric analysis upon the broken coal, in overall composition it must be classed as high-vitrain clarain.

As in the case of the Ohyubari material, the Takashima coal proved to be particularly sensitive to variations in the temperature of the oven on charging, in relation to strength of the resultant coke. From quite satisfactory figures for cold charging, both shatter and stability indices declined precipitately with increased initial oven temperature, until at 800° C charging temperature, they exhibited unusually low minimal values. In cokes produced from coals charged at 1000° C, both indices recovered to some extent, but the shatter index was again depressed when the oven temperature on charging was raised to 1200° C. Resistance to abrasion varied much less significantly, but is somewhat depressed for charging temperatures between 400° C and 1000° C. Micro-strength characteristics increase progressively and sympathetically to substantial maxima for 1000° C charging temperature; thereafter they decline slightly. Coke yield is depressed for coals charged between 200° C and 1200° C.

On the basis of overall quality (Fig. 46) coal introduced to the oven at temperatures up to 200° C was found to yield coke of quite acceptable quality; under these conditions, it is possible to produce from Takashima coal a coke which is superior to that of any other of the Japanese coals investigated when coked under their respective most favourable conditions. Under either present " standard " coking conditions, or those realized in a modern slot-type coking oven, the Takashima coal alone would most probably yield a coke of markedly inferior macro-mechanical properties. However, its particular and quite unusual qualities of yielding optimum strength coke from coal charged to " cool " or " cold " ovens, most strongly recommend it for comprehensive blend studies in relation to coke production in beehive type ovens. The general pattern of variation emerging from this study series (Fig. 12) seems to indicate that an increased " soaking " period may favour the production of stronger coke from charges introduced to the furnace at the " standard " temperature of 800 °C.

Coking Characteristics of Two Component Blends of Australian and Japanese Coals

The limitations imposed upon the scope of this study by the particular circumstances in which it was undertaken have already been indicated (p. 123). It would have been extremely interesting to explore fully the effects of controlled variation in all factors in the thermal cycle (e.g. charging temperature and rates of heating, final coking temperature and duration) upon the mechanical properties of coke produced from specially prepared charges of different size ranges and consists, as well as maceral proportions and distribution. As this was not possible, certain " standards " in conditions of coking and charge character were accepted for all blend studies.

With the exception of those of the Takashima coal, the results of the introductory investigation concerned with the effects of charging temperature upon the quality of coke produced from the individual samples indicated that optimum " overall " coke quality was usually associated with an initial oven temperature in the vicinity of 800° C. Based upon reasonable conformity in the results of other more detailed studies of comparable high volatile bituminous coals, the " blend " standards for rate of heating above charging temperature, final coking temperature and duration were accepted as 3·3 C° per minute, 1200° C and 2 hours respectively. The size range, consists and maceral distribution produced in each individual coal by the controlled method of preparation were accepted as standard.

In practice each Japanese coal was blended in turn with each of the Australian coals in various proportions. Study procedures were as previously described for the individual coals with particular attention to uniformity in distribution of blend components and coal sizes in the oven charge. For ease of comparison and interpretation, study results for each two-component blend series are graphed separately.

In the following discussion, it must be clearly understood that where comparisons are drawn between the coking characteristics of individual seams, they refer to the quality of the coke produced under the laboratory conditions of production and testing accepted as " standard " for this investigation.

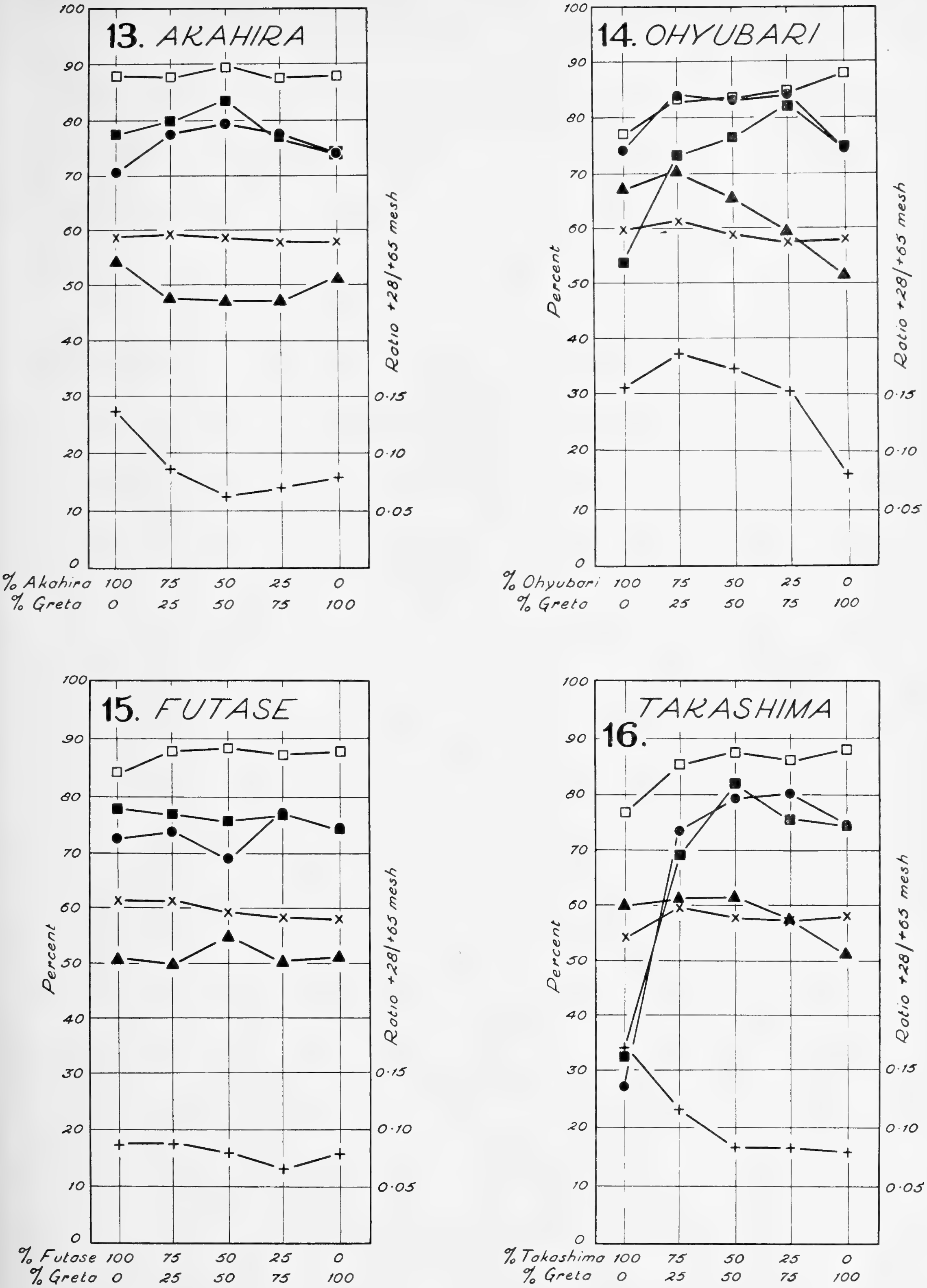
Greta Blends with Japanese Coals

Under the " standard " coking conditions of the present laboratory scale study, the Greta coal alone yielded a coke characterized by low shatter and moderate stability indices, high resistance to abrasion, and moderate to rather low micro-mechanical indices; coke yield was relatively low (Fig. 2).

With but one exception (Futase), Greta coal when blended with the Japanese samples induced definite improvements in the macro-mechanical indices of the coke produced. As would be expected, this improvement is most strikingly evident in the Greta blends with Takashima coal, where the benefits obtained are very substantial. Effects upon the coke substance as indicated by the micro-strength indices were not so generally or significantly beneficial.

Akahira-Greta Blends (*Fig. 13*)

Although these two coals appear quite reasonably comparable in their individual coking characteristics, the carbonized products of their blends do exhibit appreciable and systematic variation in their mechanical properties. Resistance to abrasion, shatter and stability indices increase modestly to maxima in the coke produced from a blend of Greta+Akahira coals in equal proportions; unfortunately micro-mechanical strength properties exhibit the reverse trend and definite minima are recorded for these indices in the same coke.



FIGS. 13–16

Variations in strength of cokes produced from blends of each Japanese coal with Greta coal

Legend : (see Figs. 2–5)

Coke yield varies but little, a very modest maximum appearing in blends of 25% Greta-75% Akahira.

Ohyubari-Greta Blends (*Fig. 14*)

Only in respect of shatter index and yield of the resultant coke do these two coals appear to be reasonably comparable as regards their individual coking properties. Greta coal is significantly superior to Ohyubari coal in respect of macro-tumbler test indices (stability and resistance to abrasion), and Ohyubari is markedly superior in both micro-mechanical strength indices. Variations in the properties of cokes produced from their blends are systematic and significant.

Resistance to abrasion increases quite markedly when 25% of Greta is introduced into the coal charge, thereafter improving more gently to a maximum for Greta coal coked alone. The shatter indices of cokes produced from all blends are very definitely superior to those of either coal coked alone, but do not exhibit significant variation over the intermediate range 25% to 75%. In contrast, the stability index exhibits a very pronounced maximum for cokes produced from blends of 75% Greta-25% Ohyubari. Both micro-mechanical indices exhibit maxima for cokes produced from blends of 25% Greta-75% Ohyubari, indicating a coke " substance " of appreciably superior strength. Coke yield showed a general tendency to decrease slightly with increasing Greta proportions in the charge.

Futase-Greta Blends (*Fig. 15*)

The two blend components appear to be quite similar in their individual coking properties, and variations in the mechanical properties of the cokes produced from their various blends are generally inconsiderable.

The shatter index achieves a very modest maximum in cokes produced from blends with 75% Greta-25% Futase, and an equally modest minimum for the coke produced from a 50–50 blend. With one very minor exception, the stability index decreases very gently as the proportions of Greta are increased. The resistance to abrasion, however, improves with the inclusion of 25% Greta in the charge but, with further increase in the proportions of this component, fluctuates very slightly. Micro-strength 65 attained a modest maximum in the coke produced from 50% Greta-50% Futase blend ; micro-strength 28/65 was a minimum in the Greta 75%-Futase 25% blend.

Coke yield decreased slightly but progressively with increased content of Greta.

Takashima-Greta Blends (*Fig. 16*)

Coke produced from Greta coal alone is very markedly superior to that of Takashima in respect of all macro-mechanical strength indices, but is considerably inferior in micro-strength. The properties of cokes produced from their blends vary widely but quite systematically.

Stability and shatter indices of coke produced from the Takashima coal are improved to a very considerable degree by the addition of even moderate proportions of Greta, these properties achieving maxima in the vicinity of 50–50 blends. Resistance to abrasion also improved rapidly with the addition of Greta coal in proportions up to 50% of the charge.

As revealed by the micro-strength indices the " mechanical quality " of the coke substance was not so improved. The 28/65 index fell rapidly with the inclusion of up to 50% Greta in the charge, while in the same range the 65 index improved very slightly and thereafter declined rapidly.

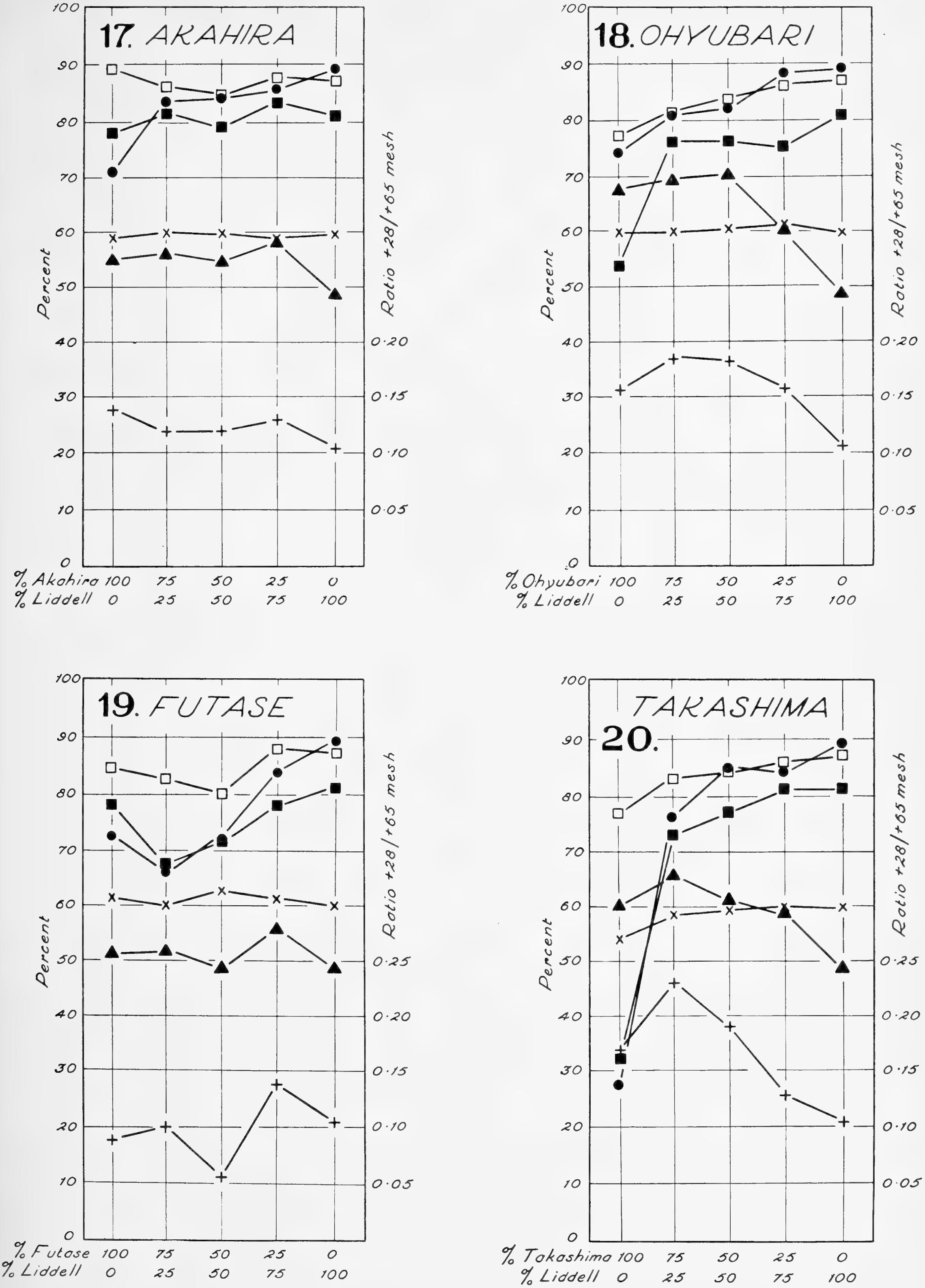
Coke yield showed a slight maximum from blends containing 25% Greta.

Liddell Blends with Japanese Coals

Under standard conditions of coking, Liddell coal alone produced a coke of high shatter, stability and resistance to abrasion ; both micro-mechanical strength indices were rather low. Yield of coke was quite normal for a high volatile bituminous coal (p. 132, Fig. 3). Liddell coal has a definitely beneficial effect on the coking characteristics of all four Japanese coals ; with the exception of blends of Futase coal, a content of as little as 25% Liddell coal in the blends achieves remarkable improvement in the " overall " macro-strength characteristics of the coke produced.

Akahira-Liddell Blends (*Fig. 17*)

Although under standard conditions Liddell and Akahira coals appear to be very broadly comparable in their individual properties, cokes produced from their blends nevertheless exhibit some modest variation in mechanical properties, especially in respect of shatter index. None of the blends yields a coke with a shatter index as high as that of Liddell coal alone ; each addition of Akahira results in a gradual decline in shatter index which becomes much more precipitate when proportions of Akahira exceed 75% in the oven charge. Stability index and resistance to abrasion vary little and generally in sympathy ; definite minima are recorded for each in cokes produced from a 50–50 blend. Micro-mechanical indices of cokes produced from



FIGS. 17–20

Variations in strength of cokes produced from blends of each Japanese coal with Liddell coal

Legend : (see Figs. 2–5)

the blends exhibit modest maxima for the Liddell 75-Akahira 25 coke. From consideration of both macro- and micro-mechanical indices it is evident that most acceptable " overall " quality will probably occur in cokes produced from blends of approximate composition: Liddell 75%-Akahira 25%.

Coke yield varies but little, a very modest maximum appearing in blends of Liddell 25%-Akahira 75%.

Ohyubari-Liddell Blends (*Fig. 18*)

In their individual coking characteristics the Liddell and Ohyubari coals are quite different, the latter yielding a product quite inferior in macro-mechanical characteristics but of superior " strength " in the coke substance. Blending these two coals produces quite systematic and considerable variation which assumes great importance in the control of preferred characteristics.

All macro-indices are greatest for the cokes produced from Liddell coal alone and least for those yielded by the entirely Ohyubari charges. The presence of only 25% Liddell coal in the blend effects considerable improvement in mechanical properties, especially in respect of tumbler stability. As the proportion of Liddell coal is increased both shatter index and resistance to abrasion improve, while tumbler stability declines very slightly.

Micro-strength indices are considerably improved in the blends, the optima not corresponding but being achieved in the cokes produced from charges in which both coals are either equally represented or in the proportions Liddell 25%-Ohyubari 75%. The best combination of strength characteristics would most probably be obtained in a coke produced from blends containing approximately equal proportions of the two components.

Coke yield varies slightly and achieves a modest maximum for charges containing Liddell 75%-Ohyubari 25% blends.

Futase-Liddell Blends (*Fig. 19*).

The mechanical strength characteristics of the cokes produced from Futase coal alone under standard conditions are reasonably comparable with those of a number of northern coalfield seams; but for a substantially inferior shatter index, they correspond quite closely with those of the Liddell. In general, the properties of the cokes produced from blends of Liddell and Futase coals vary systematically, but certain exceptions are notable.

All macro-indices are greatest for the cokes produced from Liddell coal alone. However, shatter and stability indices both exhibit pronounced minima for the Liddell 25%-Futase 75% blend coke while resistance to abrasion attains a less marked minimum in the 50–50 product. Thereafter, as the proportion of Liddell coal in the blend is increased, coke macro-strength generally improves.

Micro-strength characteristics of the blend cokes exhibit pronounced minima in the vicinity of the 50–50 blend, and equally emphatic maxima for cokes of the Liddell 75%-Futase 25% blend. Maximum " overall " quality in respect of mechanical strength is provided by cokes produced from coal charges containing Liddell 75%-Futase 25%.

Coke yield is highest for blends ranging from Liddell 50%-Futase 50% to Liddell 75%-Futase 25%.

Takashima-Liddell Blends (*Fig. 20*)

The macro-mechanical indices of the coke produced from the Takashima coal alone under standard test conditions are very markedly inferior to those of the Liddell coal, while the latter is definitely inferior to the Japanese coal in the strength of the coke substance. Cokes produced from blends of the two coals exhibit considerable and progressive variation in both macro- and micro-indices.

Macro-strength indices are greatest for cokes produced from the Australian coal alone. Inclusion of no more than 25% of Liddell coal in the oven charge is accompanied by very considerable improvement in all mechanical characteristics, including the micro-strength indices. Resistance to abrasion and tumbler stability increases progressively as the proportion of Liddell coal in blends is increased; with one minor exception (coke from blend of Liddell 75%-Takashima 25%) the shatter index similarly improves.

Micro-indices vary sympathetically, each achieving distinct maxima in cokes of the Liddell 25%-Takashima 75% blend. Most acceptable " overall " mechanical quality of the coke produced would probably be obtained from blends between Liddell 25%-Takashima 75% and Liddell 50%-Takashima 50%.

Coke yield increased gradually and progressively as the proportion of Liddell coal in blends was increased to 75%.

Borehole Blends with Japanese Coals

Under " standard " coking conditions, when carbonized alone the Borehole seam coal returned a coke of high shatter, stability and resistance to abrasion and low micro-mechanical strength characteristics. Coke yield was quite normal (Fig. 4).

In blends with the Japanese coals the Borehole seam generally produced significant and sometimes substantial improvement in the macro-mechanical characteristics but usually some deterioration in coke substance as indicated by the micro-strength indices.

Akahira-Borehole Blends (*Fig. 21*)

The two blend components appear to be reasonably comparable in their individual coking properties. The coke produced from the Borehole coal alone, however, was markedly less subject to shatter while that from the Akahira coal was slightly superior in respect of micro-mechanical strength. Except for the shatter index, variation in the mechanical properties of their blends were generally inconsiderable.

With the exception of coke produced from the 75% Borehole-25% Akahira blend, the shatter index increased with the proportion of Borehole coal, whilst stability index and resistance to abrasion both achieved modest minima in cokes from blends containing 75% and 25% of Akahira coal respectively. Both micro-mechanical strength indices were at a slight minima for the 50–50 blend cokes.

Coke yield increased progressively with greater content of Borehole coal.

Ohyubari-Borehole Blends (*Fig. 22*)

The coking properties of the two blend components are not very similar. Coke produced from Borehole coal alone is significantly superior in respect of shatter, stability, resistance to abrasion and yield, whilst that from Ohyubari coal is equally superior from the point of view of micro-mechanical strength. The effects of blending the two coals are, with minor exceptions, quite systematic and considerable.

All three macro-mechanical strength indices generally improve with increasing proportions of Borehole coal in the charge, the shatter index achieving an insignificant maximum with 75% of this component in the blend.

With one exception, all micro-strength indices decline progressively as the proportion of Borehole coal is increased in the charge; the exception occurs in coke representing a blend of the two coals in equal proportions, for which the 28/65 micro-strength index was a definite minimum.

Coke yield improved quite regularly with increase in the proportion of Borehole coal.

Futase-Borehole Blends (*Fig. 23*)

In their individual coking properties these two coals are comparable in respect of all mechanical characteristics of the coke produced, except that the Borehole coal is significantly superior in resistance to shatter. The effects of blending vary quite considerably, especially in relation to the three macro-strength indices and therefore are of great importance in the control of specific properties.

The blending of Borehole and Futase coals results in some irregularity in variation of coke quality and little overall beneficiation. None of the blends investigated yield cokes in which there is any improvement in the macro-strength indices over those of the best individual component; all achieve pronounced minima in one or other of the coked blends, the most significant being that of the shatter index in coke of Futase 75%-Borehole 25%. Lesser minima are recorded for stability (Futase 75%-Borehole 25% and Futase 25%-Borehole 75%) and for resistance to abrasion (Futase 25%-Borehole 75%). Micro-strength varies but little, the 28/65 index generally improving slightly with an increase in the proportion of Borehole coal.

Coke yield increased with addition of Borehole coal.

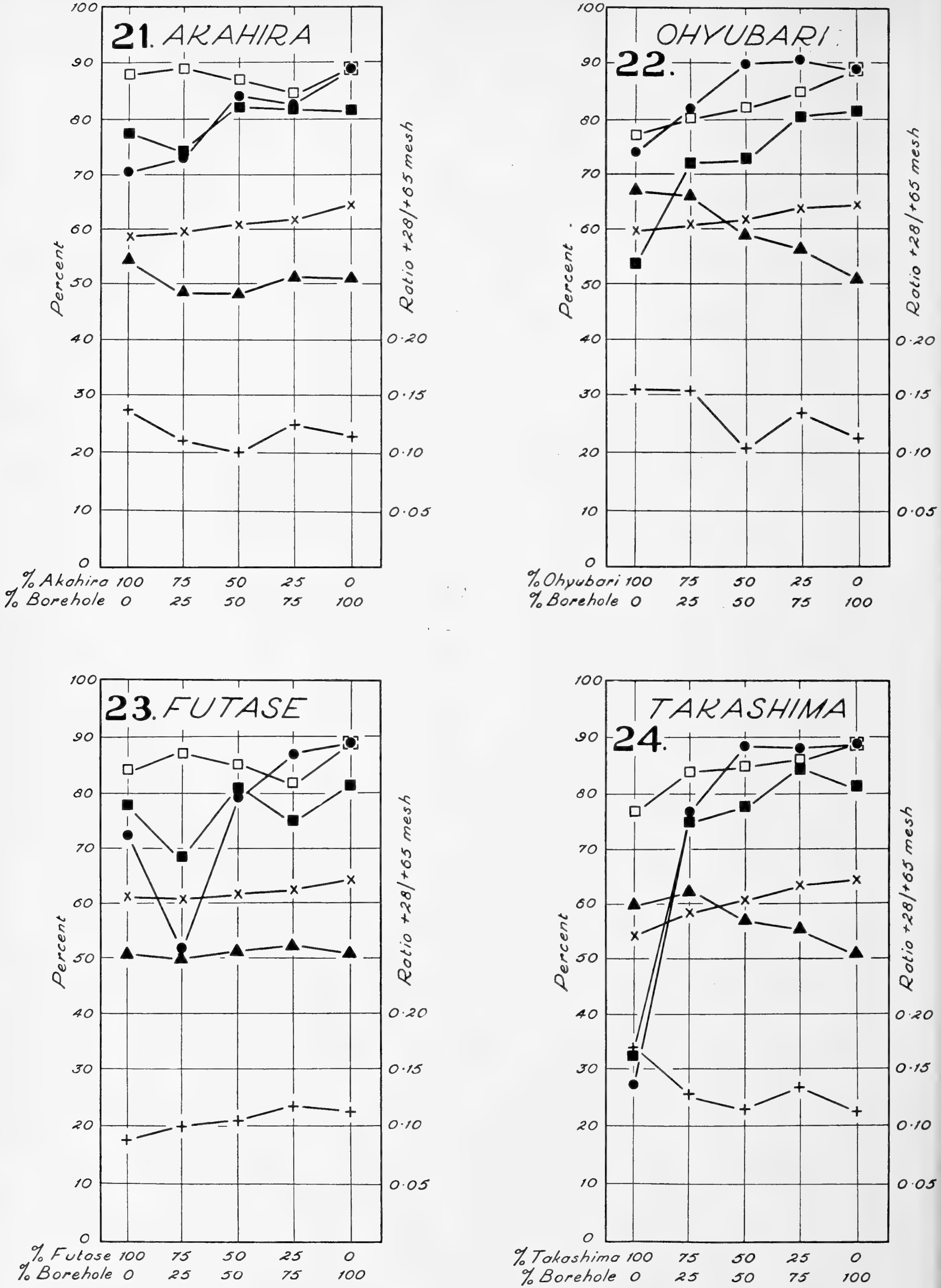
Takashima-Borehole Blends (*Fig. 24*)

In respect of the quality of the cokes yielded when carbonized individually, these two coals are quite different. The Borehole sample was greatly superior in terms of macro-strength and yield of coke, while the product of the Takashima coal was superior in micro-strength characteristics. Blending of the two coals produced substantial changes in coke quality.

The inclusion of no more than 25% Borehole coal in the oven charge produced great improvements in all three macro-strength indices of the resultant coke over those of the carbonized product from Takashima coal alone; further increases in the proportion of Borehole coal were accompanied by further but more gradual improvements in these indices, the stability index achieving a modest maximum at Borehole 75%-Takashima 25%.

The highest micro-strength 65 index was found in coke of the Borehole 25%-Takashima 75% blend but in general the strength of the coke substance declined with increase in the proportion of Borehole coal.

Coke yield improved progressively with each increase in the proportion of Borehole coal.



Figs. 21–24

Variations in strength of cokes produced from blends of each Japanese coal with Borehole coal

Legend : (see Figs. 2–5)

Young Wallsend Blends with Japanese Coals

Under "standard" conditions of the present laboratory study Young Wallsend seam coal from Boston Washery yielded a coke of moderate to fairly good physical properties as indicated by both macro- and micro-strength characteristics; coke yield was quite normal for a coal of this type.

Cokes produced from blends of the Young Wallsend sample with each of the Japanese coals were generally improved in macro-physical characteristics; the micro-mechanical properties of the coke substance were not significantly affected.

Akahira-Young Wallsend Blends (Fig. 25)

From the character of the cokes which they yield when carbonized separately, these two coals appear to be quite similar in their individual coking properties; only in respect of shatter index was the coke from Young Wallsend coal significantly superior to that of Akahira. The properties of the cokes produced from their various blends varied systematically and to a pronounced degree.

The shatter index was greatest for coke produced from Young Wallsend coal alone. From this quite high individual value a gradual decline in shatter strength accompanied each increase in the proportion of Akahira up to a content of 50%; blends in which proportions of Akahira exceed 50% yield a coke which is much more susceptible to impact breakage. The stability index exhibits a very definite maximum in the vicinity of 50–50 blend cokes, while resistance to abrasion increases very slightly in the middle ranges. On the basis of these macro-mechanical indices alone, blends which yield cokes of quite good quality range between Young Wallsend 50%-Akahira 50% and Young Wallsend 75%-Akahira 25%. The variation in the quality of the coke substance is very regular, the micro-mechanical indices being least in the blend cokes containing approximately equal proportions of the two coals.

Coke yield decreased gradually with each increment of Akahira in the blend.

Ohyubari-Young Wallsend Blends (Fig. 26)

The two components of this blend series differ quite considerably in the quality of their individual cokes. The Young Wallsend coal returns a coke of significantly superior macro-mechanical strength characteristics and slightly higher yield, whilst Ohyubari coke is much better in respect of micro-strength. Blends of these two coals showed considerable and progressive improvement in all mechanical properties as compared with those of the individual seams; unfortunately no single blend yielded a coke in which all mechanical properties were most highly developed.

Tumbler stability attained a pronounced maximum for cokes from blends of Young Wallsend 75%-Ohyubari 25%; both shatter index and resistance to abrasion were greatest in cokes from equal part mixtures, the former recorded as a pronounced maximum. Micro-mechanical indices varied progressively and in marked sympathy, with maxima in cokes representing the blend Young Wallsend 25%-Ohyubari 75%.

Coke yield increased appreciably with addition of Young Wallsend in proportions up to 50% of the blend, but further increments produced no significant change.

Futase-Young Wallsend Blends (Fig. 27)

With the exception of the superior shatter index for coke produced from Young Wallsend coal, the cokes produced from these two coals individually are quite comparable. With few exceptions, both macro- and micro-mechanical indices of the blend series varied progressively with changing proportions of the two components.

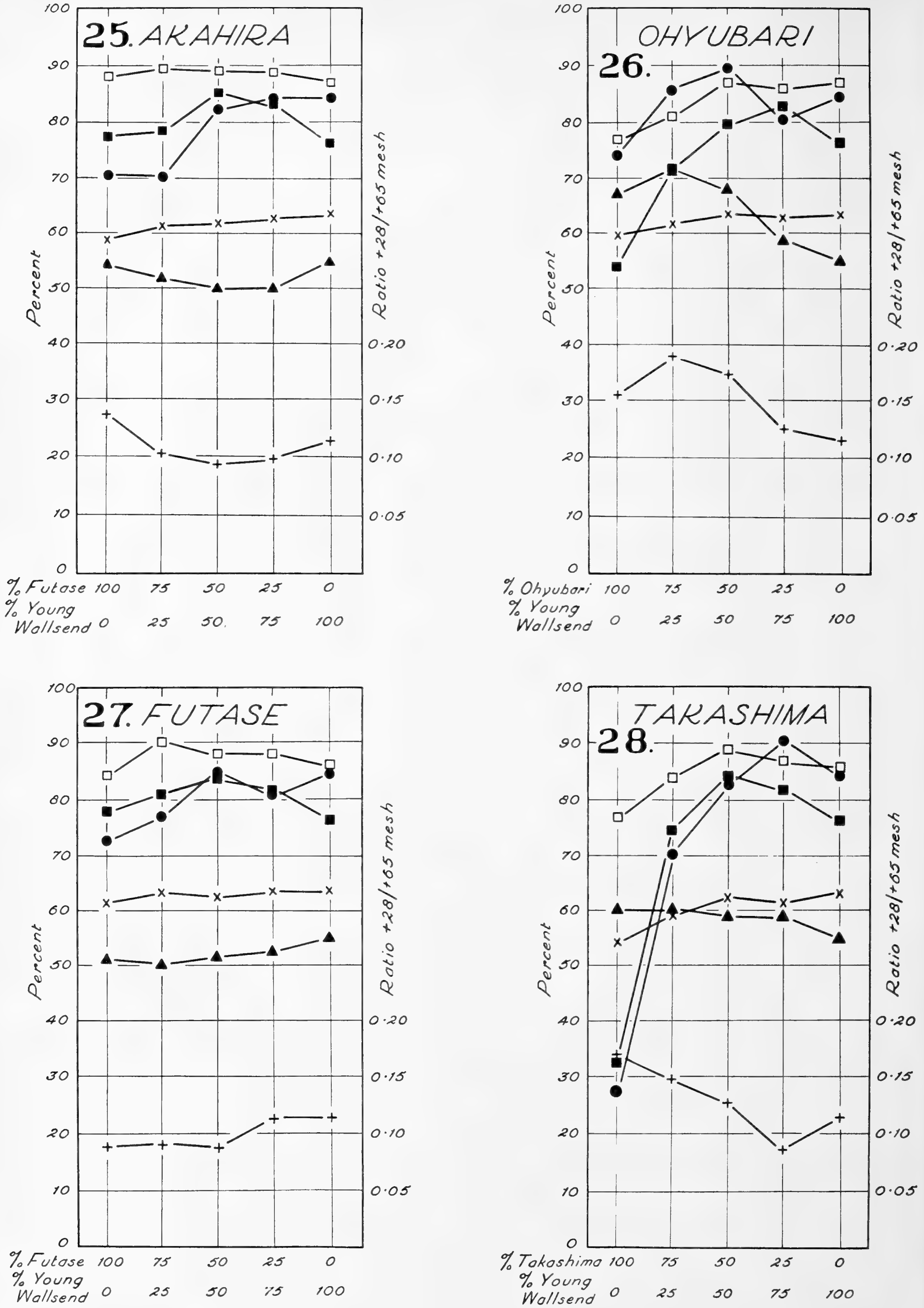
Maximum shatter and stability indices occurred in cokes obtained from the blend Young Wallsend 50%-Futase 50%; resistance to abrasion was greatest for the coke from the blend Young Wallsend 25%-Futase 75%. The micro-mechanical indices improved greatly with each increase in proportion of Young Wallsend coal in the charge.

Coke yield varied but slightly, Futase coal when carbonized alone providing the least return.

Takashima-Young Wallsend Blends (Fig. 28)

As demonstrated by the contrast in the physical characteristics of their individual cokes, these two blend components are very different in their coking properties. Macro-mechanical strength indices and yield of coke from the Australian coal are much greater than from the Japanese coal, whilst the micro-strength indices of the entirely Japanese coke are appreciably superior. The effects of blending Young Wallsend and Takashima coals are systematic and substantial.

Even modest proportions of Young Wallsend coal in the oven charge greatly improve the macro-mechanical properties of the coke.



FIGS. 25–28

Variations in strength of cokes produced from blends of each Japanese coal with Young Wallsend coal

Legend : (see Figs. 2–5)

Stability index and resistance to abrasion are greatest in cokes of 50–50 blends, while the shatter index exhibits a pronounced maximum for the carbonized product of the blend Young Wallsend 75%-Takashima 25%. Micro-mechanical indices, however, deteriorate generally with increased proportions of Young Wallsend, the 65 index but slowly, the 28/65 more definitely to a minimum for cokes of the Young Wallsend 75%-Takashima 25% blend coke. As compared with that of Takashima coal alone, coke yield increases significantly with additions of Young Wallsend up to 50%.

Victoria Tunnel Blends with Japanese Coals

Victoria Tunnel coal, when carbonized under the " standard " conditions of the present study, produced a " stable " coke with high resistance to abrasion, stability and shatter, as well as moderate micro-strength characteristics. Coke yield was also quite good for coals of this rank.

In blends with the Japanese coals, cokes were produced with very good macro-mechanical properties and improved strength in the coke substance.

Akahira-Victoria Tunnel Blends (*Fig. 29*)

Of these two blend components, the Victoria Tunnel is superior in respect of the micro-mechanical properties of its individual coke, and quite comparable with Akahira coke in micro-strength. The cokes produced from their blends exhibit appreciable and significant variations.

In cokes produced from blends of the two coals the shatter index is considerably improved by the presence of quite modest proportions of Victoria Tunnel coal, a maximum being achieved from the 50–50 blend. Coke stability was improved with each increment of the Victoria Tunnel coal while resistance to abrasion was slightly impaired in all blends. Both micro-strength indices attain appreciable maxima in cokes of the 50–50 blend, the " 28/65 " values being rather erratic in their distribution.

Coke yield proved to be best for the 50–50 blend.

Ohyubari-Victoria Tunnel Blends (*Fig. 30*)

In so far as the mechanical properties of their individual cokes are concerned, the Victoria Tunnel product is definitely superior in macro-strength and that of Ohyubari is superior in terms of micro-strength; coke yield is slightly higher for Victoria Tunnel coal. The effects of blending the two coals are significant, variation in coke quality being reasonably systematic.

Both stability index and resistance to abrasion improve markedly with increase in the proportions of Victoria Tunnel coal up to 50%; shatter index was recorded as a definite maximum in the 50–50 blend coke. Micro-strength is most highly developed in cokes of the Ohyubari 75%-Victoria Tunnel 25% blend, and thereafter (with one exception) declines progressively as the proportion of Victoria Tunnel is increased.

Coke yield increases with the proportion of Victoria Tunnel coal up to a content of 75%.

Futase-Victoria Tunnel Blends (*Fig. 31*)

As related to the mechanical properties of their cokes these two coals are reasonably comparable in individual carbonization properties. The effects of blending upon the macro-mechanical properties of the cokes produced are generally modest and progressive; in relation to micro-strength they are emphatic and critical.

There is a general progressive improvement in shatter resistance with increases in the proportion of Victoria Tunnel coal, to a maximum for the coke produced from blends containing 75% of the Australian coal. Variation in macro-tumbler characteristics and resistance to abrasion is generally progressive, slight improvement accompanying increased proportions of Victoria Tunnel coal.

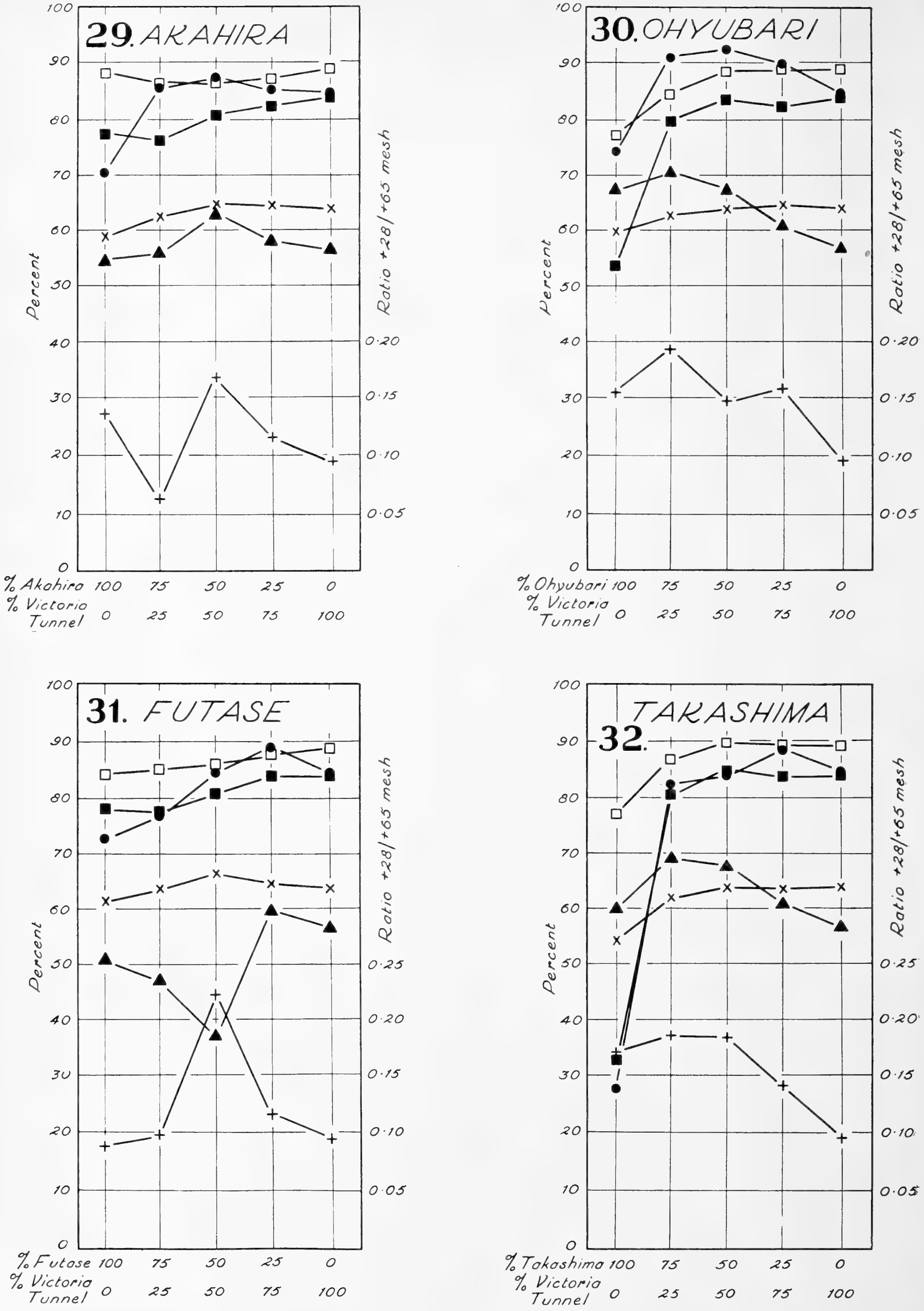
The effects of blending upon the micro-mechanical characteristics of the coke are conspicuous and critical; micro-strength 65 shows a pronounced minimum and micro-strength 28/65 an equally pronounced maximum for the carbonized product of the 50–50 blend. The rate of variation in the quality of the coke substance over the intermediate range of blends is very great.

Coke yield is at an appreciable maximum for the 50–50 blend.

Takashima-Victoria Tunnel Blends (*Fig. 32*)

The physical qualities of the individual cokes of the Victoria Tunnel and Takashima coals differ greatly and are in fact only comparable in respect of the micro-strength 65 index. The Australian coal is very much superior in respect of coke yield and macro-mechanical strength, while the Japanese coal returns a higher micro-strength 28/65. The blending of the two coals produces well defined changes of considerable magnitude.

The macro-strength of the Takashima coke is markedly improved by addition of 25% Victoria Tunnel coal in the charge; further increments induce little or no significant change



FIGS. 29–32

Variation in strength of cokes produced from blends of each Japanese coal with Victoria Tunnel coal

Legend: (see Figs. 2–5)

in either stability or resistance to abrasion, but shatter index achieves a maximum in coke of the Takashima 25%-Victoria Tunnel 75% blend.

As revealed by micro-strength indices, the mechanical quality of the resultant coke substance is at a maximum in Takashima 75%-Victoria Tunnel 25% blends, and decreases progressively with further increases in the proportion of the Australian coal.

The addition of even modest proportions of Victoria Tunnel coal improved coke yield quite substantially over that of the Takashima coal alone.

Wollondilly Bulli Blends with Japanese Coals

When coked alone under "standard" laboratory conditions Wollondilly Bulli coal returned a coke of moderate stability and resistance to shatter and of high resistance to abrasion; strength of coke substance and yield were good.

With few exceptions, the mechanical qualities of coke produced from blends of Wollondilly Bulli and the Japanese coals were improved significantly over those of the individual coals.

Akahira-Wollondilly Bulli Blends (*Fig. 33*)

As related to the mechanical properties of the cokes produced, the individual coking characteristics of these blend components were reasonably comparable; only in respect of coke yield was the Australian coal much superior. The effects of blending the two coals are especially significant in terms of coke shatter and stability indices.

Resistance to abrasion appeared to remain quite unaffected by blending, whilst shatter and stability varied progressively towards optimum quality in the coke produced from blends in which the two coals were equally represented. Micro-mechanical strength was rather variable, the "65" index being a maximum in the 50–50 blend coke and the "28/65" being highest for the Akahira 25%-Wollondilly Bulli 75% product.

Coke yield improved progressively and quite substantially with increase in the proportion of Wollondilly Bulli coal.

Ohyubari-Wollondilly Bulli Blends (*Fig. 34*)

As indicated by the majority of the mechanical properties of their individual cokes, the Wollondilly Bulli coal is generally superior to that of Ohyubari. The effects of blending are quite considerable.

All individual macro-strength indices are improved as a result of blending, the proportions Ohyubari 25%-Wollondilly Bulli 75% yielding a coke in which all macro-strength indices are at gentle to moderate maxima. Micro-mechanical qualities vary considerably, micro-strength 65 generally declining with increased proportions of Wollondilly coal, and micro-strength 28/65 attaining a maximum in cokes of equal-proportion blends.

Coke yield increased generally but not quite regularly with the proportion of Wollondilly Bulli coal in the charge.

Futase-Wollondilly Bulli Blends (*Fig. 35*)

The individual coking properties of the blend components are reasonably comparable, the Wollondilly Bulli coal being somewhat superior in terms of micro-strength and yield of coke. The effects of blending, however, are quite significant for both shatter index and micro-strength of the cokes which they yield.

Both coke stability and resistance to abrasion show slight deterioration as a result of blending, the former being at a minimum in cokes of the 50–50 blend, and the latter in the Futase 75%-Wollondilly Bulli 25%. On the other hand shatter indices of the blend cokes are significantly superior to those of either of the components.

As revealed by the micro-mechanical indices, the strength of the coke substance is at a maximum for cokes produced from blends in the proportions: Futase 25%-Wollondilly Bulli 75%.

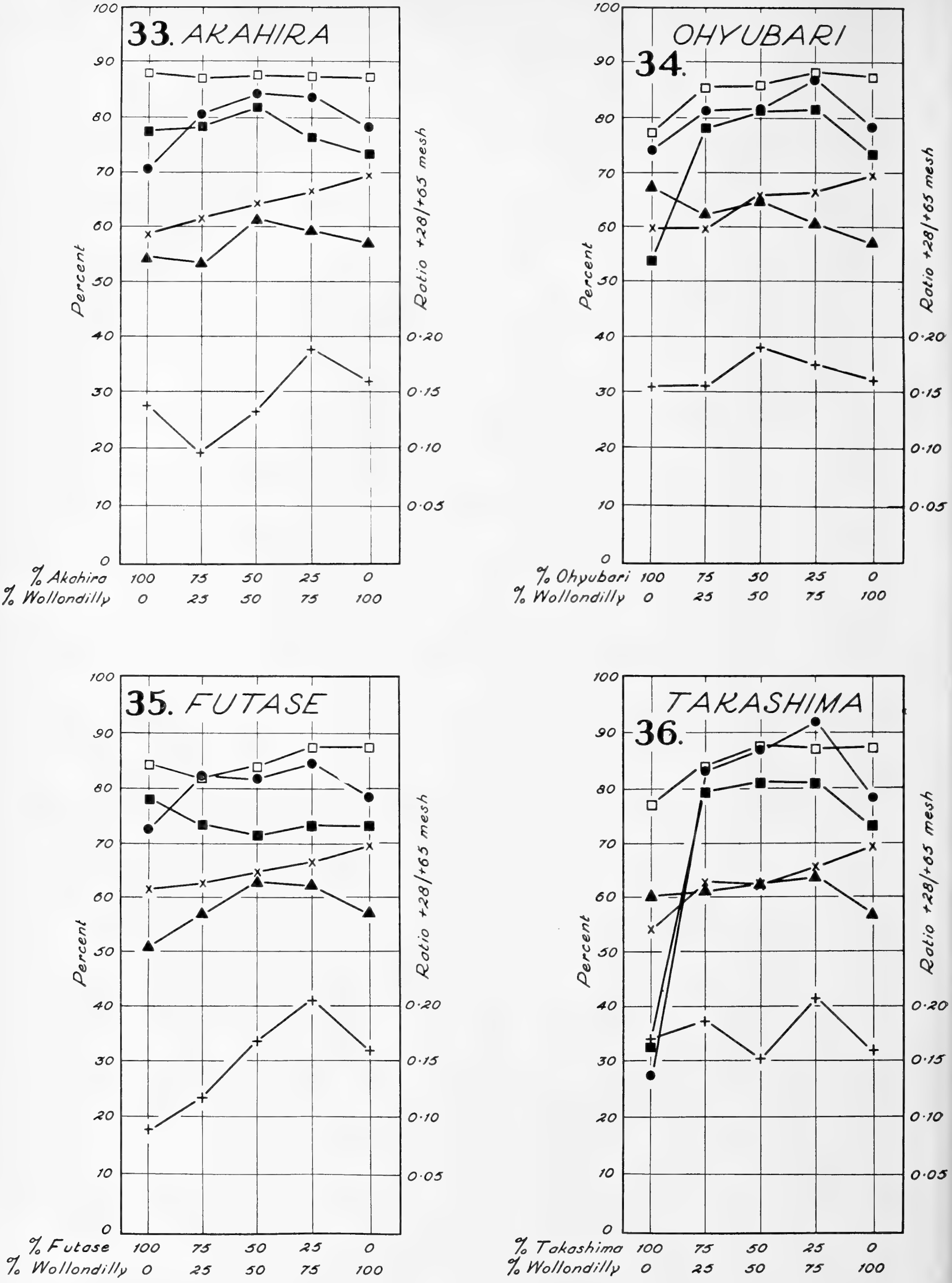
Coke yield increased progressively and substantially with increase in the proportions of Wollondilly Bulli coal.

Takashima-Wollondilly Bulli Blends (*Fig. 35*)

When carbonized alone, the individual blend components produce cokes of almost identical micro-mechanical strength, but in all other physical respects the Wollondilly Bulli coal is very much superior. The effects of blending are significant and generally systematic.

Coke shatter index improved to a very substantial maximum for the product of the Takashima 25%-Wollondilly Bulli 75% blend. The stability indices of the cokes produced from all blends studied are very comparable and significantly superior to those of the individual components; resistance to abrasion increased with additions of Wollondilly Bulli coal up to proportions of 50% in the coal charge.

Both of the micro-strength indices are at a maxima in coke produced from the Takashima 25%-Wollondilly Bulli 75% blend; micro-strength 28/65 attains a minimum value for the 50–50 blend coke.



Figs. 33–36

Variations in strength of cokes produced from blends of each Japanese coal with Wollondilly Bulli coal

Legend : (see Figs. 2–5)

Coke yield improved more or less progressively, with increased proportions of Wollondilly Bulli coal.

South Coast Bulli Blends with Japanese Coals

Under the " standard ", laboratory coking conditions of the present test series, the Bulli coal sample when carbonized alone, yielded a coke with moderate shatter, quite high stability and very high resistance to abrasion ; the micro-strength indices were excellent. Coke yield was also very high. In view of these characteristics, it is not surprising that although the macro-mechanical indices of the blend cokes are generally and sometimes quite substantially improved, the effects upon the physical properties of the coke substance are quite exceptionally good and usually regular.

Akahira-South Coast Bulli Blends (*Fig. 37*)

The two blend components are completely unlike in their individual coking properties ; the coke produced from the Bulli coal alone is superior in all respects to that yielded by the Akahira coal. With one exception, the range of variation in the mechanical properties of the cokes which they provide from blends is considerable, most especially in micro-strength.

Resistance to abrasion increased modestly with each increase in the proportion of Bulli coal in the blend. The shatter and stability indices achieved very satisfactory maxima with 25% and 50% of Bulli coal respectively in the charges. Micro-mechanical indices were generally improved greatly by increased proportions of Bulli coal in the blend.

Coke yield increased rapidly and proportionately as the content of Bulli coal in the charge was increased.

Ohyubari-South Coast Bulli Blends (*Fig. 38*)

Only in respect of shatter strength and micro-strength 65 of the resultant cokes are the two blend components at all comparable in their individual coking properties ; the Bulli coal returns a coke which is markedly superior in all other respects. Cokes produced from their blends exhibit considerable variation, and as would be anticipated, the effects assume importance in the control of virtually all properties.

Both shatter and stability indices are a maximum for cokes produced from blends in the proportions : Bulli 75%-Ohyubari 25% ; resistance to abrasion increases throughout with greater content of the Bulli coal.

Micro-strength 65 is a modest minimum for cokes of 50–50 blends, while the 28/65 index increases rapidly with the proportions of Bulli coal.

Coke yield also improves progressively throughout the blend range with increase in the Bulli content.

Futase-South Coast Bulli Blends (*Fig. 39*)

In respect of macro-strength indices of the resultant cokes the two blend components are not so very different in their individual coking properties, but both micro-strength indices and yield are much higher for the product of the Bulli coal alone. Variations in the mechanical properties of the cokes from these blends are systematic, significant and of particular importance in relation to the strength of the coke substance.

In general both coke stability index and resistance to abrasion increased progressively with greater proportions of Bulli coal in the charge. The shatter index attained a pronounced maximum in cokes produced from the 50–50 blends.

Micro-mechanical indices improved very substantially and progressively with increased proportions of Bulli coal in the charge.

Coke yield was increased proportionately by each increment of Bulli coal in the blend.

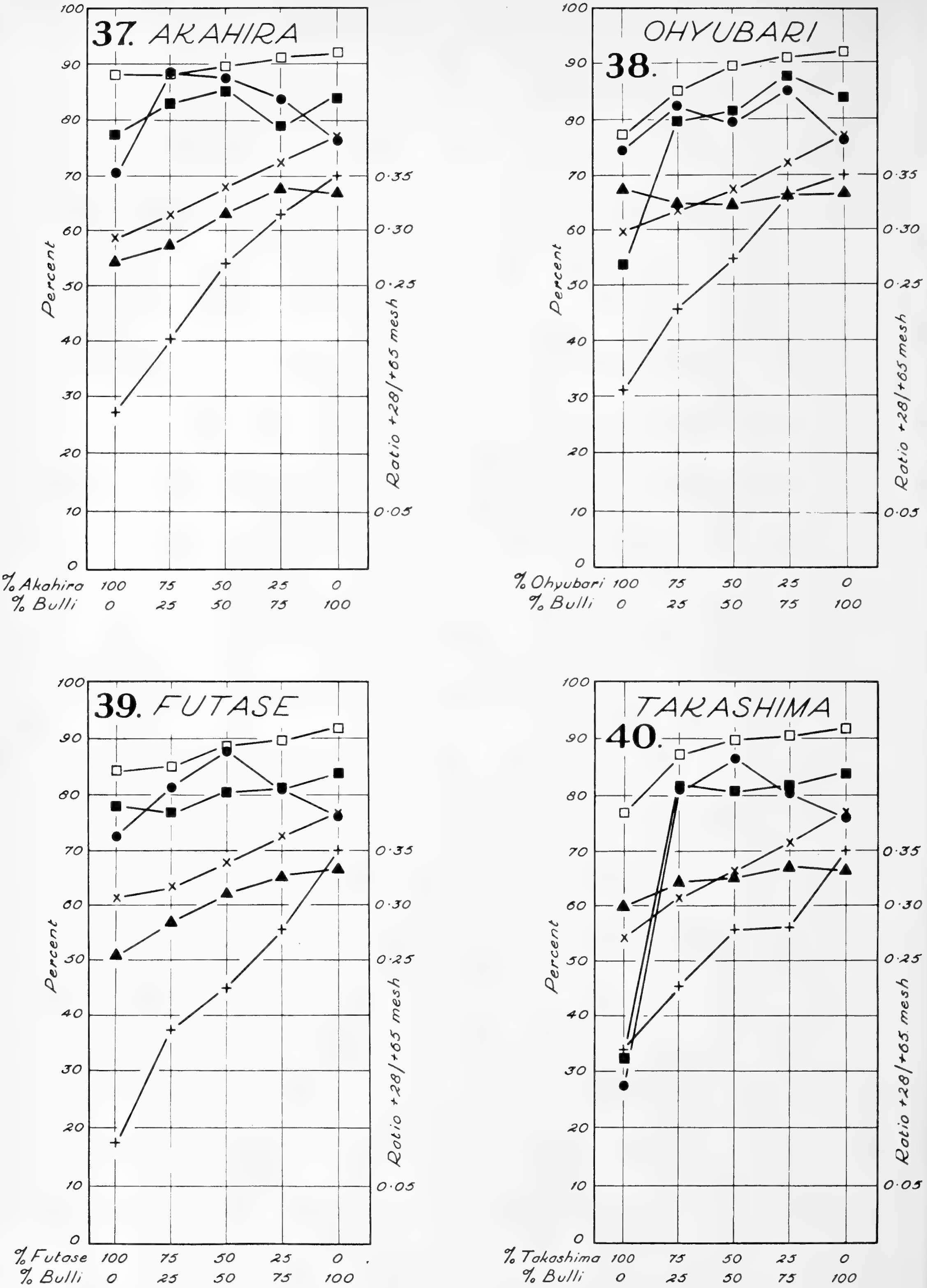
Takashima-South Coast Bulli Blends (*Fig. 40*)

Bulli coal is markedly superior to that of Takashima in its individual coking properties ; all strength indices, especially those of shatter, stability and micro-strength 28/65 as well as the yield are substantially higher for the coke produced from the Bulli coal. In general, the greatest proportionate effects of blending the two coals are obtained with up to 50% of Bulli coal in the oven charge.

With one minor exception the stability index and resistance to abrasion increased with the proportion of Bulli coal in the oven charge, the effect being particularly pronounced with up to 25% of the Australian coal present. Shatter index also exhibited great improvement over the same range, but the maximum was attained in cokes produced from blends in which the coals are present in equal proportions.

Both micro-mechanical indices increased generally with greater content of the Bulli coal.

Coke yield increased proportionately with Bulli content in the oven charge.



FIGS. 37–40

Variations in strength of cokes produced from blends of each Japanese coal with Coalcliff Bulli coal

Legend : (see Figs. 2–5)

Three Component Blends of Selected Japanese, Bulli and Liddell Coals

Previous discussion has been concerned with the generally significant and sometimes quite remarkable improvements in the mechanical properties of coke produced from two-component blends of certain Australian and Japanese coals ; in some cases the quality of the blend-coke may be such as to transcend that of either individual coke in the majority, if not all strength indices. Based upon this experience, considerable potential benefits could be expected as a result of blending in the coke oven charge, three coals of suitable individual characteristics in favourable proportions.

The magnitude of the task involved in critical and comprehensive evaluation of the factors concerned in the determination of coke quality, either from individual or blend charges, has already been indicated. As similar investigation of the factors controlling the quality of coke produced from three-component blends entails a very much greater volume of critical study the present three-component blend programme was of necessity limited to an introductory examination of the coking characteristics of blends in which two Australian coals were used in various proportions with each of the four selected Japanese coals.

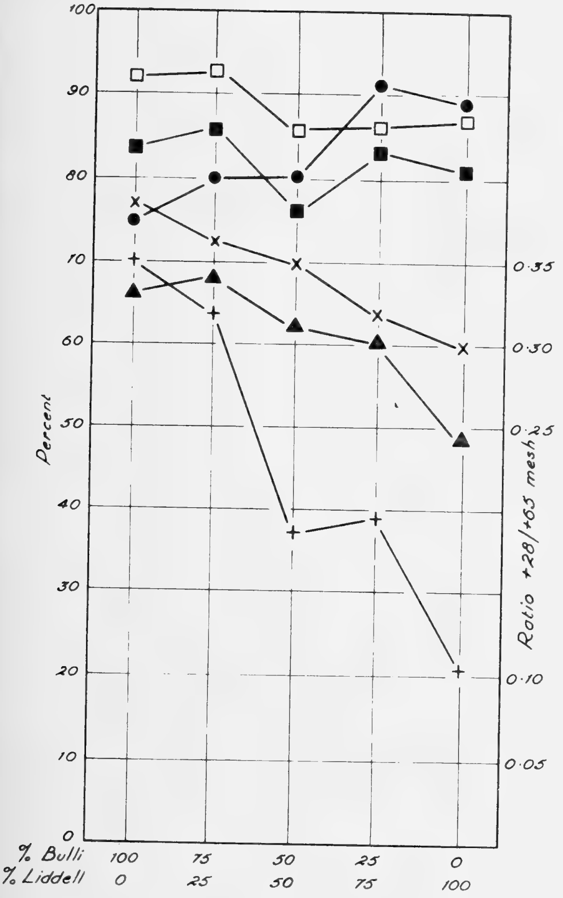


FIG. 41

Variations in strength of cokes produced from Liddell-Bulli blends

Legend : (see Figs. 2–5)

For this purpose, the Bulli coal of the South Coast and the Liddell of the Northern Coalfield were selected, these seams having formed the subject of previous extensive studies and appearing to offer immediate prospects of interesting results.

The standard conditions of preparation and coking developed for the two component blend studies were observed throughout the investigation. Under these conditions it emerges that both Bulli and Liddell coals make substantial contributions to the quality of the cokes produced from the three-component blends. In particular, the Liddell coal contributes significantly to improvements in coke macro-strength, especially as represented by the shatter index ; resistance to abrasion, micro-strength and coke yield are almost invariably greatly improved by the Bulli content of the oven charge.

The variations in the strength characteristics of the coke with different proportions of the three oven charge components are reproduced in the ternary diagrams, Figs. 42–45. It must be emphasized that these variation diagrams, based upon a relatively " coarse " pattern of blend distribution, represent trends which are subject to qualification in the light of results which may be gained from more detailed study.

Bulli-Liddell Blends (*Fig.* **41**)

As of possible assistance to the interpretation of the results of the three component blend studies, a preliminary investigation of the quality of the coke produced from blends of the Liddell and Bulli coals was undertaken. The results are graphed in Fig. 41.

Under standard conditions of coking, Bulli coal alone produced a coke of moderate shatter, good stability and very good resistance to abrasion. Micro-strength indices were exceptionally high and coke yield good.

The Liddell seam coked alone yielded a coke of high resistance to shatter and abrasion, moderate stability and rather low strength in

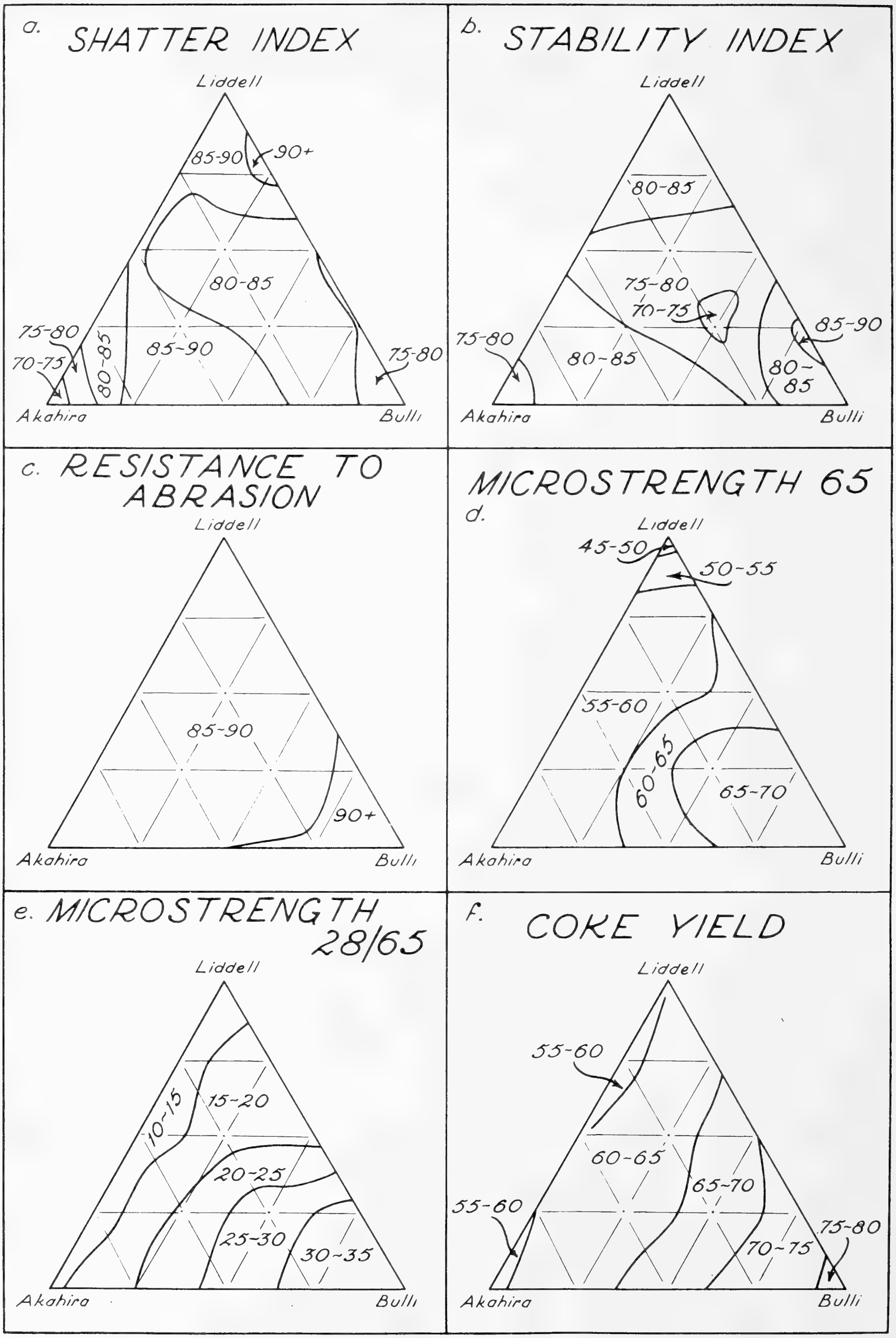


FIG. 42

Variations in strength of coke produced from Akahira-Liddell-Bulli three-component blends the coke substance. Coke yield was relatively low.

Cokes produced from blends of Liddell and Bulli coals establish highly significant trends in their strength characteristics, which assume critical importance in the control of preferred mechanical qualities; briefly, to produce a coke of high impact strength requires a high proportion of Liddell coal in the charge and for a coke of optimum stability and hardness characteristics a high proportion of Bulli coal must be employed.

Highest shatter index was recorded for cokes produced from Bulli 25%-Liddell 75% blends. The stability index and resistance to abrasion were both at their maximum for coke of the Bulli 75%-Liddell 25% blend; minima for each were recorded for 50–50 blends.

In general, both micro-strength indices deteriorate rapidly from very high figures for the coke from Bulli coal alone with each increase in the proportion of Liddell coal; a modest maximum for micro-strength 65 occurs with the Bulli 75%-Liddell 25% blend.

Coke yield decreased progressively and rapidly with each increase in the proportion of Liddell coal.

Akahira-Liddell-Bulli Blends (*Fig. 42*)

Blends of these three coals in certain proportions in the oven charges yield cokes having mechanical strength superior to any one of the cokes produced from the individual components alone. As in no blend-coke do the various maxima for all macro- and micro-indices correspond, selection of an " optimum " blend would depend entirely upon particular consumer requirements.

Extremely good resistance to shatter was developed in cokes produced from oven charges of approximately 75% Liddell, 25% Bulli, 25% Akahira. Almost as high shatter indices were obtained in cokes of two general types of blend: one in which the content of Liddell coal exceeded 70%, and the second in which this same seam made up less than 30% of the oven charge (Fig. 42).

High stability indices were characteristic of the cokes produced from a variety of blends notably those in which the proportion of Liddell coal exceeded 60–65%, in which the representation of Bulli coal exceeded 75–80%; or in which the contribution of Akahira coal lay between 50% and 85%. In each case the relative proportions of the other components were apparently of minor significance (Fig. 42b). Markedly inferior stability was developed in cokes formed from blends containing approximately equal proportions of the three components.

Resistance to abrasion was quite high for the cokes of all blends considered (Fig. 42c). In general, cokes of exceptionally high abrasion resistance were produced from blends in which the proportion of Bulli coal exceeded 65%.

Both coke micro-strength indices were improved progressively as the proportion of Bulli coal in the oven blends was increased, the indices being rather low for the cokes produced from Liddell or Akahira coal alone (Figs. 42d and 42e). All blends in which the proportions of Bulli coal exceeded 65% resulted in cokes of quite high micro-strength.

Coke yield was increased progressively as the proportion of Bulli coal increased (Fig. 42f).

The results of these three component blend studies indicate clearly the importance of Liddell coal in the development of high stability and resistance to shatter, while the Bulli coal contributes greatly to the quality of the coke substance. Particular quality requirements will dictate the composition of the blend to be used.

However, from the consideration of all macro- and micro-strength indices and coke yield (Fig. 58) it appears that blends of Akahira, Liddell and Bulli coals possessing the " optimum " combination of all assessed characteristics (i.e. an overall index of 70 or more) can accept as little as 44% Bulli coal, provided the content of Liddell coal does not exceed 5%. Cokes produced from the two extreme blends satisfying these requirements would be expected to have the following characteristics.

Index	Maximum for Bulli-Akahira-Liddell Series	Bulli 44% Liddell 5% Akahira 51%	Bulli 44% Liddell 0% Akahira 56%
Shatter	91% (Liddell 75-Bulli 25)	87% High	87% High
Stability	88% (Bulli 50-Akahira 50)	87% V. High	88% V. High
Resistance to abrasion	93% (Bulli 75-Liddell 25)	90% V. High	90% V. High
Micro-strength 65	69% (Bulli 50-Liddell 25-Akahira 25)	63% High	62% High
Micro-strength 28/65	0·35 (Bulli alone)	0·26 High	0·26 High
Coke Yield	77% (Bulli alone)	66% Mod. High	66% Mod. High

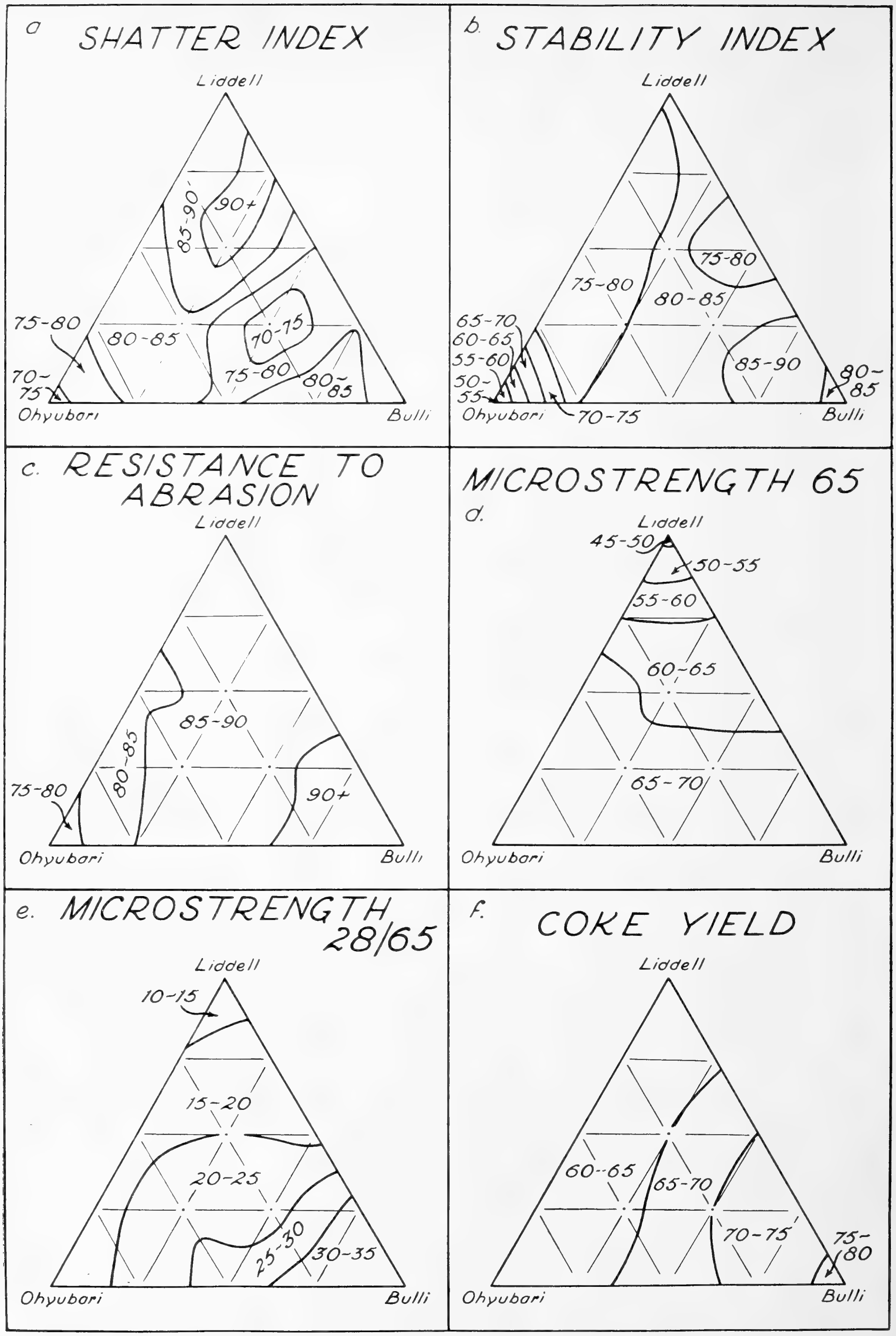


FIG. 43
Variations in strength of coke produced from Ohyubari-Liddell-Bulli three-component blends

Ohyubari-Liddell-Bulli Blends (*Fig. 43*)

From the various blends of Ohyubari, Liddell and Bulli coals were produced cokes of superior macro- and micro-strength as compared with those yielded by any of the three component seams when carbonized alone. Unfortunately, no single blend was characterized by maxima for all strength indices.

To obtain coke with the best possible resistance to shatter, not less than 25% Liddell coal should be included in the charge, the proportions of the remaining two components being generally weighted slightly in favour of Ohyubari coal; if the proportion of Bulli coal exceeds that of Ohyubari, a coke of low impact strength may result. Blends in the proportions Liddell 40–85%, Bulli 15–30%, Ohyubari 0–30% produce coke which is extremely resistant to shattering (Fig. 43a).

Cokes with best stability characteristics are obtainable from blends in which the content of Bulli coal lies between 60% and 90%. Quite good stability characteristics are secured with as little as 20% Bulli in the oven charge, the relative proportions of the other two components affecting the situation but little. If the content of Bulli coal is reduced below 25%, as high a proportion as possible of Liddell coal is necessary for the production of coke of acceptable stability (Fig. 43b).

Resistance to abrasion improves with the content of either Bulli or Liddell coal, the effect of the former being the more pronounced (Fig. 43c).

Maximum micro-strength 65 was developed in cokes produced from equal proportion blends of Ohyubari and Liddell but this factor decreased progressively with greater proportions of Liddell coal (Fig. 43d); micro-strength 28/65 improved with increased proportions of Bulli coal (Fig. 43e).

Coke yield improved as the content of Bulli coal in the blends was increased (Fig. 43f).

From this three-component coking study there again emerges the importance of the Bulli coal in relation to strength of coke substance and resistance to abrasion; control of shatter is similarly dominated by the content of Liddell coal.

Consideration of all mechanical indices and coke yield (Fig. 59) indicates that the " optimum " combination of the various strength and yield characteristics can be achieved with a minimum of approximately 62% Bulli coal in the charge. In these circumstances the relative proportions of Liddell and Ohyubari coal appear to be of relatively minor consequence; if strength of coke substance is of major importance then the content of Liddell coal in the charge should not exceed 25%. Cokes produced from the two extreme cases satisfying these requirements are predicted as having the following characteristics.

Index	Maximum for Bulli-Ohyubari-Liddell Series	Bulli 62% Liddell 25% Ohyubari 13%	Bulli 62% Liddell 0% Ohyubari 38%
Shatter	92% (Liddell 50-Bulli 25-Ohyubari 25)	76% Moderate	82% Mod. High
Stability	87% (Bulli 75-Ohyubari 25)	85% V. High	85% V. High
Resistance to abrasion	93% (Bulli 75-Liddell 25)	91% V. High	90% V. High
Micro-strength 65 ..	70% (Liddell 50-Ohyubari 50)	67% V. High	66% V. High
Micro-strength 28/65 ..	0·35 (Bulli alone)	0·27 High	0·30 V. High
Coke Yield	77% (Bulli alone)	71% High	69% Mod. High

Futase-Liddell-Bulli Blends (*Fig. 44*)

The blending of these three coals in certain definite proportions yields cokes of mechanical qualities which are in most respects superior to those produced from any of the components alone. However, in no single blend do the various mechanical strength indices all exhibit their particular maxima.

Highest shatter indices are again recorded for the cokes of blends in which the content of Liddell coal is high (approximately 75%), and where the remainder of the blend is made up of a slight preponderance of Bulli coal (Fig. 44a).

In general, highest stability indices were obtained for cokes produced from blends containing no more than minor proportions of Futase coal (Fig. 44b).

Cokes with acceptable resistance to abrasion were produced from practically all blends except those in which the proportion of either Bulli or Liddell coal fell below 60%. Particularly high resistance to abrasion was recorded for cokes of blends having in excess of 75% Bulli coal. The lowest resistance to abrasion occurred in cokes produced from blends in which the Liddell and Futase components were present in approximately equal proportions and of which the Bulli coal was a minor part (Fig. 44c).

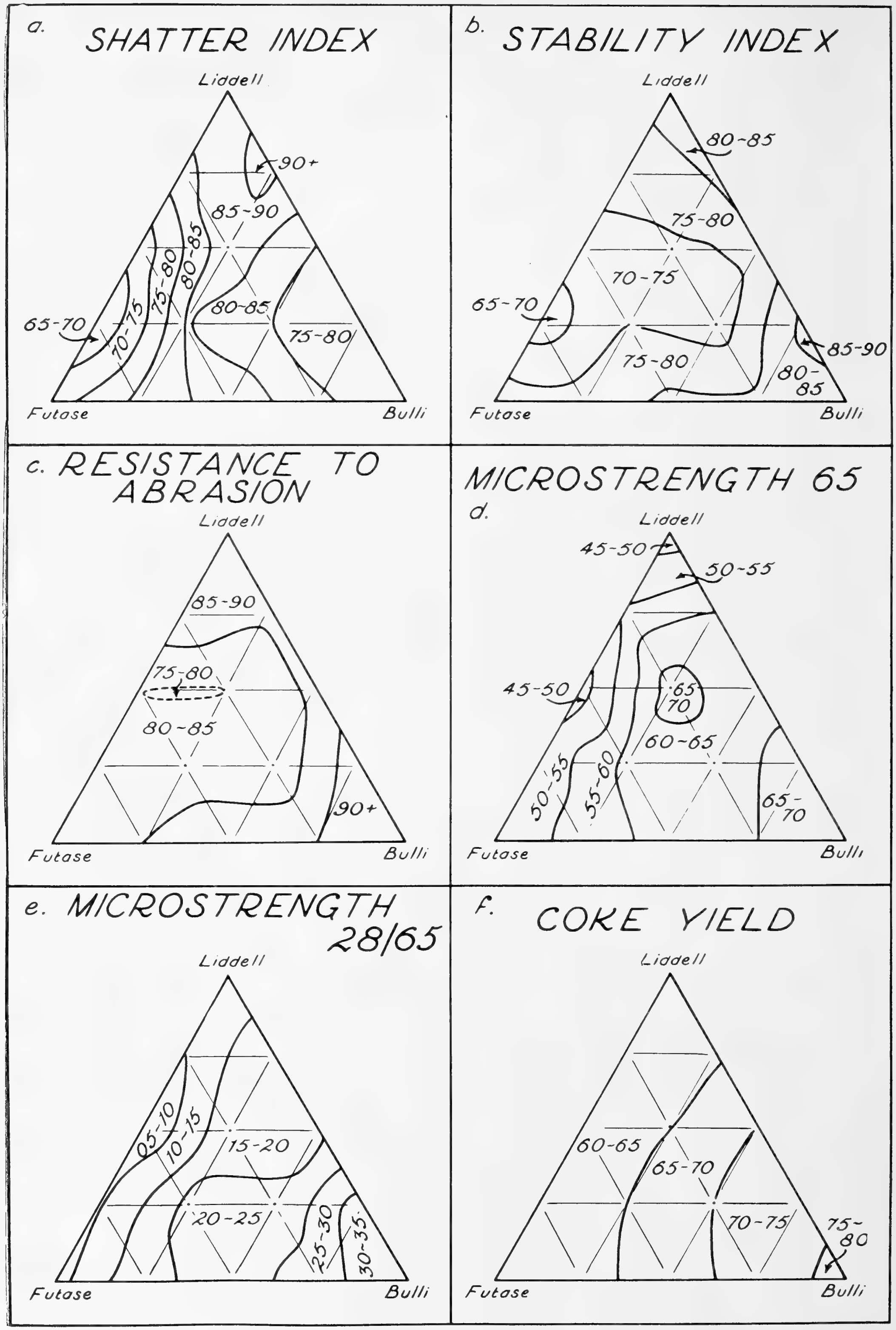


Fig. 44

Variation in strength of coke produced from Futase-Liddell-Bulli three-component blends

In general, the strength of the coke substance (micro-strength indices) improved as the proportion of Bulli coal in blends was increased; the indices were relatively low for cokes produced from both Liddell and Futase coals alone, but were much improved where the proportion of Bulli coal in the blends exceeded 25%, becoming very high where this component exceeded 75% of the charge. The micro-strength 65 index was at an unexpected maximum in cokes produced from blends containing 25% Bulli, 50% Liddell, 25% Futase (Fig. 44d).

Coke yield increased progressively with the proportion of Bulli coal in the oven charge (Fig. 44f).

The relative importance of the Liddell and Bulli coals in the development of high resistance to shatter and greatest strength of coke substance respectively, is again evident in the results of this three component blend study. From the consideration of all mechanical indices and yield it appears that coke of " overall optimum " quality (i.e. overall index of 70 or more) will be produced from blends in which the proportion of Bulli coal is as low as 68% provided that a maximum of 7% Futase is used. Coke produced from the two extreme cases satisfying these requirements would probably have the following characteristics.

Index	Maximum for Bulli-Liddell-Futase Series	Bulli 68% Liddell 25% Futase 7%	Bulli 68% Liddell 32% Futase 0%
Shatter	91% (Liddell 75-Bulli 25)	80% Moderate	80% Moderate
Stability	86% (Bulli 75-Liddell 25)	83% High	85% V. High
Resistance to abrasion ..	93% (Bulli 75-Liddell 25)	90% V. High	91% V. High
Micro-strength 65 ..	68% (Bulli 75-Liddell 25)	67% High	67% High
Micro-strength 28/65 ..	0·35 (Bulli alone)	0·29 High	0·29 High
Coke Yield	77% (Bulli alone)	71% High	71% High

Takashima-Liddell-Bulli Blends (*Fig. 45*)

From one blend of these three coals there was obtained a coke in which practically all strength characteristics approached or achieved their maxima. Although selection of a blend to yield " optimum " coke quality would still depend upon consumer requirements, it is possible to define one in which all mechanical characteristics of the coke produced would be good.

Variations in the shatter indices of the blends of Takashima, Liddell and Bulli coals differ somewhat from those of the other three component blends (Fig. 45a). Greatest resistance to shatter was provided in cokes yielded by blends approximating Liddell 75%, Bulli 15–30%, Takashima 0–5%. In general, more than 65% Liddell coal, 60–70% Takashima, or 40–75% Bulli (provided other component proportions were correct) would be conducive to good resistance to shatter in the coke produced from the blend. Proportions of Bulli coal in excess of 75% are accompanied by substantial deterioration in this strength index (Fig. 45a).

The proportion of Bulli coal in the blend and, to a lesser extent, that of Liddell, has a dominant influence upon coke stability (Fig. 45b); content of Bulli less than 25%, or a proportion of Liddell between 70% and 40% appears generally critical for this quality.

Resistance to abrasion improved as the proportion of Bulli coal (and to a lesser degree that of Liddell) was increased in the blends; particularly high indices were measured in cokes representing blends with a content of Bulli coal in excess of 50% (Fig. 45c).

Both micro-strength 65 and 28/65 decreased progressively with increased proportions of either Liddell or Takashima coal in the oven charges. Even quite low proportions of Bulli coal in the blend may provide coke of relatively high micro-strength 65 provided that the proportions of the other components are carefully balanced (Fig. 45d). In general, the proportions of Bulli coal are dominant in determining the micro-strength characteristics of the coke substance.

Coke yield improved progressively with greater proportions of Bulli coal in the blends.

The results of this three component blend study again demonstrate the respective importance of the Bulli and Liddell coals in the development of greatest strength of coke substance and resistance to shatter.

Consideration of all mechanical strength indices and coke yields (Fig. 61) indicates that blends most likely to yield cokes of " overall optimum " quality (i.e. overall indices of 70 or more) could contain as little as 50% Bulli coal, provided in such cases the content of Liddell

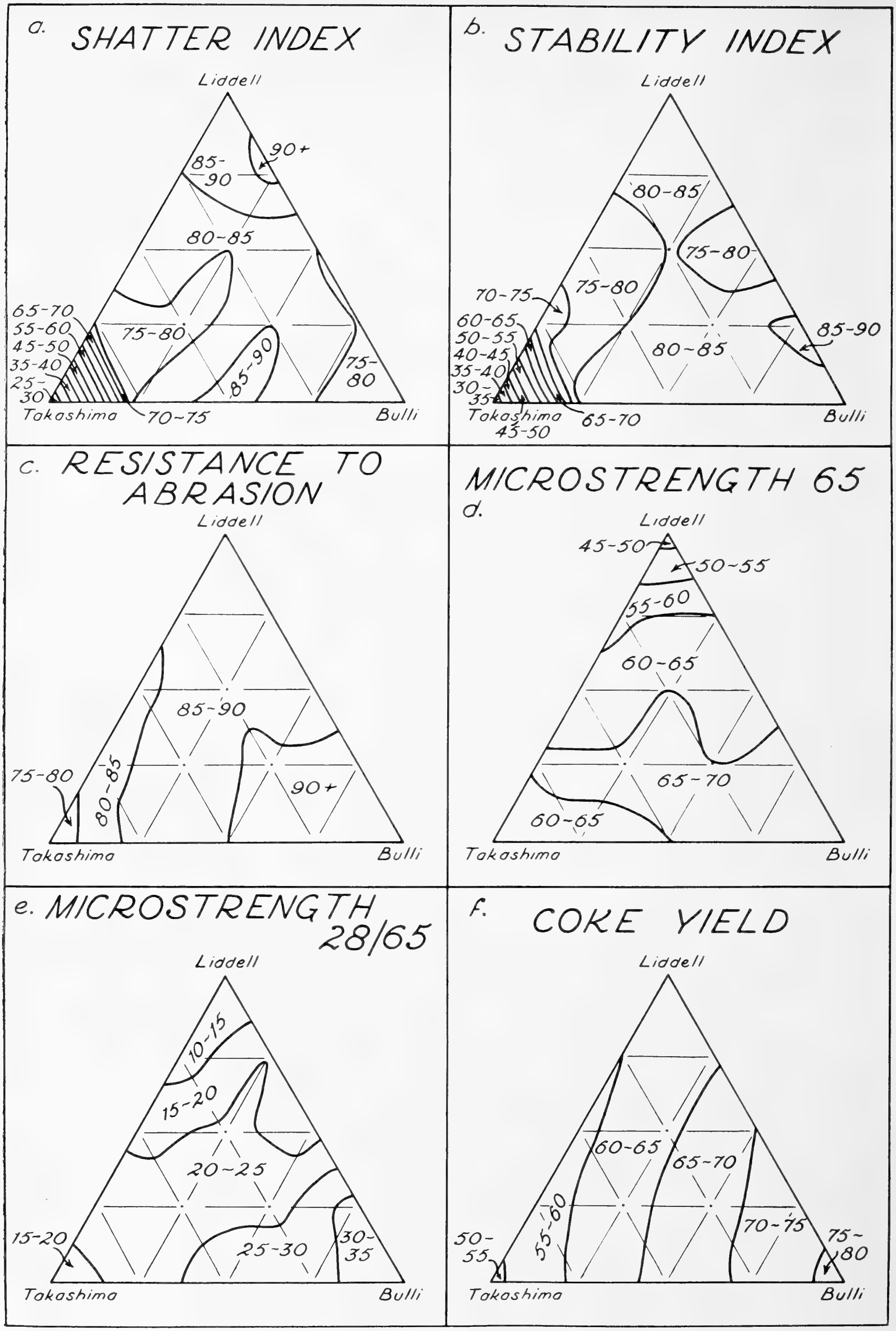


Fig. 45

Variations in strength of coke produced from Takashima-Liddell-Bulli three-component blends

Index	Maximum for Bulli-Liddell-Takashima Series	Bulli 50% Liddell 25% Takashima 25%	Bulli 50% Liddell 0% Takashima 50%
Shatter	91% (Liddell 75-Bulli 25)	85% High	89% High
Stability	86% (Bulli 75-Liddell 25)	83% High	81% High
Resistance to abrasion ..	93% (Bulli 75-Liddell 25)	91% V. High	90% V. High
Micro-strength 65 ..	68% (Bulli 75-Liddell 25)	65% V. High	65% V. High
Micro-strength 28/65 ..	0·35 (Bulli alone)	0·24 Mod. High	0·28 High
Coke Yield	77% (Bulli alone)	69% Mod. High	67% Mod. High

coal did not exceed 25%. Cokes produced from the two extreme cases satisfying these requirements may be expected to have the characteristics shown in the table.

Summary

The principal objectives of this study were two in number, mutually supporting, equally important, and both of immediate and future concern. The basic purpose was to ascertain the potential variation in coking characteristics of coals of different types, ranks and ages, under various controlled conditions, singly and in blends, so as to determine whether more critical and detailed studies would be justified, and if so to serve as a guide and basis for such studies. The more immediate purpose was to determine the relative suitability of a number of well-known New South Wales coals for blending with four selected Japanese coals, and to indicate the order of improvement in the physical quality of the resultant cokes which might be expected in each case. In order to accomplish these purposes within a reasonable time, it has been necessary to ignore many facets of the study which preliminary work and other detailed studies have indicated as potentially significant. It is proposed to extend later work into these presently neglected fields of interest.

Earlier studies have demonstrated the importance of petrographic, chemical and size control in the determination of the coking characteristics of a single seam. The particular circumstances of the present investigation have permitted only partial assessment of these factors in coals of widely differing age and sometimes contrasted rank but they have served to emphasize the need for critical, individual study of each particular coal. The results indicate clearly the vast amount of work necessary to give a complete picture of the interplay of all factors in relation to preparation and carbonization behaviour.

Thermal Regime and Carbonization Characteristics

The preliminary brief assessments of the suitability of various oven charging temperatures for each of the coals used in the blending study have been most rewarding. They have confirmed in large measure the results of previous work and current investigations which indicate that for the majority of the coals examined, an oven charging temperature of 800° C favours production of coke of an overall superior mechanical quality.

Summary graphs show the relationship of an " overall strength index " and an " overall strength-yield index " respectively with variations in oven charging temperature for each of the coals (Figs. 46 and 47). Inclusion of coke yield in the overall index (Fig. 47) does not alter the general trend of quality variation with charging temperature ; because of their greater coke yield only the indices of the Coalcliff and Wollondilly Bulli samples are significantly affected. Figures 46 and 47 also indicate that, under the condition of test, an oven charging temperature of 800° C appears most suitable for all save one of the Australian coals and for two of the four Japanese coals. For the Greta coal a slightly superior coke is produced at a charging temperature of 600° C, while for Ohyubari and Takashima coals the most favourable initial oven temperatures range from laboratory temperature to 200° C.

Under " standard " thermal conditions (including an oven charging temperature of 800° C) the Coalcliff Bulli coal yields a coke of excellent " overall strength " (index 71) ; in this respect it is superior to the cokes of the Victoria Tunnel, Borehole, Liddell, Wollondilly and Young Wallsend coals of which the indices range in order between 64½ and 62½. The overall strength of Greta coke (index 59) is appreciably less. Under the same conditions all Japanese coals yield cokes which are markedly inferior to those of the selected Australian coals ; the Akahira, Futase and Ohyubari return cokes of " overall strength " 61, 58½ and 57½ respectively

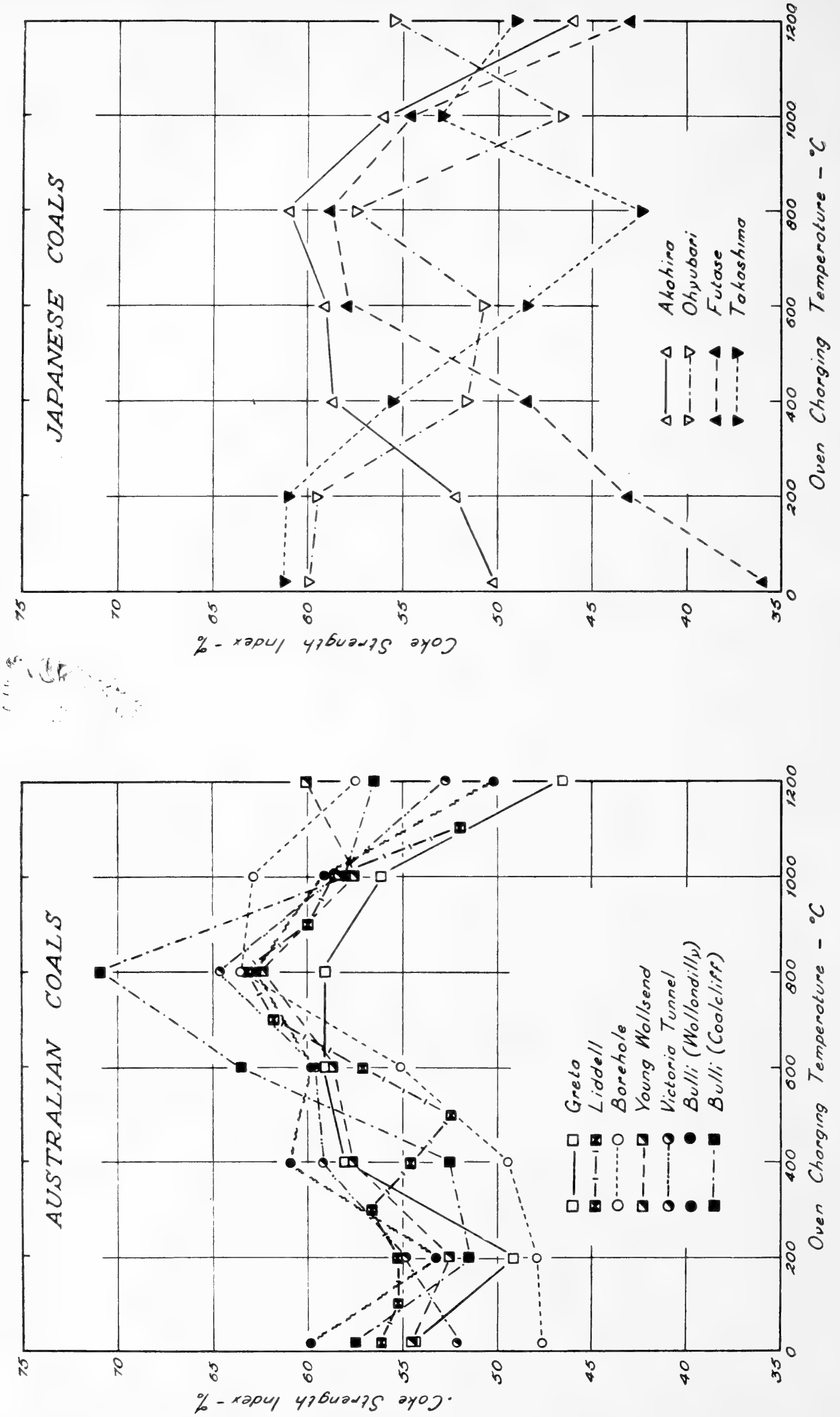


FIG. 46

Effect of charging temperature on overall strength index of cokes produced from each blend component

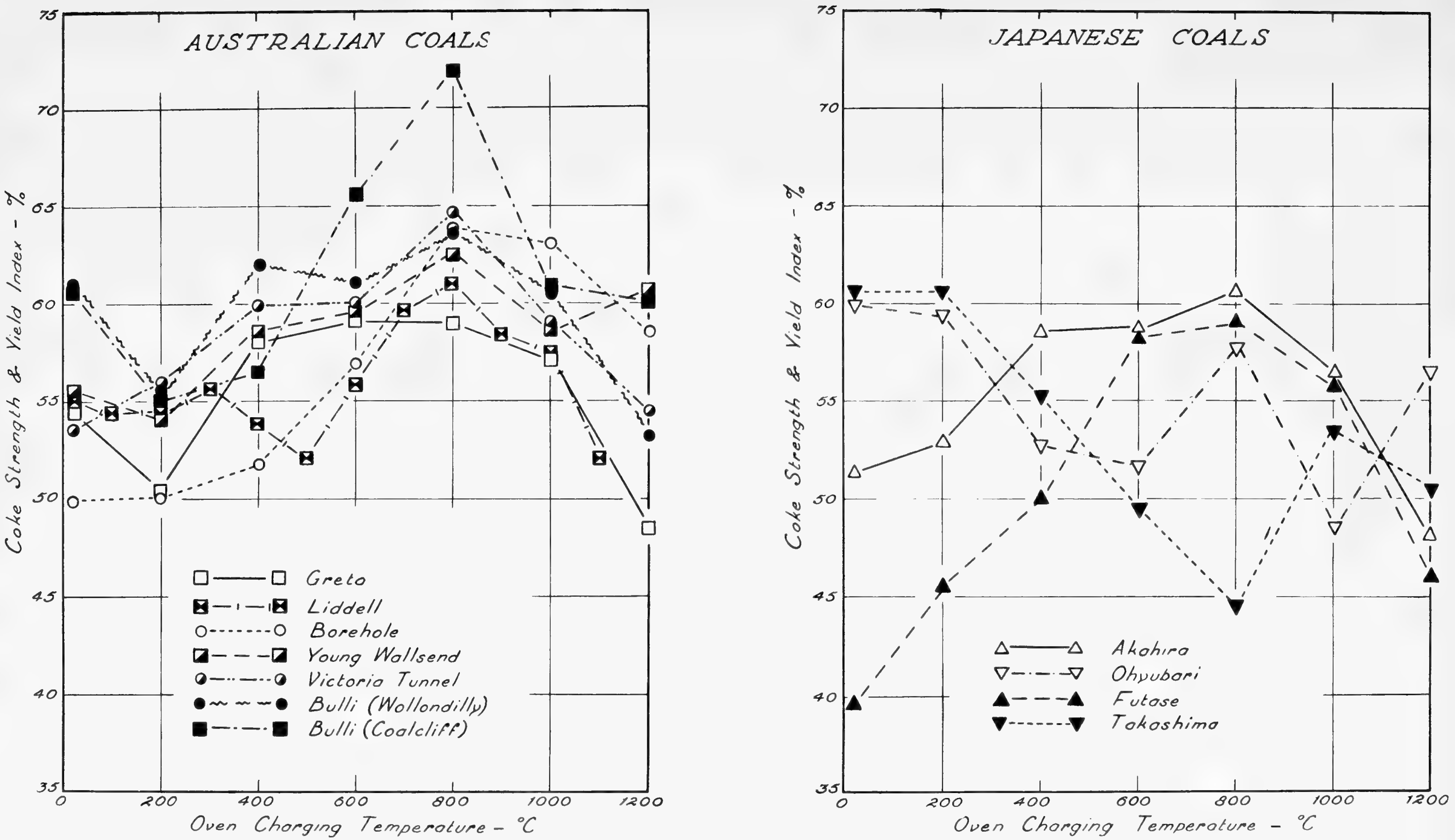


Fig. 47
Effect of charging temperature on overall strength-yield index of cokes produced from each blend component

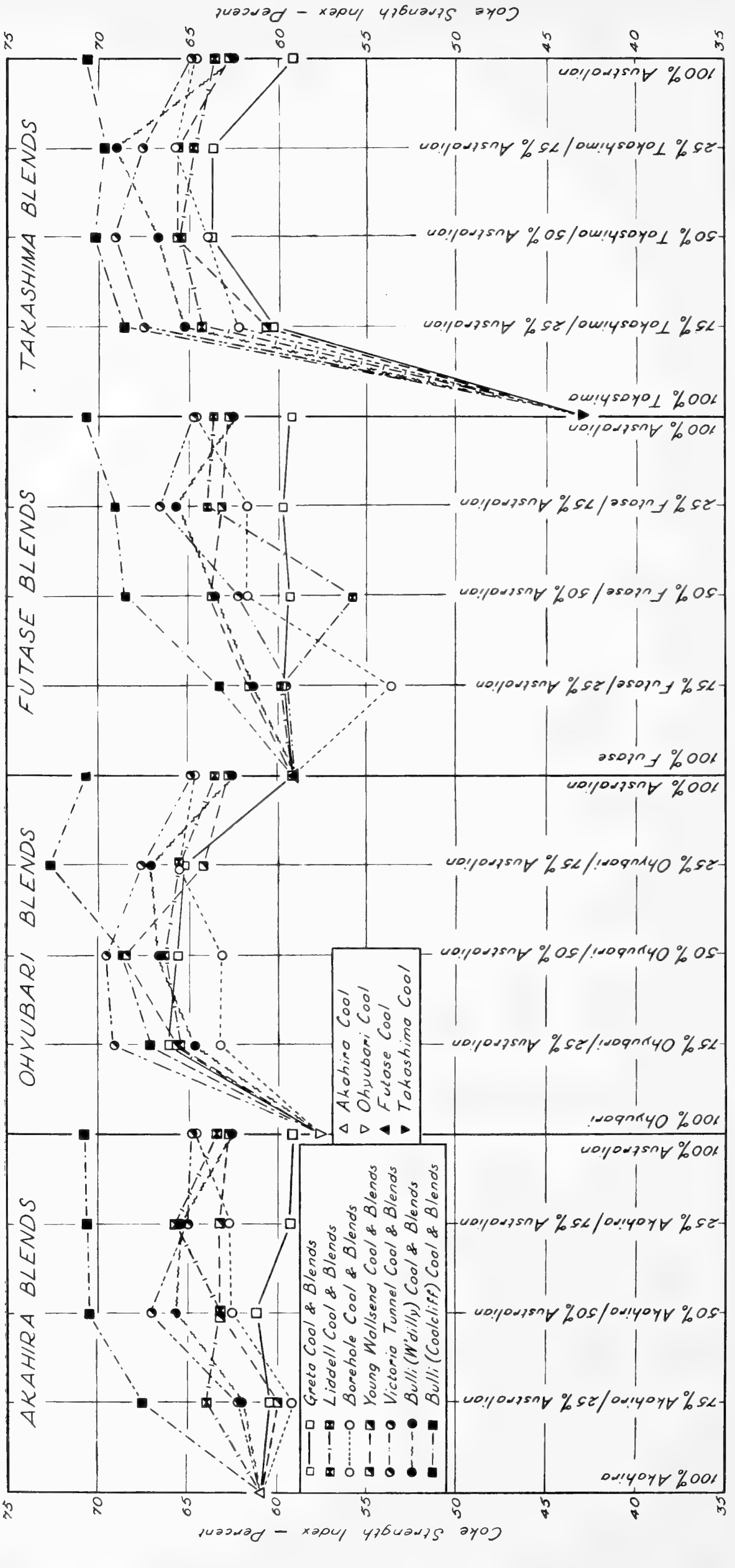


Fig. 48

Comparative variations in the overall strength indices of cokes produced from each Japanese coal when blended with individual Australian coals in various proportions

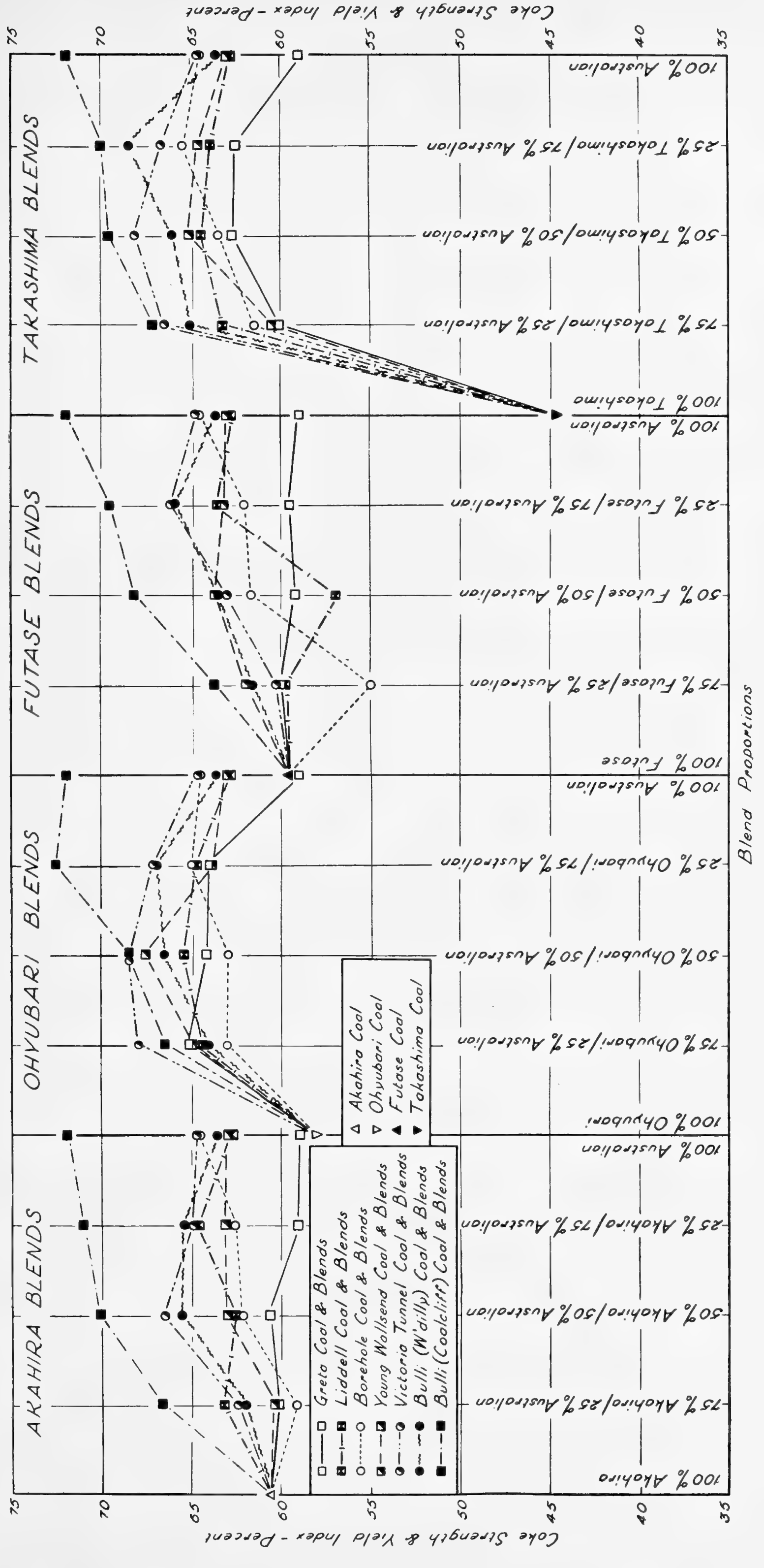


FIG. 49

Comparative variations in the overall strength-yield indices of cokes produced from each Japanese coal when blended with individual Australian coals in various proportions (making them reasonably comparable with the poorest of the Australian coals) whilst Takashima coke is characterized by an extremely low index of $42\frac{1}{2}$.

It is evident from Figure 46 that the trends of overall quality in relation to temperature of charging and associated rate of heating through the initial range of increase of temperature up to that of the oven, are by no means uniformly systematic. One significant feature is the pronounced "local" deterioration of coke quality in an otherwise progressive improvement to a maximum, exhibited by the majority of Australian coals when the charging temperature is either in or immediately adjacent to their plastic range; exceptions were provided by Victoria Tunnel and Borehole coal. Extremely variable trends characterized both Ohyubari and Takashima cokes, in contrast with the much more regular behaviour of those of Futase and Akahira. The pronounced deterioration of coke quality in relation to these particular charging temperatures indicates significant modification and variation of coke structure.

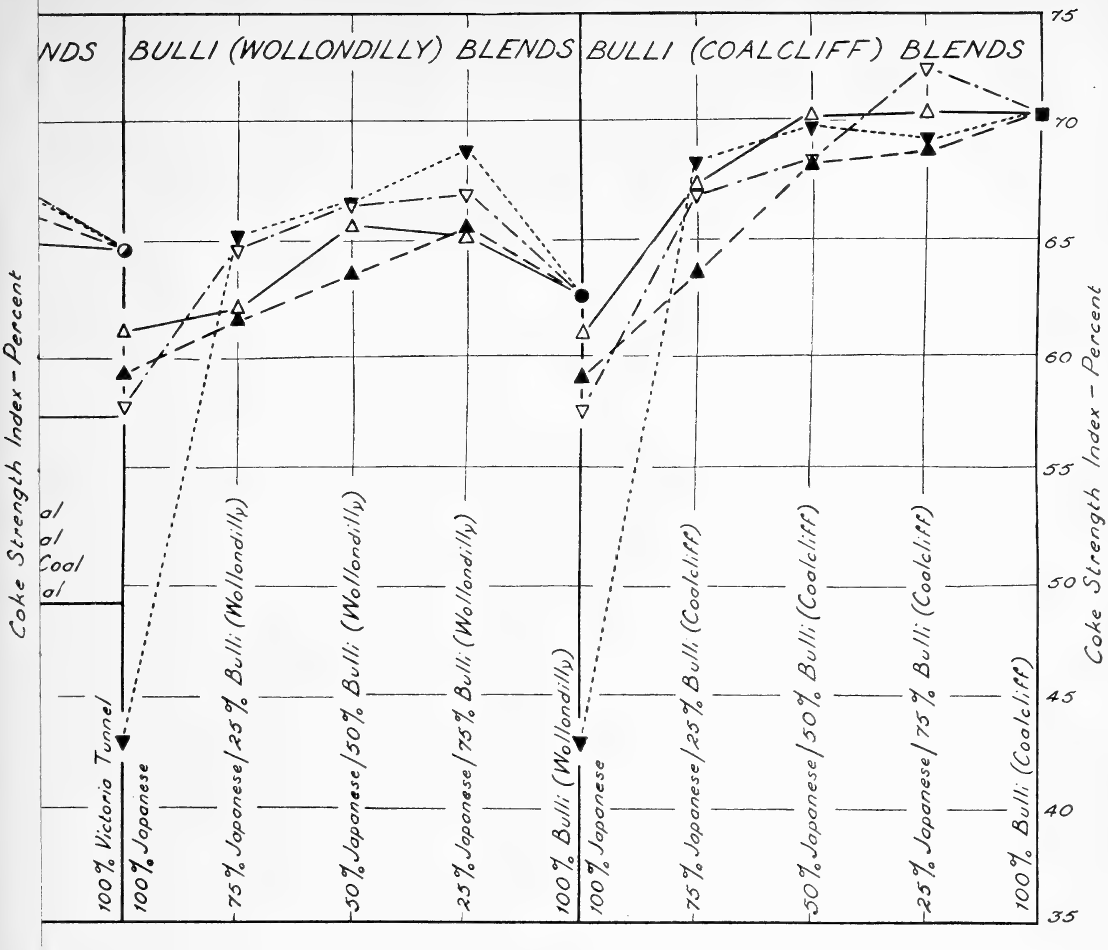
The inferior overall quality associated with cokes formed from Australian coals charged in the lower temperature ranges is characterized by markedly higher proportions of fine coke or "breeze" which generally contribute to low values for both macro- and micro-mechanical strength indices. No such effect has been observed in cokes produced from either Australian or Japanese coals when charged at higher temperatures, any deterioration then being limited and made apparent only in macro-strength.

Deterioration in the mechanical quality of coke as made evident by minimal values for one or more of the strength indices, thus appears to be critically related to the rate of heating of the charge through the plastic range of the coal; depending upon the particular characteristics of the coal (petrographic, physical and chemical), rates of heating which are too low and/or too high may produce coke of inferior quality. From observations made during previous and present studies, these quality variations appear to be related both to the fundamental micro-structure of the coke substance and the macro-structure of the coke mass, each apparently being affected by the conditions and rate of heating of the charge through the plastic range. The potential scale and rate of volume changes in the coal charge, the time available for their development as controlled by the rate of heating in the plastic range, the subsequent history of adjustment to the stresses developed, must affect the intensity and distribution of fracturing and jointing (evident or incipient) and thus condition the macro-strength characteristics. The destruction of the original "petrological" structure of the coal substance through carbonization, and the development of a new coke "micro-constituent" of quite remarkable properties, have been demonstrated; it is almost certainly and possibly critically affected not only by the petrographic constitution and character of the coal in oven charges, but also by specific features of the thermal cycle. Detailed studies of the macro- and micro-structure of coke as produced under critically controlled rates of heating throughout the whole thermal cycle and especially referred to the plastic range, related to the petrological, physical and chemical characteristics of the original coal substance, are considered to be matters of fundamental and economic importance which demand immediate and comprehensive attention.

Two-Component Blends

The results of the two-component blend studies show that any one of the seven Australian coals examined is capable of effecting some degree of improvement in the "overall strength" of the coke produced from each of the Japanese coals. In some cases, notably in blends of the relatively poorly coking Greta with either the Akahira or Futase coal (which are reasonably comparable in coking characteristics with this particular Australian coal), improvement is relatively slight and only occurs in some of the blends. Further, certain blends of Futase coal with either Liddell or Borehole seam, provide cokes of appreciably lower overall strength than those of either component when carbonized alone. In the case of the particular Futase-Liddell blends under discussion, this deterioration is brought about by reduction in all strength characteristics; for the Futase-Borehole blends, only the shatter and stability indices are affected.

Figures 48–53 inclusive summarize the results of the two-component blend studies on the basis of overall strength characteristics. Figures 48 and 49 depict comparative variations in, respectively, the mechanical properties and the combined mechanical and yield properties of the cokes produced from each Japanese coal when blended with individual Australian coals in various proportions. Figures 50 and 51 relate the same information to the cokes produced from each of the Australian coals when blended with individual Japanese coals.



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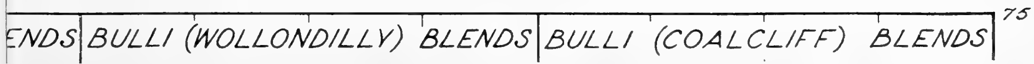


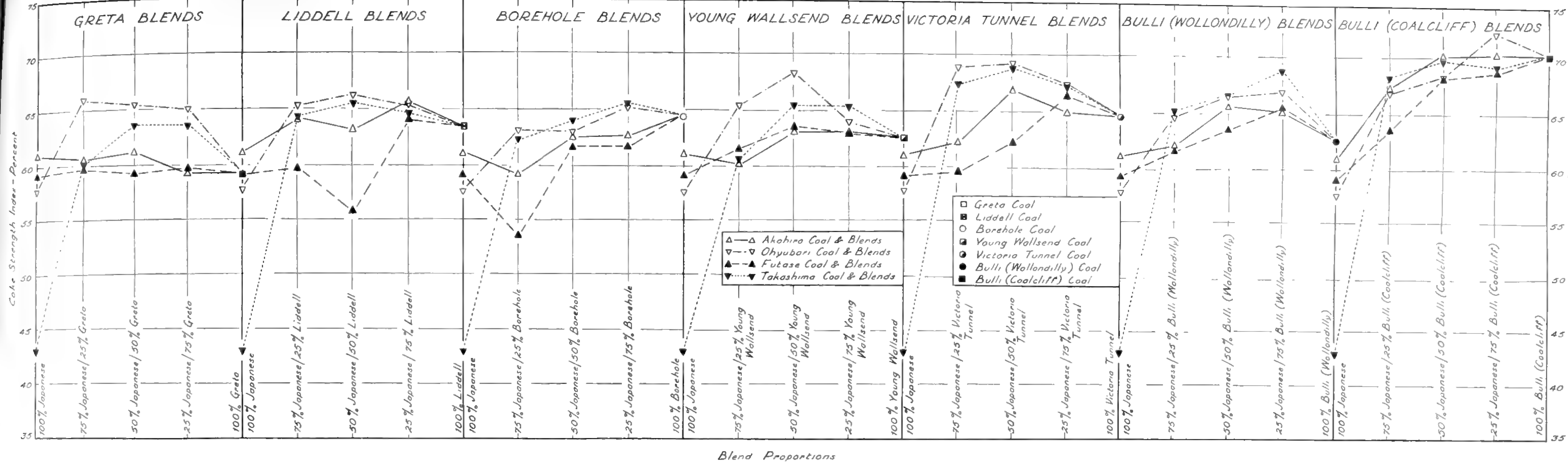


FIG. 50

Comparative variations in the overall strength indices of cokes produced from each Australian coal when blended with individual Japanese coals in various proportions

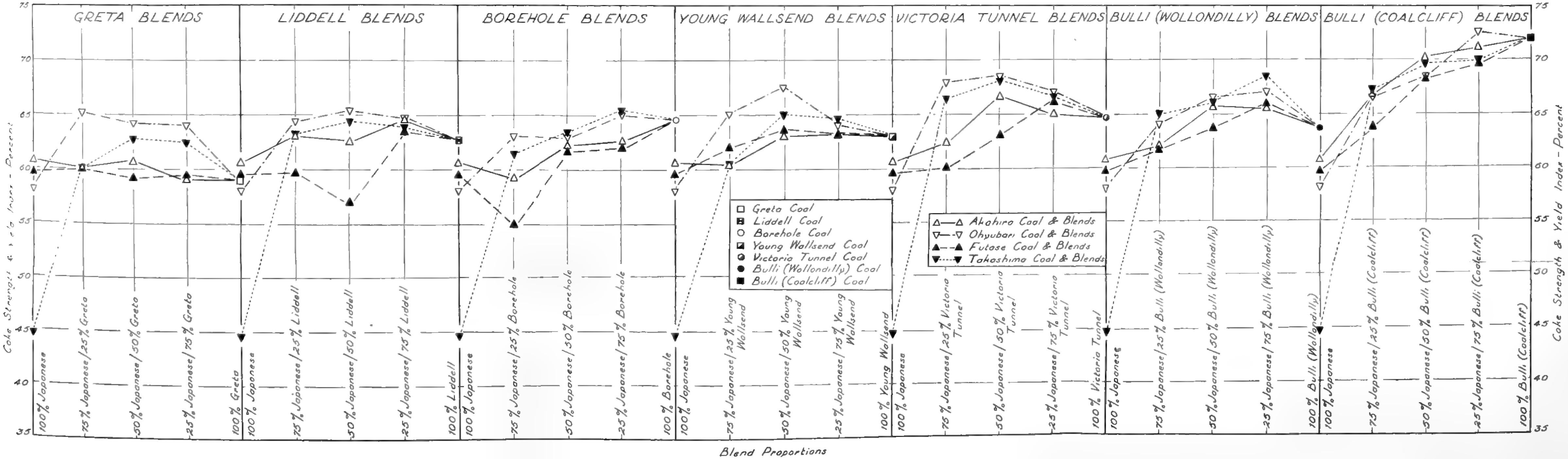


FIG. 51

Comparative variations in the overall strength-yield indices of cokes produced from each Australian coal when blended with individual Japanese coals in various proportions

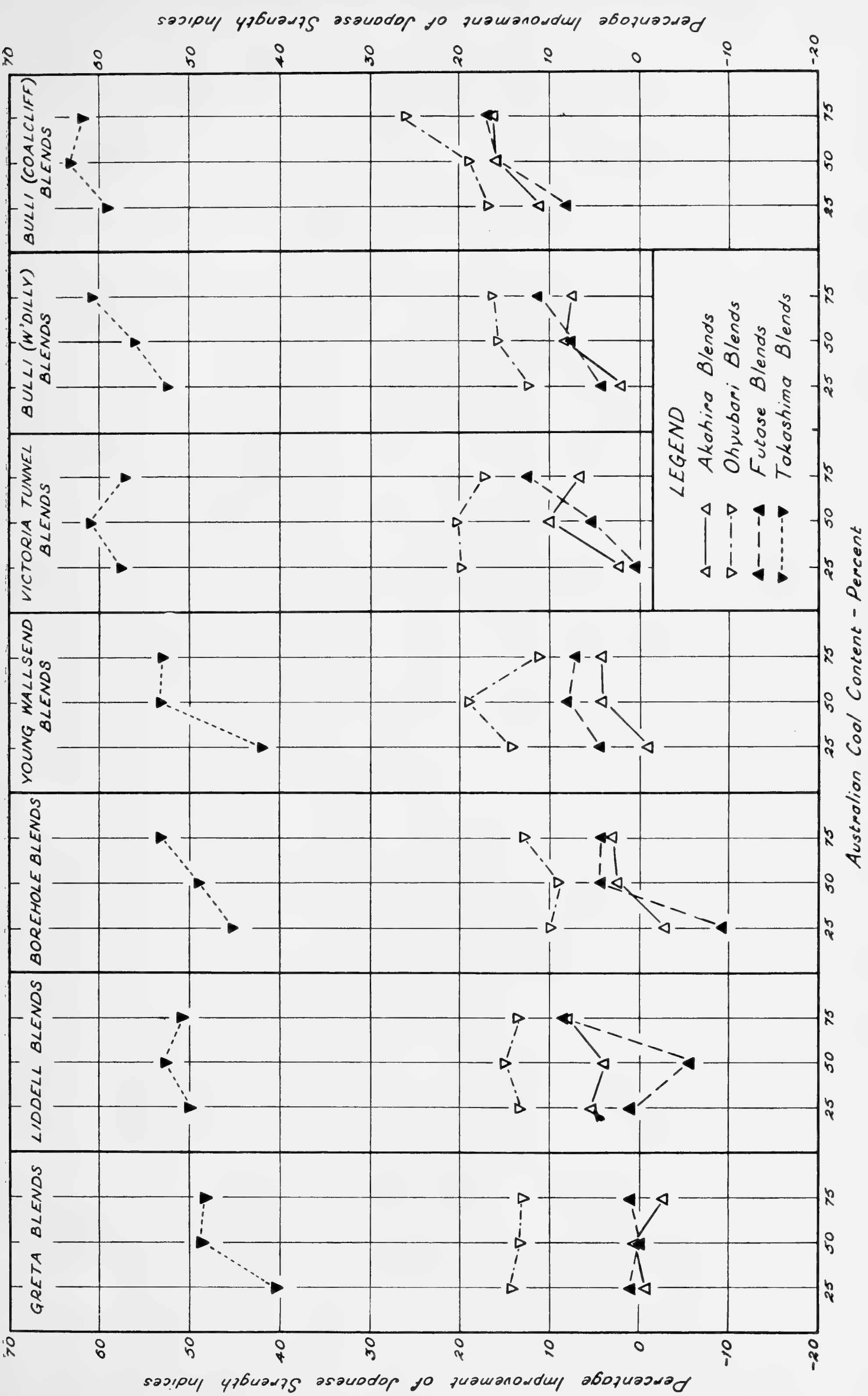


FIG. 52

Percentage improvement of overall strength indices of cokes produced from Japanese coals when blended in various proportions with individual Australian coals

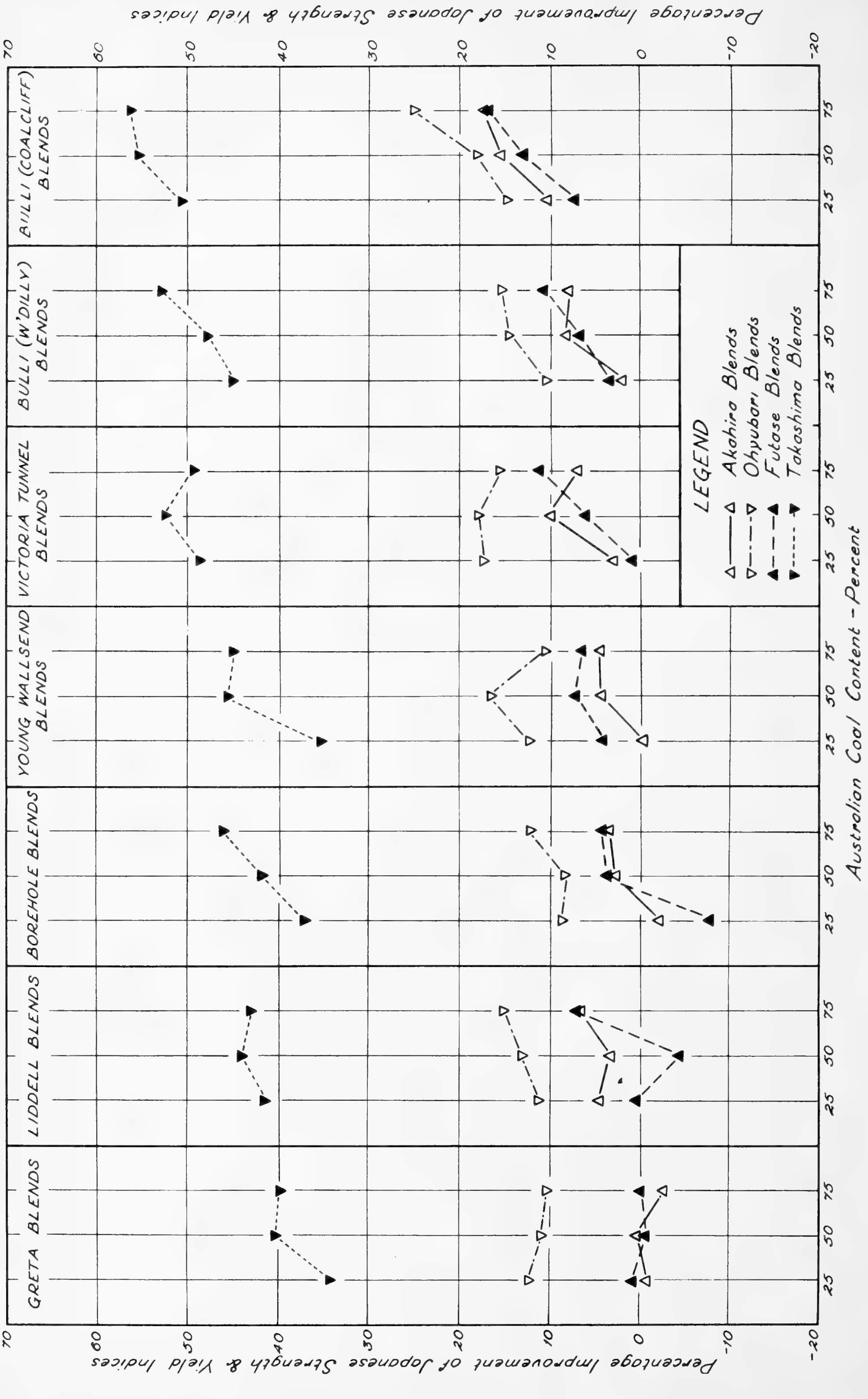
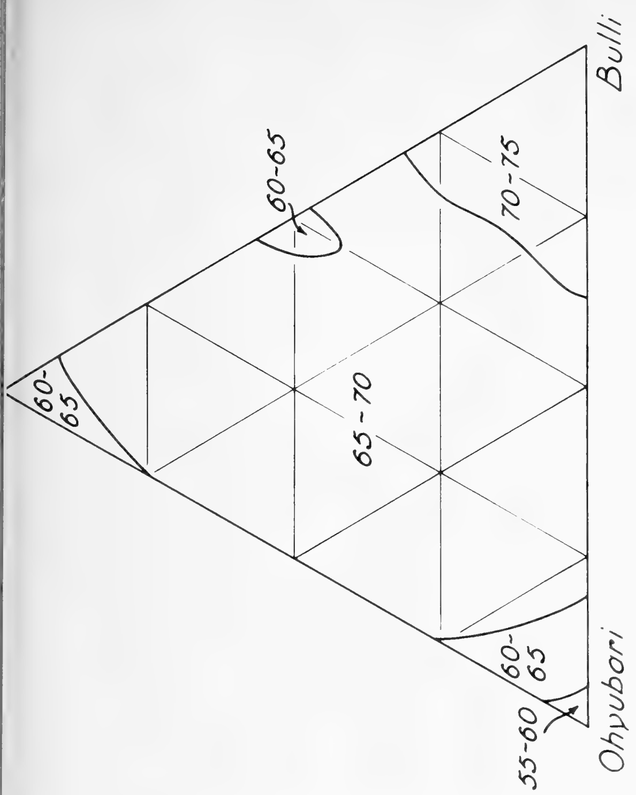


Fig. 53

Percentage improvement of overall strength-yield indices of cokes produced from Japanese coals when blended in various proportions with individual Australian coals



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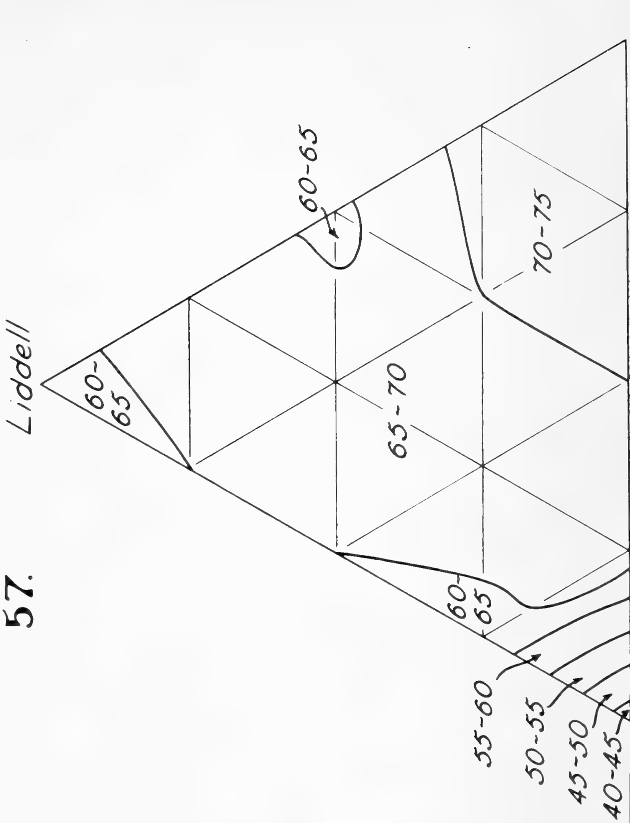

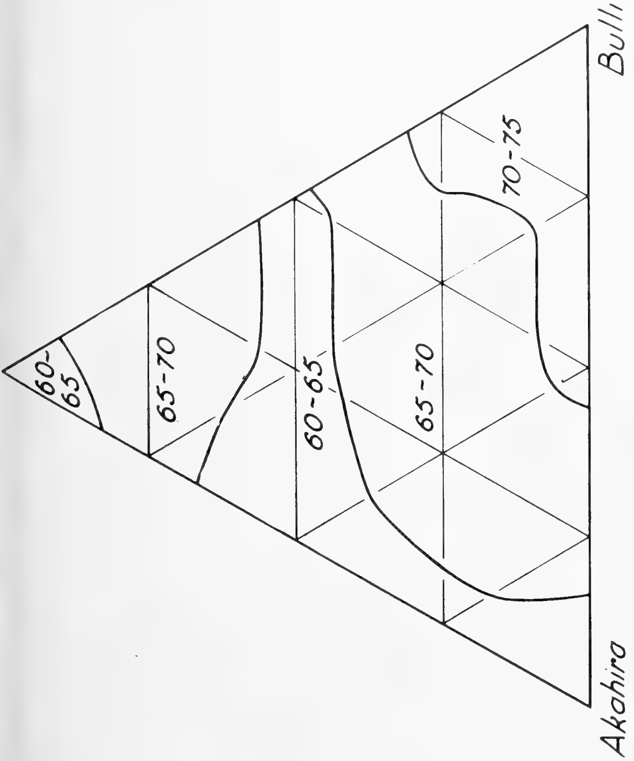

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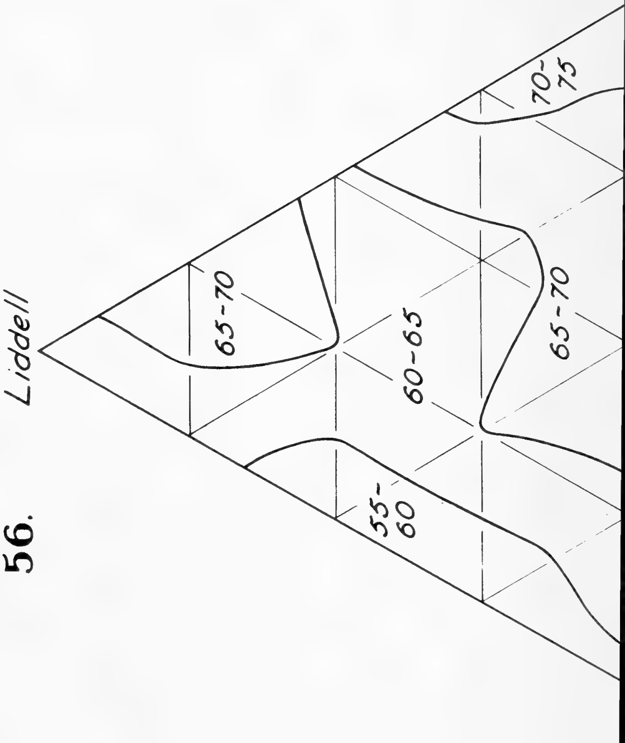

Figs. 54–57

ariations in overall strength indices for cokes produced from three-component blends of Japanese coals with Liddell and Bulli

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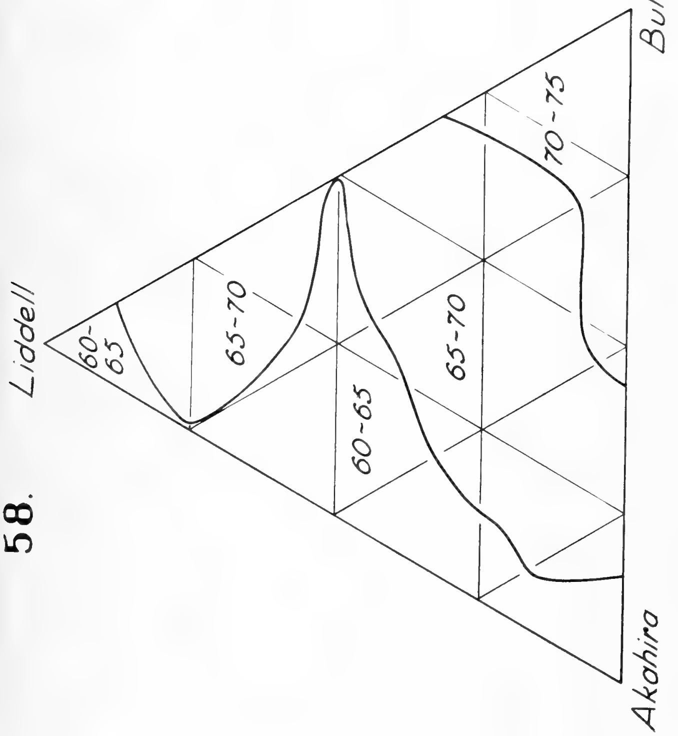

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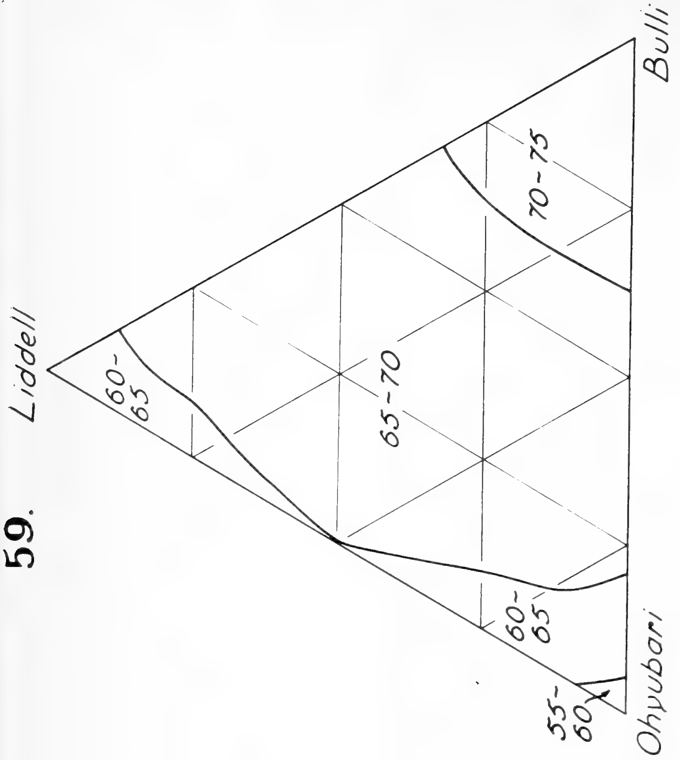

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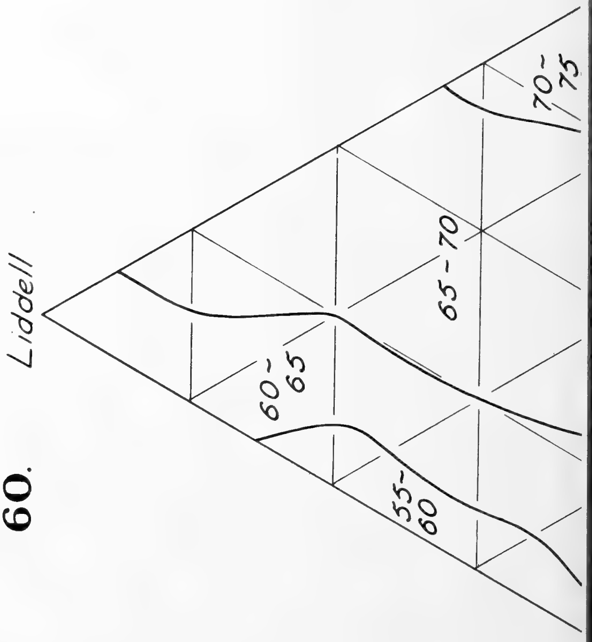

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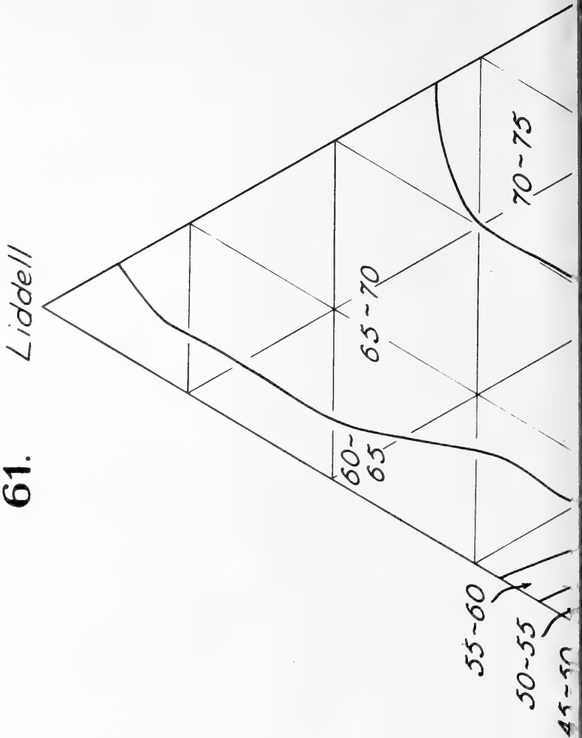

Figs. 58–61

Variations in overall strength-yield indices for cokes produced from three-component blends of Japanese coals with Liddell and

The remaining two-component summary graphs (Figs. 52 and 53) indicate the percentage improvement in both overall coke strength indices and combined overall coke strength-yield indices respectively, which may be effected by blending each of the Japanese coals with each individual Australian coal.

The general order of strength of coke produced from the individual Australian coals may serve as an approximate guide to the order of improvement which may be achieved in blends with any of the Japanese coals. There are, however, a number of well marked exceptions to this general rule. The Ohyubari coal, for example, appears to be significantly more amenable to blending with either the weakly coking Greta, or with the Liddell coal, than it is with the Borehole. Further, this same Japanese coal, in certain of its blends with the Victoria Tunnel, produces stronger coke than in corresponding blends with either of the two strongly coking Bulli coals. Similarly, for certain blend proportions, the Liddell coal is more suitable in combination with both the Akahira and Takashima than is the more strongly coking Borehole, and in the same way Victoria Tunnel coal is superior to the Wollondilly Bulli.

As may be expected from the characteristics shown by the cokes produced from the individual Japanese coals the least overall improvement in blending is achieved with Akahira and Futase coals which when coked alone may yield reasonably satisfactory cokes. Somewhat greater improvement results from the blending of any of the Australian coals with that of Ohyubari, and a very substantial degree of improvement is obtained in all blends with the extremely poorly coking Takashima coal.

In a small minority of cases, continued increases in the Australian coal content of the blends bring about corresponding progressive improvements in strength of the resultant cokes. On the contrary, it is quite evident that an excess of the Australian coal is frequently to be avoided, the most notable example being the series of blends with Young Wallsend coal. Inclusion of more than 50% of this particular material yields either no additional benefit or even deterioration in coke quality, as is evident in the case of its blends with Ohyubari coal.

Three-Component Blends

The results of the study of three-component blends of Liddell, Bulli and the Japanese coals are summarized graphically in Figures 54–61 inclusive; Figures 54–57 relate to the overall strength of the cokes produced from the various blends, and Figures 58–61 to the combined overall strength and yield properties.

The most arresting feature of this series of graphs is the dominant part played by Bulli coal in each case, especially in relation to combined coke strength and yield characteristics (Figs. 58–61), in which the actual indices are almost directly related to the proportion of Bulli coal in any blend.

Another significant feature is the apparently greater degree of compatibility of the weakly coking Ohyubari and Takashima coals with the Liddell and Bulli, as compared with that of both the more strongly coking Japanese coals, the Ahakira and Futase. A combined strength-yield index of 65 or more is achieved with the Ohyubari-Liddell-Bulli and Takashima-Liddell-Bulli three-component blends where the content of Bulli coal is 20% or more.

Conclusion

The usually non-coincidental and frequently considerable variations in the quality of the cokes yielded by these various coals when carbonized under various conditions, either individually or in two- and three-component blends, emphasizes the importance of strict control of all factors concerned in coke production, with due regard for the particular characteristics of the individual coals.

Under present industrial conditions, not all factors may be adjusted or controlled to achieve " optimum " circumstances for carbonization; notably concerned are those of the thermal cycle, especially oven charging, temperature and rate of heating through the plastic range. Factors which may be economically controlled in the oven charge, such as petrographic composition and maceral distribution in relation to size consist of the coal, should receive very particular attention. For the range of seams examined to date, these factors are potentially vital to the development of optimum coke characteristics, and even to the determination of the coal as " coking " or " non-coking ".

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OF THE

ROYAL SOCIETY OF NEW SOUTH WALES

VOLUME 94 1961 PART 5

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Journal and Proceedings, Royal Society of New South Wales, Vol. 94, pp. 173–188, 1961

Stratigraphy of the Tamworth Group (Lower and Middle Devonian), Tamworth-Nundle District, N.S.W.

KEITH A. W. CROOK

(*Received October 23, 1959*)

ABSTRACT—The Tamworth Group is described and subdivided into nine formations; five members are recognized. These subdivisions are related to earlier subdivisions of the unit, which are unsatisfactory in some cases, and the nomenclatural history of the unit is discussed.

The group consists of radiolarian argillites and graywackes with coralline limestone lenses, passing down into graywackes and graywacke rudites with some limestone, and with further radiolarian argillites, red keratophyric breccias and limestone lenses low in the sequence. Penecontemporaneous dolerite-spilite masses occur in the Nundle district.

The group is the lowest recognizable unit deposited in the Tamworth Trough, which is defined. Brief mention is made of the Woolomin Beds, thought to be older than the Tamworth Group, against which the former are faulted.

Introduction

There occurs in western New England, N.S.W., a belt of sediments of Lower Devonian to Permian age which contains several characteristic lithologies. The belt extends from Warialda for some 250 miles southwards and then eastwards to reach the coast north of Newcastle (Fig. 1).

The Devonian in this belt has been recognized by Benson (1922) as faunally and lithologically different from the Devonian in other parts of New South Wales. It is thus a distinct faunal and stratigraphic province.

This province is part of a major ortho-geosyncline occupying northeastern New South Wales and southeastern Queensland, which may be termed the " New England Geosyncline ". It contains sediments from Lower Silurian to Upper Permian age, and older units may be present.

In New South Wales these sediments are separated from those of the Ordovician-Upper Devonian ortho-geosyncline of western New South Wales and Victoria, termed the " Lachlan Geosyncline " by Dr. G. H. Packham (pers. comm.), by Mesozoic sediments. Packham and the author consider that evidence obtained by each in the two geosynclines suggests that the Mesozoic conceals a major arch-like structure which separated the two geosynclines for much of the Paleozoic, particularly during the Devonian.

In New South Wales the Devonian and Carboniferous are particularly well developed on the western margin of the New England Geosyncline between the Hunter-Mooki and Peel Fault Systems (Fig. 1). Data to be presented in a subsequent paper suggest that the sediments accumulated in a trough trending 340° (true) along the western margin of the geosyncline. The eastern margin of this trough has not been recognized.

It is proposed to term this depression the Tamworth Trough. Its recognizable eastern limit is the Peel Fault System, and it is limited on the north and west by Mesozoic cover. In the south the trough passes near Mount Royal into another trough which trends closer to west-northwest.

The present paper deals with the stratigraphic subdivision of the Tamworth Group, the lowest recognizable unit in the trough, within the area fringe-hachured in Fig. 1. Maps of this area accompany the present paper and the following paper which deals with the stratigraphy of the overlying Parry Group.

Brief mention is made of the Woolomin Beds which occur faulted against the Tamworth Group on the east and are thought to be older than it. They do not form part of the Tamworth Trough sequence as herein defined.

Terminology used in this and subsequent papers follows that of Pettijohn (1957), with the following exceptions: The classification of arenites followed is that of Packham (1954), as amplified by the author (Crook, 1960). The term " cherty argillite " is applied to fine dense argillites with a tough splintery to conchoidal fracture which usually contain radiolaria with admixed detrital material. Most are siliceous argillites, but a few are true cherts.

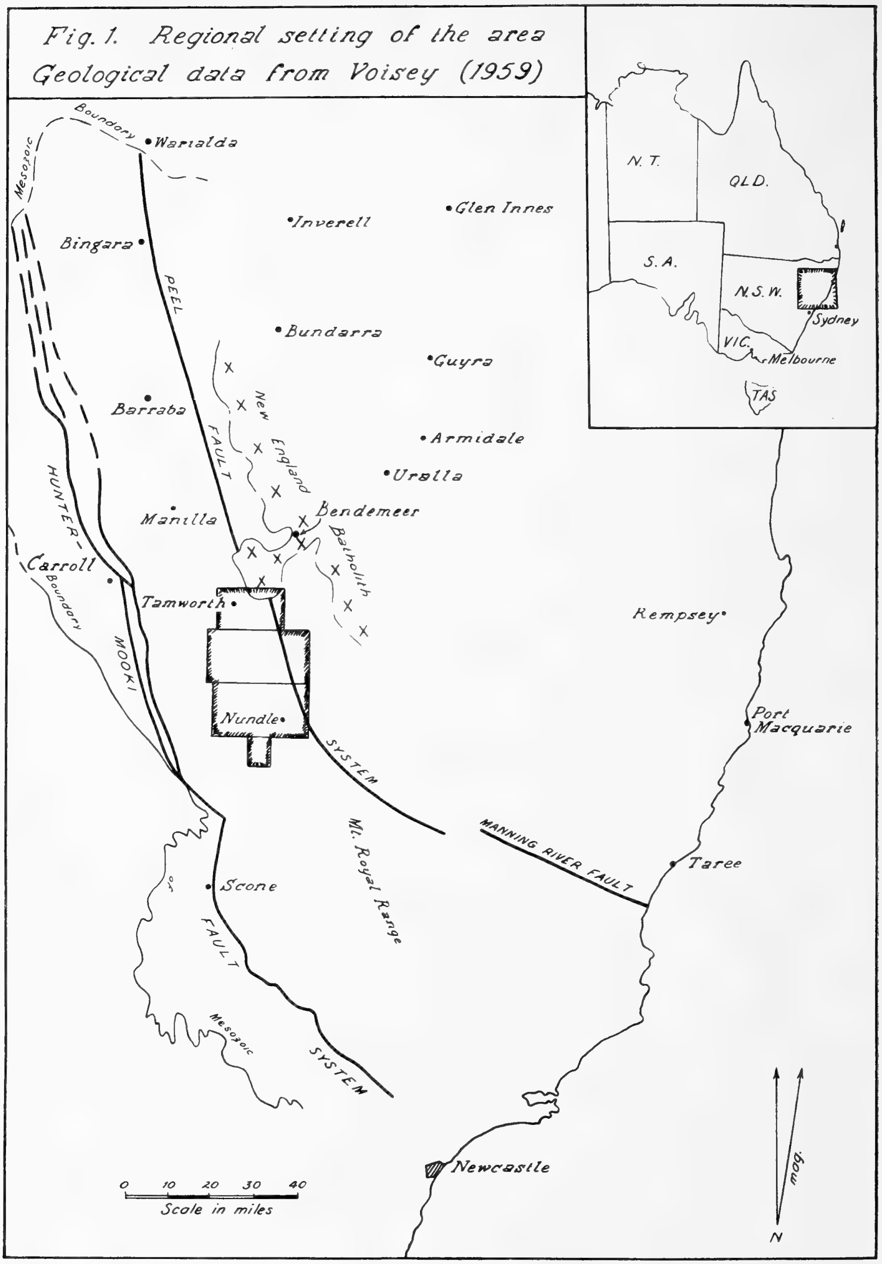


Fig. 1. Regional setting of the area Geological data from Voisey (1959)

The terminology of cross-stratification used follows McKee and Weir (1953), as amplified by Crook (1957). The description of sole-markings follows Kuenen (1957) and Kuenen and Prentice (1957).

The following relations apply between Benson's terminology (1912–20) and that herein. Benson's " claystone " is termed " argillite " and his " cherts " are covered by " chert ", " cherty argillite " and rarely " argillite ". Benson's " tuffs " are arenites of pyroclastic or fluvial origin with abundant rock fragments and/or feldspar and little quartz. They are termed ' labile arenites ' herein, most being labile graywackes. Benson's " pyroclastics " are referred to by non-genetic terms—rudite, breccia, arenite. His " agglomerates " are termed "rudites", or "breccias" or "conglomerates" when applicable.

Locality grid-references refer to the four maps entitled "Geology of the Tamworth-Liverpool Range district". They are read in the same manner as military map references, eastings followed by northings.

Thicknesses of units have, in most cases, been estimated from maps and cross-sections, and are not based on field measurements.

Previous Work

Portions of the Tamworth Trough sequence were described by Benson (1911–20) in a series of classic papers. Subsequently Carey (1934, 1935, 1937) described the area west of and immediately adjoining that dealt with here. A small area containing L. and M. Devonian limestones north of the present area was described by Brown (1942). The district south of the present area was mapped regionally by Osborne (1950), and Osborne *et al.* (1950) record some details of the Isis River-Timor district. The southwestern corner of the area was mapped by Hallinan (1950).

More recently members of the University of New England have worked north and northwest of the present area, Voisey (1958*b*) in the Manilla district, Williams (1954) in the Carrol-Wean district and Engel (1954) in a portion of County Darling. Chappell (1959) has described the geology of the Tamworth-Manilla-Bendemeer district and Pickett (1959) the geology of the Black Mountain district.

Benson (*op. cit.*) stratigraphically subdivided the Paleozoic sequence. Modifications have been introduced by Brown (1942) and Voisey (1958*b*). The nomenclature current in 1958 has been summarized by Voisey (1958*a*).

Benson (1912–20) recognized the following major divisions:

Burindi Series		Lower Carboniferous
Barraba Series	Barraba Mudstone Baldwin Agglomerate	Upper Devonian
Tamworth Series		Middle and Lower Devonian

Some persistent units within these were recognized.

Stratigraphy

The stratigraphic nomenclature of the Tamworth Trough sequence is complicated by several factors, and no complete statement of the present situation has been published. These factors are:

(i) Erection of units which are inadequately defined and which, at times, are of doubtful objective status.

(ii) The widespread use of junior synonyms.

(iii) Use of the same term in different senses at different times.

(iv) Widespread variation in terminal (i.e. rock unit) nomenclature, both before and since the introduction of the Australian Code of Stratigraphic Nomenclature.

(v) Errors of correlation based on misinterpretation of field evidence, which give rise to subjective synonyms (i.e., 'A' is erroneously held to be a synonym of 'B').

(vi) Subsequent emendations to original subdivisions which do not meet the definitional requirements of the Code.

(vii) Long-continued temporal persistence of dominant lithologies coupled with gradational changes in the same vertically and horizontally.

In order to clarify the situation the history of the nomenclature is discussed where relevant, and synonymies are given. This will also enable a better understanding of Benson's stratigraphic nomenclature, which is not as straightforward as a cursory examination of his papers might suggest.

Wooloomin Beds (Benson 1912, emend. herein)

Synonymy—Woolomin Series (Benson, 1912, p. 100; 1913*a*, p. 496); Woolomin Beds (Benson); Eastern Series (Benson, 1915*b*, p. 546); Woolomin Series (Browne (in David, 1950, p. 205)); Woolomin Group (Voisey, 1958*b*, p. 209); *not* Woolomin Series (Voisey, 1942, p. 289); *not* Woolomin Group (Spry, 1954, p. 129).

This unit includes the "jaspers, altered spilitic rocks, schistose tuffs, slates, phyllites and hornstones" (Benson, 1913*a*) outcropping east of the Great Serpentine Belt. Initially considering it to be older than his Tamworth Series, against which it is faulted, Benson subsequently realized (1915*b*, p. 546) that the rocks to the east of the Serpentine Belt were, in part, altered Tamworth Series. He therefore dropped the term Woolomin and instituted the term Eastern Series to cover " the whole complex ".

Browne (in David, 1950) used the term Woolomin Series in Benson's original sense, considering these rocks to be distinct from the altered Tamworth Series.

In 1942 Voisey applied the term Woolomin Series to the sediments of the Armidale district, and in this he was followed by Spry who used the term " Woolomin Group ". In view of the subsequent bathylith between Armidale and Benson's type area this usage is not relevant to discussions on the type area. Mappable continuity of beds between the two regions has yet to be demonstrated.

Voisey (1958*b*) followed Spry's terminology, applying the term " Woolomin Group " to rocks east of the Great Serpentine Belt in the Manilla district. These form part of Benson's Eastern Series.

Whilst there are places where rocks of Tamworth Group aspect appear within and to the east of the Peel Fault System, this is in part due to the multiple nature of that System, five faults having been recognized (see maps). However, many of the rocks of this region are distinctly different from the Tamworth Group, being slates with jasper bars and minor labile arenites. Also Dr. J. F. G. Wilkinson (pers. comm.) has recently discovered Silurian limestones with *Halysites* lying within and to the east of the westernmost serpentinite north of Attunga. This suggests that the beds east of the serpentinite may be, in part, of this age.

The Woolomin Series of Benson thus has objective validity, and should be retained, with suitable terminal modification. The unit, for which the name " Woolomin Beds " is appropriate, may be briefly defined as follows :

Derivation—Woolomin, a township between Nundle and Nemingha.

Representative Section—Nundle-Woolomin road near Anderson's Flat (220198 to 222.5;206 Goonoo Goonoo).

Lithology—Slates, at times phyllitic, with massive red jasper bars.

Thickness—Unknown.

Age and Relations—Faulted against Tamworth Group, and outcropping within and east of the Peel Fault System. Lower Devonian (?) and older.

Tamworth Group (Benson, 1913, emend. Voisey, 1958)

Synonymy—Bowling Alley Series (Benson, 1912, p. 100) ; Tamworth Series (Benson, 1913*a*, pp. 495, 496) ; Tamworth Beds (Benson) ; Tamworth Group (Voisey, 1958*a*, p. 175).

This is the Tamworth Series (or Group) of authors, Benson having used this term in preference to " Bowling Alley Series ". He included in it all rocks west of the Great Serpentine Belt and stratigraphically below his Baldwin Agglomerate. Voisey (1958*a*) emended the name, recognizing several units of Formation-status.

The unit may be briefly defined as follows :

Derivation—City of Tamworth (097.5;373 Tamworth).

Lithology—Radiolarian argillites and graywackes with coralline limestone lenses, passing down into graywackes and graywacke breccias with some limestone, and with further radiolarian argillites, red keratophyric breccias and limestone lenses low in the sequence. Penecontemporaneous dolerite-spilite masses occur in the Group in the Nundle district.

Thickness—Maximum observed 8000+ feet ; base not seen.

Age and Relations—Lower and Middle Devonian ; conformably underlies the Parry Group.

The unit has been subdivided, several names of Formation-status appearing in the literature. None have been formally defined. These can be fitted to the published sections (Benson, 1915*b*, p. 549 ; 1918*a*, p. 352 ; Brown, 1944, p. 121) as follows, *descending* :

MOORE CREEK STAGE (Brown, 1942, p. 171).

Synonym (*subjective*)—Nundle Series (lower part), Benson, 1918*a*, p. 326, 340.

Components—Unnamed radiolarian claystones (cherts) ;

Moore Creek Limestone (Benson, 1913*a*, p. 497 (as Moor Creek Limestone), and 1915*b*, p. 551) ;

Crawney Limestone (Benson, 1918*a*, p. 321 footnote, and 1918*b*, p. 595), probably coeval with Moore Creek Limestone ;

Timor Limestone (Osborne *et al.*, 1950, p. 313), coeval with Crawney Limestone.

SULCOR STAGE (Brown, 1942, p. 170)

Components—Unnamed radiolarian claystones (cherts) ;

Loomberah Limestone (Benson, 1915*b*, p. 548 ; 1918*a*, p. 334) ;

Sulcor Limestone (Brown, 1942, p. 170), probably coeval with Loomberah Limestone.

NEMINGHA STAGE (Brown, 1942, p. 167)

Components—Upper Bowling Alley Tuffs and Breccias (Benson, 1913*b*, p. 578).

Synonyms (*objective*)—Lower Bowling Alley Tuffs and Breccias (Benson, 1913*b*, p. 573 (see Benson, 1918*a*, p. 327)); Igneous Zone (Benson, 1915*b*, p. 550 (see Benson, 1918*a*, p. 327)); *not* Igneous Zone (Benson, 1915*b*, p. 604 (see Benson, 1918*a*, p. 347)).

Upper Banded Radiolarian Claystones (cherts) (Benson, 1913*a*, p. 496);

Synonym (?)—Lower Banded Radiolarian Clay-stones (cherts) (Benson, 1913*a*, p. 496).

Silver Gully Agglomerate (Benson, 1918*a*, p. 347);

Unnamed argillites;

Nemingha Red Breccia (Benson, 1918*a*, p. 346);

Synonym (*objective*)—Igneous Zone (Benson, 1915*b*, p. 604 (see Benson, 1918*a*, p. 347); *not* Igneous Zone (Benson, 1915*b*, p. 550);

Nemingha Limestone (Benson, 1915*b*, p. 551);

Unnamed keratophyre;

Unnamed radiolarian claystones (cherts);

(? Lower Banded Radiolarian Claystones (cherts) (Benson, 1913*a*, p. 496)).

In 1918 Benson, in modifying some of his correlations between the Tamworth and Nundle districts, correlated the lower part of his Nundle Series, which he had previously considered to be synonymous with his Barraba Series (in the emended usage of that term), with the upper part of his Tamworth Series. This would place the lower portion of the Nundle Series in synonymy with Brown's Moore Creek Stage. This correlation is invalid, however, as will be shown in a subsequent paper.

In 1913 Benson, having examined the Bowling Alley Point region, recognized two tuff-breccia units, the Upper and Lower Bowling Alley Tuffs and Breccias. Subsequently, in 1915, he recognized in the Tamworth district an " Igneous Zone " which he traced southwards across East and West Gap Hill, Parish Nemingha. On further consideration of the relationship between these three units he became convinced of their synonymity (1918*a*, p. 327). At the same time, having mapped the Loomberah region between Tamworth and Bowling Alley Point, he recognized a further rudaceous unit, the Nemingha Red Breccia. He then realized (1918*a*, p. 347) that a considerable part of the Igneous Zone on East and West Gap Hill belonged to this last unit.

Brown (1942) erected the term " Sulcor Limestone " for masses in the Attunga district north of Tamworth which she considered probably coeval with Benson's Loomberah Limestone.

Osborne *et al.* (1950) proposed the name Timor Limestone for the limestone occurring in the core of the Timor Anticline. Mappable continuity with the Crawney Limestone cannot be demonstrated due to basalt cover, but it seems certain that the two are continuous.

Field work has shown that the Upper Bowling Alley Tuffs and Breccias of Benson are identical with his Silver Gully Agglomerate. This synonymity results in a considerable telescoping of the lower part of the Tamworth Group section. Benson failed to appreciate fully the disturbed nature of the rocks in the Bowling Alley Point region, where he overlooked a marked swing in strike and several faults.

The synonymy for the Silver Gully Agglomerate then becomes:

Upper Bowling Alley Tuffs and Breccias (Benson, 1913*b*, p. 578);

Lower Bowling Alley Tuffs and Breccias (Benson, 1913*b*, p. 573 (see Benson, 1918*a*, p. 327));

Igneous Zone (Benson, 1915*b*, p. 550 (see Benson, 1918*a*, p. 327));

not Igneous Zone (Benson, 1915, *b*p. 604 (see Benson, 1918*a*, p. 347));

Silver Gully Agglomerate (Benson, 1918*a*, p. 347).

The unnamed argillites between the Silver Gully Agglomerate and the Nemingha Red Breccia (Benson, 1918*a*, p. 352) become synonymous with the Upper (and Lower) Banded Radiolarian Claystones of Benson (1913*a*, p. 496).

It is proposed to subdivide the Tamworth Group into several formations in the manner shown in Table 1. The relationship between this nomenclature and a composite of the older subdivisions is shown in simplified form in Table 2. The Moore Creek and Sulcor (Loomberah) Limestones, which form the basis for Brown's three-fold subdivision of the group, are not persistent, and are therefore unsuitable as boundaries for lithological units. These limestones, and the Nemingha Limestone, are treated as members for the present, although they appear as intermittent lenses at slightly varying levels in the sequence. All lenses appearing at the same general level in the sequence are referred to the same member, regardless of the lack of mappable continuity. This is not good stratigraphic practice, but the naming of each individual lens is not justifiable at present.

Table 1. Subdivision of the Tamworth Group

AGE (after Brown, 1944, p. 121)		EASTERN REGION			NORTHERN REGION	
UPPER DEVONIAN		PARRY GROUP Baldwin Formation				
MIDDLE DEVONIAN	Givetian	Yarrimie Formation	Passage Beds	TAMWORTH GROUP	Yarrimie Formation	Passage Beds
			Moore Creek Limestone Member			Moore Creek Limestone Member
			Crawney Limestone Member			Levy Graywacke Member
	Couvinian	Silver Gully Formation			Silver Gully Formation	
		Loomberah Limestone Member			Loomberah Limestone Member	
LOWER DEVONIAN	Coblenzian	Wogarda Argillite			Seven Mile Formation	
		Drik-Drik Formation				
		Nemingha Limestone Member			Nemingha Limestone Member	
	Gedinnian	Cope's Creek Keratophyre				
		Pipeclay Creek Formation			Base not exposed	
		Stratigraphic position uncertain: Hawk's Nest Beds.				

The constituent formations of the group (Table 1) will be defined and described in descending order.

Yarrimie Formation

Derivation—Yarrimie Creek (170233 Goonoo Goonoo).

Type Section—Silver Gully (191200.6 to 198.4;200 Goonoo Goonoo).

Lithology—Cherty argillites, greenish gray or green, becoming black and white banded with radiolarian limestone lenses as the sequence is ascended, with local biohermal limestones and some graywackes. High in the sequence olive-green to olive-brown mudstone interbeds enter and eventually become dominant. These are Passage Beds into the overlying Baldwin Formation.

Thickness—2900 ft. in the Type Section.

Age and Relations—M. Devonian, conformable on Silver Gully Formation. The base of the Formation is taken at the point where the arenites and rudites of the Silver Gully Formation pass up into a sequence of greenish-gray argillites. The Passage Beds commence at the base of the first bed of olive-green mudstone. Their top, here taken as the top of the Formation, is the top of the last bed of black and white banded argillite below the first massive (Baldwin-type) arenite.

Three members are recognized within the Yarrimie Formation. They are briefly defined below :

LEVY GRAYWACKE MEMBER

Derivation—Levy's Springs (111393 Tamworth).

Type Section—Spring Creek (108.5;395 to 111395.5 Tamworth).

Lithology—Massive labile graywackes with interbedded argillites.

Thickness—Type Section 900 ft.

Relations—Intertongues with argillites of the Yarrimie Formation. Top and bottom marked by change from massive graywacke to argillite sequence.

MOORE CREEK LIMESTONE MEMBER (Benson, 1913)

Derivation—Moore Creek, north of Tamworth.

Table 2. Relation Between New and Old Subdivisions of the Tamworth Group.

	OLD	NEW
Moore Creek Stage	Unnamed radiolarian claystones	Yarrimie Formation with Moore Creek Limestone Member and Crawney Limestone Member
	Moore Creek Limestone and Crawney Limestone	
Sulcor Stage	Unnamed radiolarian claystones	
	Loomberah Limestone	Silver Gully Formation with Loomberah Limestone Member
Nemingha Stage	Silver Gully Agglomerate (= Upper and Lower Bowling Alley Tuffs and Breccias)	
	Upper (?and Lower) Banded Radiolarian Claystones	Wogarda Argillite
	Nemingha Red Breccia (= Igneous Zone)	Drik-Drik Formation with Nemingha Limestone Member
	Nemingha Limestone	
	Unnamed keratophyre	Cope's Creek Keratophyre
	Unnamed radiolarian claystones	Pipeclay Creek Formation

Type Section—(provisional) Spring Creek (096389.5 Tamworth).

Lithology—Massive biohermal coralline limestone.

Thickness—Maximum recorded 450 ft. (Benson, 1915*b*, p. 560).

Age and Relations—Givetian (Hill, 1942, p. 144). Lenticular masses within the Yarrimie Formation. Top and bottom marked by change from limestone to thick argillite sequence.

CRAWNEY LIMESTONE MEMBER (Benson, 1918)

Derivation—Parish Crawney, County Parry.

Type Section—Tributary of Wombramurra Creek (170.3;055.5 to 158.7;056 Nundle).

Lithology—Massive biohermal coralline limestone, with associated calcarenites, largely crinoidal.

Thickness—Type Section, about 380 ft.

Age and Relations—? Givetian. A large mass within the Yarrimie Formation. Top marked by change to argillite sequence, base by change to feldspathic labile arenites and argillites.

A correlative of the Crawney Limestone in the Isis River district, which is treated as a separate formation pending more detailed work, is also defined here for convenience :

TIMOR LIMESTONE (Osborne, Jopling and Lancaster, 1950)

Derivation—Timor, on the Isis River.

Representative Section—Near Allston station (189972 Timor). (See Osborne *et al.*, 1950, pp. 314–315.)

Lithology—Massive coralline limestone, at times bedded. Richly fossiliferous.

Thickness—760 ft., maximum (Osborne *et al.*, 1950).

Age and Relations—M. Devonian, and perhaps older. Conformable within Tamworth Group beneath beds referred to the Yarrimie Formation. Top is 1500 feet below the top of the Group, and marks change from argillite sequence to massive limestone. Base not defined herein.

The Type Section of the Yarrimie Formation on Silver Gully commences at the top of the last arenite bed of the Silver Gully Formation, the change to argillites being quite abrupt. The argillites are silty, cherty, and banded, occasionally conspicuously. Sedimentation units have parallel bounding surfaces and extend for tens of yards along the strike. They are usually less than one and rarely more than three inches thick. Small radiolarian (?) limestone lenses are occasionally present.

In the lower parts of the sequence gray, greenish-gray, and green argillites occur. Some 2000 feet above the base, black and white banded radiolarian cherty argillite appears, sparsely at first, but, after a strong development of bright green cherty argillite, becoming dominant. The bright green argillites have green graywackes with excellent graded bedding associated. These terminate about 2500 feet above the base of the Formation, and above this the black and white banded varieties occur, with occasional interbeds of unindurated olive-green mudstone. The mudstones increase in volume as the sequence is ascended, finally becoming dominant, and passing into the overlying Baldwin Formation. Good examples of mudstone with black and white argillite interbeds are seen near the top of the Formation (Plate 1, fig. 1).

Occasional beds of creamy-white or pale gray feldspathic labile graywacke occur throughout. They are well graded and do not exceed two feet in thickness. One example (Plate 1, fig. 2) contained well-rounded argillite pebbles.

The Formation can be traced south to Bowling Alley Point without lithological change. Locally dolerite invades the argillites. Benson (1918*a*) mapped two limestone lenses as Loomberah Limestone within this area. Being above the bright green argillites, both are referred to the Moore Creek Limestone Member, which is well developed in the Formation near Tamworth. The lenses have not been examined.

South of Bowling Alley Point the unit has not been clearly separated from other parts of the Tamworth Group, due to structural complexities. Features in this area are described under ‘ Tamworth Group (undifferentiated) ’.

Seven miles southwest of Nundle the Formation occurs in the core of the Crawney Anticline. The lowest beds exposed directly underlie the Crawney Limestone Member, and are feldspathic labile arenites and argillites. The Crawney Limestone is massive, gray, and richly fossiliferous. The argillites immediately overlying it contain thin beds of crinoidal calcarenite.

The Formation here consists dominantly of black and white banded argillites with graywacke interbeds up to ten feet thick. Green or gray argillites have not been observed. Some coarse graywackes contain rounded argillite pebbles near the top of their sedimentation units. Kuenen (1957) attributes this to the bouyant action of the high-density turbidity current on the relatively light mud fragments.

Near the top of the Formation, below the Passage Beds, a mappable graywacke is developed. This contains occasional argillite beds and shale pebbles. Immediately above it mudstone interbeds appear within the argillites, and very rapidly become dominant to the exclusion of the argillites.

On Ryan’s Oakey Creek at 175053.2 Nundle, and again at 166.8;047 Nundle on Wombramurra Creek, is developed a lithology not encountered elsewhere, with the possible exception of the infra-limestone strata referred to above. It consists dominantly of yellowish feldspar-rich arenites with sedimentation units up to 1 ft. thick which vary rapidly in thickness along the strike. Faint suggestions of curved planar cross-stratification are present, and green and red argillite pebbles may occur. Exposures are very weathered, due to the proximity of the pre-Tertiary surface, and the relationship of these rocks to the typical Yarrimie Formation is in doubt.

South of the Liverpool Range in the Isis River Valley the Tamworth Group reappears from beneath Tertiary cover in the Timor Anticline (Osborne *et al.*, 1950). The core of this structure is occupied by the Timor Limestone, which is similar to the Crawney Limestone. About 1500 feet of argillite lies between the top of this unit and the base of the Baldwin Formation. These argillites, referred to the Yarrimie Formation, are initially black and white banded, but higher up become greenish, silty, and noticeably flaggy. Mudstones, often rather cherty, and banded or laminated siltstones, are common. Minor labile graywackes occur. Mudstone interbeds are more common as the base of the Baldwin Formation is approached.

At 195947 Timor a 6 inch graywacke unit was noted showing in the upper 3 inches a set of straight planar cross-stratification, and graded bedding in the lower 3 inches.

North of Silver Gully the Yarrimie Formation develops several mappable graywacke beds. These are prominent east and north of Nemingha, but die out northwestwards towards Tamworth. They are dark green and labile, with a little rudite near Reedy Creek, north of Yarrimie Creek. Banding, graded bedding, and shale fragments are frequent.

North of the Black Jack Fault No. 1 bright green cherty argillites have been observed just above the Silver Gully Formation near the Wogarda Fault, and higher in the Formation near the southwest end of the same fault. Two bands of bright green cherty argillite appear to the north of the alluvium along Sandy Creek and extend northwards for some distance. The lower of these is again seen on the western side of West Gap Hill, east of Nemingha.

Near Tamworth the Formation contains two Members which are absent or scarcely developed to the south. The Moore Creek Limestone Member is well developed north of Tamworth along Spring Creek. It is a massive gray limestone with abundant corals (see Hill, 1942), locally with rough bedding, and occurs as lenticular masses within the black and white banded cherty argillites. The junction between the limestone and the underlying argillites is sharp and there is only minor interdigitation of argillite and limestone at the ends of the lenses.

The argillites are well exposed in North Tamworth quarry (095385 Tamworth), where they contain abundant radiolaria, and the radiolarian limestone lenses described by David and Pittman (1899) and Benson (1915*b*). Chemical analyses of the argillites from this district (David and Pittman, 1899, p. 32) show that chert, siliceous argillite and normal argillite, all radiolarian, are represented.

On the upper part of Spring Creek and along Levy's Springs a strong development of graywacke occurs. This is the Levy Graywacke Member. The rock is similar to that elsewhere in the Yarrimie Formation, labile and coarse with graded bedding and some interbedded argillites. Shale fragments, some with white aureoles, are present.

Sedimentary structures—Graded bedding is widespread, being particularly obvious in some of the arenite beds less than 6 inches thick. Convolute bedding and load-cast structures are often present, and an example of flow-casts has been noted. Silt units frequently exhibit ripple-cross-stratification, and ripple-marked bedding surfaces are occasionally visible. Benson (1915*b*, Fig. 8) illustrates ripple-cross-stratification from Nemingha railway cutting. Little can now be seen in the cuttings due to weathering.

Fossils—Macro-fossil remains are rare outside the limestones. *Leptophloeum australe* is known from the Passage Beds near Crawney (171.5;073.8 Nundle), but not elsewhere. This does not accord with Benson's observations (1915*b*, pp. 553, 581 footnote). Its apparent absence from Long Gully and Loder's Gully may be due to sixty years of fossil collecting. This form has not been found by the author below the Passage Beds of the Formation.

Radiolaria are particularly abundant in the argillites, particularly the black and white banded types, and in the small limestone lenses they contain. From Tamworth Hinde (1899) described 53 new species.

Silver Gully Formation (Benson, 1918, emend. herein)

Synonym—Silver Gully Agglomerate (Benson, 1918*a*).

Derivation—Silver Gully (200202.5 Goonoo Goonoo).

Type Section—Silver Gully (198.4;200 to 201.3;203 Goonoo Goonoo).

Lithology—Coarse massive rudites with volcanic, granitic and coralline limestone pebbles. Minor arenites and argillites. Colours generally drab. Lenses of biohermal limestone locally. Arenites dominant in north.

Thickness—Type Section, 2300 ft. Maximum observed ca. 2800 ft. north of Hyde's Creek.

Age and Relations—M. Devonian, lies conformably above Wogarda Argillite. Top is marked by argillites of Yarrimie Formation, base by a change from coarse clastics to an argillite sequence.

The term " agglomerate " is not descriptive of the lithology of this Formation, and has been replaced by a more general term. In the Type Section on Silver Gully the Formation is dominantly rudaceous. Its base is poorly exposed, but a thin argillite unit appears to separate it from the Drik-Drik Formation. The lowest beds are coarse polymictic breccias, containing a wide variety of lithologies, dominantly volcanic. Arenites become more prominent as the sequence is ascended.

Locally, some 300 ft. from the top of the Formation, bright green arenites are developed. Coralline limestone and granite pebbles occur in the rudite immediately below this. Generally, however, the arenites and rudites are drab greenish gray to greenish black when viewed from a distance. This distinguishes them from those in the upper part of the Drik-Drik Formation, which are reddish-purple and bright green.

The Formation extends southwards, somewhat broken by faulting, to near Bowling Alley Point. Limestone fragments are usually present in the rudite, and these are fossiliferous on the Peel River at 216179.4 Goonoo Goonoo, where *Phillipsastraea maculosa* Hill occurs.

North of Silver Gully, near Cope's Creek, arenites are well developed near the base of the Formation. Some are well laminated, and have associated argillites.

North of the Black Jack Faults the Formation is dominantly rudaceous, limestone fragments being frequent. *Atrypa* sp. was obtained from the rudite at 177.8;252 Goonoo Goonoo, near the Wogarda Fault.

Northwards the Formation appears to thin considerably for some miles, although outcrops are poor, and then thickens again on West Gap Hill, where it lacks rudaceous material. It is traceable on the northwest side of the Cockburn River to near the Cleary's Hill road where it disappears into a mass of dolerite. At 124.2;378 Tamworth, arenites with graded bedding, referred to this Formation, contain argillite pebbles with halos.

At various points coralline limestone lenses are developed within or immediately above the rudites, and are termed the Loomberah Limestone Member. The lenses referable to this member may appear near the top of the Formation, or occasionally in the basal part of the overlying Yarrimie Formation.

Loomberah Limestone Member (Benson, 1915)

Derivation—Parish Loomberah, County Parry.

Type Section—Por. 58, Parish Loomberah (163.3;310 Tamworth).

Lithology—Coarsely brecciated biohermal limestone, with abundant large brachiopods.

Thickness—Maximum observed, 150 ft. (Benson, 1918*a*, p. 335).

Age and Relations—Early Couvinian (Hill, 1942). Lenses near the top of the Silver Gully Formation bounded by coarse clastics or argillite.

Benson (1918*a*) recognized this unit at various points between the south bank of the Peel River near Nemingha and Bowling Alley Point. Some of the limestones east of the Peel Fault No. Z, north of Piallamore, where repetition of the sequence seems to occur, may also belong to this Member, as may the small mass near the head of Seven Mile Creek.

Corals are abundant in the Loomberah Limestone (see Hill, 1942). The rock is usually a breccia, and appreciable amounts of allocthonous material may be present, certain of the lenses being best described as limestone-rich polymictic rudites.

Wogarda Argillite

Derivation—Wogarda Creek (180255 Goonoo Goonoo).

Type Section—Munro's Creek (226166 to 227165.5 Goonoo Goonoo).

Lithology—Greenish-gray cherty argillites and fine graywackes.

Thickness—Type section, 350 feet.

Age and Relations—Late L. Devonian (cf. Brown, 1944, p. 121). Conformably overlies Drik-Drik Formation. Top is at base of coarse clastics of Silver Gully Formation. Base marked by coarse red or green clastics with keratophyre fragments characteristic of the Drik-Drik Formation.

This unit is usually poorly exposed, and is quite thin. In wide areas of it shown on the map north of Cope's Creek the outcrops are poor, and considerable areas may be occupied by other Formations.

Although the Type Section is separated from the main sequence by one of the Peel Faults, there can be little doubt of its stratigraphic position. Immediately overlying it is a fine rudite of typical Silver Gully Formation aspect, and it is underlain by a thin, poorly exposed bed of red argillaceous sediment of typical Drik-Drik Formation aspect.

The upper part of the Type Section contains pale greenish-gray cherty argillites, banded with fine graded graywacke interbeds. These interbeds tend to become less common lower down, and the whole Formation has a strongly silicified appearance.

Intermittent exposures occur on Wogarda, Sandy and Cope's Creeks. The lower beds are bright green cherty argillites. Higher, thin bands of arenite may appear, and very hard greenish-gray argillites of very fine grain-size. A minor outcrop of mudstone associated with these has been observed on a tributary of Sandy Creek (183233.5 Goonoo Goonoo).

Drik-Drik Formation

Synonym—Nemingha Red Breccia (Benson, 1918*a*).

Derivation—Drik-Drik Creek (190241.5 Goonoo Goonoo).

Type Section—Spring Creek (184.2;234.8 to 187.2;230.9 Goonoo Goonoo).

Lithology—Upper parts, green arenites with occasional red fragments, and green argillites. Lower parts, purple-red breccias, arenites and minor lutites with biohermal limestone lenses. Clastics contain abundant authigenic feldspar and epidote.

Thickness—Maximum observed, ca. 2600 feet, south of East Gap Hill.

Age and Relations—L. Devonian, conformably overlying Pipeclay Creek Formation, where Cope's Creek Keratophyre is absent. Top is at base of Wogarda Argillite. Base is marked either by the appearance of keratophyre or of the argillite sequence of the Pipeclay Creek Formation.

The name " Nemingha Red Breccia " is suppressed as the geographic name " Nemingha " is established for the Nemingha Limestone (see below).

The Formation is usually poorly exposed along creeks, an exception being the Type Section on Sandy Creek. It is notable for its brilliant colouring, the greater part being purplish-red in hand specimen, but beds near the top are bright green.

The unit is largely rudaceous, red aphanitic keratophyre (?) fragments being the dominant material, with appreciable amounts of other volcanics locally. Arenites, calcareous siltstones, and poorly fissile shales, all red, are locally developed. The last contain questionable algal pisoliths. The siltstones contain ostracods and algae. Feldspars, epidote, chlorite and rarely laumontite act as cements in the coarser rocks, and similar minerals form minute vugh-like masses in the shales, and occasionally appear to replace the coarser material in the rudites.

The higher beds are largely arenaceous, and dominantly green, due to chlorite. Feldspars and scattered bright red rock fragments are abundant, the latter being diagnostic. Bright green argillites and fine graded arenites are also present.

The unit appears to die out southwards, and is last observed on Munro's Creek. North of Sandy Creek it seems to thin considerably through the area of poor outcrops, but thickens again and is very well developed on East and West Gap Hill.

Dolerite-spilite masses and the Cope's Creek Keratophyre may disrupt the Formation locally, but relationships are not clear. They may be penecontemporaneous intrusions similar to the dolerite-spilite masses near Nundle.

At several points massive gray or pink biohermal limestone lenses occur. These belong to the Nemingha Limestone Member, and at times contain corals (Hill, 1942) ; locally they are conglomeratic, the rounded limestone blocks being set in a red argillaceous matrix.

NEMINGHA LIMESTONE MEMBER (Benson, 1915)

Derivation—Parish Nemingha, County Parry.

Type Section—East Gap Hill (160363 Tamworth).

Lithology—Massive biohermal coralline limestone, sometimes brecciated.

Thickness—Maximum observed ca. 200 feet.

Age and Relations—L. Devonian, developed as lenses within Drik-Drik Formation.

Cope's Creek Keratophyre

Derivation—Cope's Creek, west of Woolomin.

Type Section—Cope's Creek (195.5;219 to 197.8;219 Goonoo Goonoo).

Lithology—Deep green to gray keratophyre and quartz-keratophyre. Usually massive, but may be vesicular or brecciated. (See Benson, 1915*a*, p. 133 f ; 1918*a*, p. 369 f).

Thickness—Type section ca. 1000 feet.

Age and Relations—L. Devonian. Relations with adjoining strata obscure. Probably largely flows, but may be in part contemporaneous shallow-intruded sills. At times apparently transgressive, lying completely within Pipeclay Creek Formation or the Drik-Drik Formation.

This unit has been very fully described by Benson (1914*a*, pp. 132–137, 149–156 ; 1918*a*, pp. 348–349, 369–375). It does not include the magnetite-keratophyre mass termed by Benson the " Hyde's Creek Complex ", which is situated near the base of the Yarrimie Formation at 207.2;191.6 Goonoo Goonoo.

Pipeclay Creek Formation

Derivation—Pipeclay Creek (205209 Goonoo Goonoo).

Type Section—(provisional) Cope's Creek (201222.2 to 198219.5 Goonoo Goonoo).

Lithology—Black argillites and minor graywackes below Drik-Drik Formation.

Thickness—Type Section, 2000+ feet.

Age and Relations—Lower Devonian. Top of unit is base of Drik-Drik Formation when Cope's Creek Keratophyre is absent. Base is faulted.

Little is known of this unit due to very poor exposures. It appears to consist of black and white banded cherty argillites similar to those of the Yarrimie Formation, with occasional graywackes, and green argillites near the top of the unit. Dolerite, probably intrusive, occurs within it, and it is in places disrupted by the Cope's Creek Keratophyre.

Seven Mile Formation

Derivation—Seven Mile Creek (130392.3 Tamworth).

Type Section—(provisional) Tributary of Seven Mile Creek (124.2;378 to 130.5;380.4 Tamworth).

Lithology—Black and white banded argillites with graywacke beds and intermittent biohermal limestone lenses.

Thickness—Maximum observed, ca. 3400 feet, east of Tamworth.

Age and Relations—L. and early M. Devonian. Conformably underlies the Silver Gully Formation north of the Cockburn River. It is the equivalent of the Wogarda Argillite plus the Drik-Drik Formation plus the Pipeclay Creek Formation. Base not seen.

This unit is developed northwest of the Cockburn River, where it occupies the stratigraphic interval below the Silver Gully Formation. The lowest beds visible are those in the core of the Tintinhull Anticline on Seven Mile Creek. The provisional Type Section is not satisfactorily exposed.

The unit consists dominantly of black argillites, with arenite interbeds, particularly in the lower portions. The argillites may contain siltstone bands and radiolarian (?) limestone lenses. Siltstones in the upper part of the Type Section show graded bedding and slump structures. They pass into graded bedded arenites containing argillite pebbles with halos, which are referred to the Silver Gully Formation. All rocks are metamorphosed to hornfelses with abundant biotite.

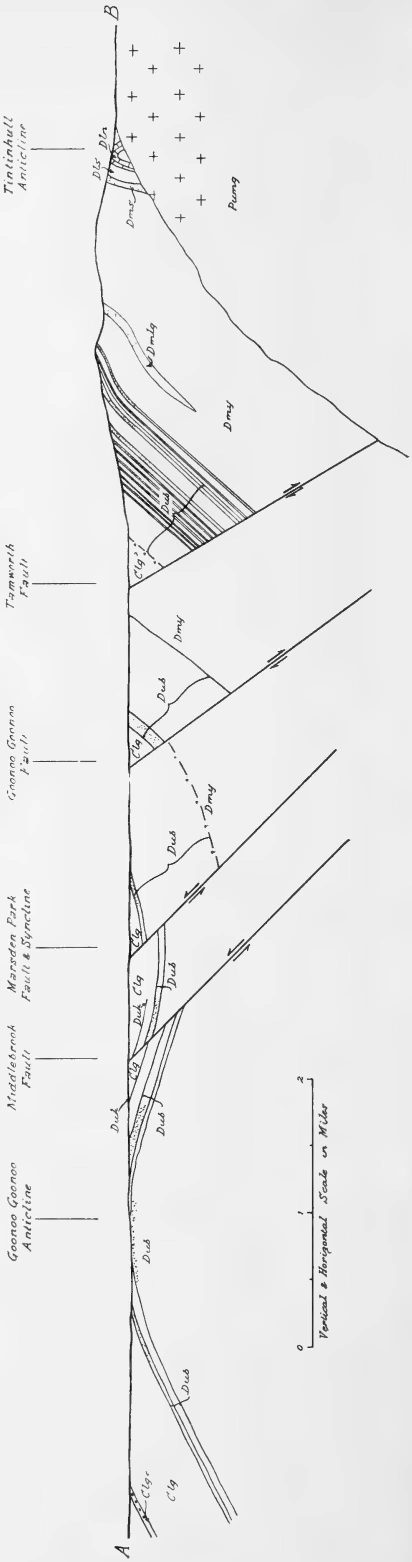
The Nemingha Limestone Member is developed at several points within this Formation. It is frequently recrystallized, due to the proximity of granite. The rock is frequently rudaceous, and may be cavernous in outcrop due to the solution of the limestone blocks. Calcarenites are occasionally associated.

Identifiable fossils have been observed on a tributary of Seven Mile Creek (124.5;390.7 Tamworth) in biotite hornfels. A bed of pure garnet rock (metasomatic ?) occurs about 20 yards downstream from this locality.

Hawk's Nest Beds

Derivation—Hawk's Nest Creek (230084 Nundle).

Representative Section—Hawk's Nest Creek (226.4;086 to 235.5;084.3 Nundle).



Section I: WARRAL – SEVEN MILE CREEK A–B on Sheet I

Lithology—Interbedded black pyritic shales and graywackes, with occasional thick graywacke beds.

Thickness—Unknown.

Age and Relations—Age unknown, possibly L. Devonian. Relationship to other units obscure, probably faulted. Base not seen. Stratigraphic position unknown.

This unit occurs southeast of Nundle, and also in a small area adjacent to the serpentinite on Folly Creek (242136 Nundle). It consists of interbedded black indurated fissile shales and indurated lithic and feldspathic labile graywackes. Occasional massive graywackes occur in beds up to 20 feet thick, and these contain shale pebbles, some of which are bleached and surrounded by a halo. Some rudite occurs.

The interbedded shale-graywacke sequence shows excellent graded bedding, occasional slump structures, and commonly ripple-micro-cross stratification in the silty layers. The shales contain graphitized plant remains which simulate graptolites. Pyrite, in bands and as isolated crystals, is frequently seen.

The unit is intruded by the Mt. Ephraim Granite in the east, and sills and sheets of granite porphyry occur along Hawk's Nest Creek. Felsitic intrusives occur on Nundle Creek. They are fine, aphanitic, yellow to gray rocks, dominantly of potash feldspar.

Tamworth Group (Undifferentiated)

The Tamworth Group has not been subdivided south of Bowling Alley Point because of structural complexities and dolerite-spilite masses. Most of the exposures along the Peel River and the Hanging Rock road below the Devil's Pinch probably belong to the Yarrimie Formation.

The dominant lithology is cherty argillite, the black and white banded variety being the most prominent. The greater part, however, is gray to greenish-black, laminated, massive, and inconspicuously banded. Grain-size varies from fine sand to clay, silty varieties being most common. Small pyrite cubes are locally abundant. Outcrops near the Baldwin Formation on the Peel River at 210132 Nundle contain mudstone interbeds which increase in bulk as the sequence is ascended.

On the Peel River (218.5;153.8 and 218.5;150.5 Goonoo Goonoo and 223137 Nundle) green cherty argillites are developed, at times to the exclusion of other varieties. Minor purple argillites are locally associated.

Bands of labile graywacke from $\frac{1}{4}$ inch to many feet in thickness are widespread. These quite frequently show graded bedding and may be laminated. In general, bed thickness varies directly with grain-size, beds over 10 feet thick being partly or wholly rudaceous.

Arenite and rudite beds frequently contain abundant argillite blocks and pebbles, which may be angular or rounded. They may be randomly distributed or occur in definite layers, sometimes at the base of a unit. Occasionally they form beds of shale breccia. The fragments are lithologically similar to the adjacent argillites, and were derived by penecontemporaneous erosion. The pebbles are often surrounded by a white halo visible in hand specimen (see Benson, 1915*b*, pp. 610–611).

Coralline limestone lenses are developed at various places. A calcarenite is associated near the Devil's Pinch (240110.5 Nundle). At Bowling Alley Point (221164 Goonoo Goonoo) large fossiliferous limestone blocks occur in a breccia.

Small radiolarian (?) limestone lenses, up to $1\frac{1}{2}$ by 3 feet, similar to those from North Tamworth quarry, occur frequently. One, on the Peel River (217.5;142 Nundle), shows bedding traceable from the argillite into the limestone without distortion, rather suggesting that the lens might be a replacement body (Plate 1, fig. 3). Signs of differential compaction about these lenses (see Benson, 1915*b*, p. 562) have been seen only in North Tamworth quarry.

Penecontemporaneously intruded dolerite-spilite masses are common in this region. Some show excellent pillow structure, e.g. in Swamp Creek gorge (231.3;137.5 Nundle) (Plate 1, fig. 4).

A wide range of sedimentary structures has been observed. Graded bedding is exhibited by almost every bed of silt-size or coarser. The graded units generally pass upward into clay-sized material. Along their base load-casts are often present. These have been observed only in two dimensions, and appear to be flute casts and flow casts.

The upper part of the silt portion of the graded units may be finely laminated and show ripple cross-stratification. Occasionally the form of the ripple-marks is preserved, either in cross-section or on bedding surfaces. The latter are usually large scale, two occurrences having: amplitude 1″; wave-length 9″–12″ and amplitude $\frac{3}{8}$″; wave-length 9″.

The silt and clay layers not uncommonly show convolute bedding (Plate 1, fig. 5). Slump structures are rare, but an example occurs on the Peel River at 210132 Nundle.

Rare instances of a typical cross-stratification have been observed. The sets, which are extensive, have parallel bounding surfaces, and do not exceed 3 inches in thickness. The cross-strata are gently curved. These were produced by traction currents of appreciable strength, as sand-sized material is involved.

Benson (1913*b*, p. 578) has referred to intrusive relationships between the " tuffs " (i.e. arenites) and " cherts " (i.e. argillites) where the former overlie the latter. These are the " intrusive tuffs " of authors (see Browne, 1929, pp. xv-xvi). Later (1915*b*, Figs. 5–7, 10 and 12) Benson illustrates examples, mainly from Nemingha railway cutting, in what is here termed Yarrimie Formation. It is quite clear from his figures that these structures would be considered to be of sedimentary origin by modern workers. His figs. 6 and 7 are examples of shale breccias, fig. 10 of a shale pebble conglomerate (cf. Plate 1, fig. 2, herein), and figs. 5 and 12 of some form of pull-apart or load-cast structure.

These structures are due either to the disruption of bedded argillaceous material by the passage of a turbidity current, or to the disruptive effect of a suddenly deposited load of coarse material from a turbidity current (see Kuenen, 1957). The author has observed similar structures south of Bowling Alley Point at 233.4;136 Nundle on Swamp Creek.

Macrofossils are rare, except in the limestones. Worm tracks are occasionally observed in the argillites.

Notes on Maps

A series of four maps entitled " The Geology of the Tamworth-Liverpool Range district ", are relevant to this paper and the subsequent papers on the Parry Group and the post-Carboniferous stratigraphy. The base maps for the geological maps were compiled from parish maps and surveyor's plans, with extensive correction of creek courses and roads from aerial photographs, the maps being prepared on a scale of 2 inches=1 mile. No other maps of the area were available. No control was attempted, and, whilst the maps are morphologically of good accuracy, the scale is only approximate.

A reliability diagram for the geological detail on the maps is included in the author's Ph.D. thesis (Crook, 1959). The eastern portions of maps 1–3 were mapped by Benson (1911–20). Geological detail shown in these areas is a composite of Benson's observations and new observations of the author, combined with structural interpretation of both sets of observations. Part of the boundary of the Liverpool Range Beds in the Quirindi Creek Valley is taken from Hallinan (1950). The remainder of the maps, and most of the structural interpretation, is original.

Figures margining the maps are co-ordinates of the reference grid which has been used in the preceding text. It is not related to the Australian Military Survey Grid, but references are read in the same manner as on the military maps—eastings (i.e. lines trending north-south) followed by northings (i.e. lines trending east-west), followed by the sheet name. E.g. the grid reference of Goonoo Goonoo Village is 084228 Goonoo Goonoo.

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Explanation of Plate

Plate 1

Fig. **1** : Hard black-and-white-banded argillite interbedded with soft mudstones, Passage Beds of Yarrimie Formation, Silver Gully, **193.5;198** Goonoo Goonoo.

Fig. **2** : Well-rounded argillite pebbles in feldspathic labile graywacke. Drift block from Yarrimie Formation, Silver Gully.

Fig. **3** : Argillaceous limestone lens, showing bedding continuous with surrounding argillite, Yarrimie Formation (?), Peel River, **217.5;142** Nundle.

Fig. **4** : Spilite showing pillow structure (light material is sediment), Tamworth Group, Swamp Creek, **231.3;137.5** Nundle.

Fig. **5** : Convolute bedding in black-and-white-banded cherty argillite, Yarrimie Formation (?), Peel River **217.5;142** Nundle.

TAMWORTH GROUP


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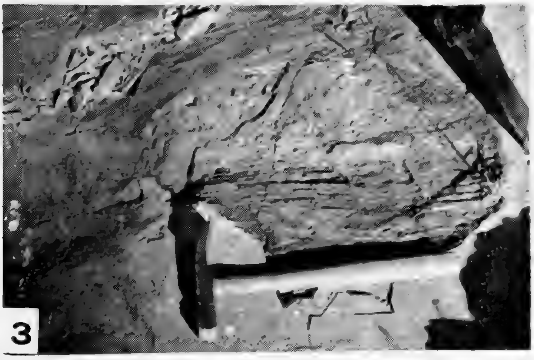
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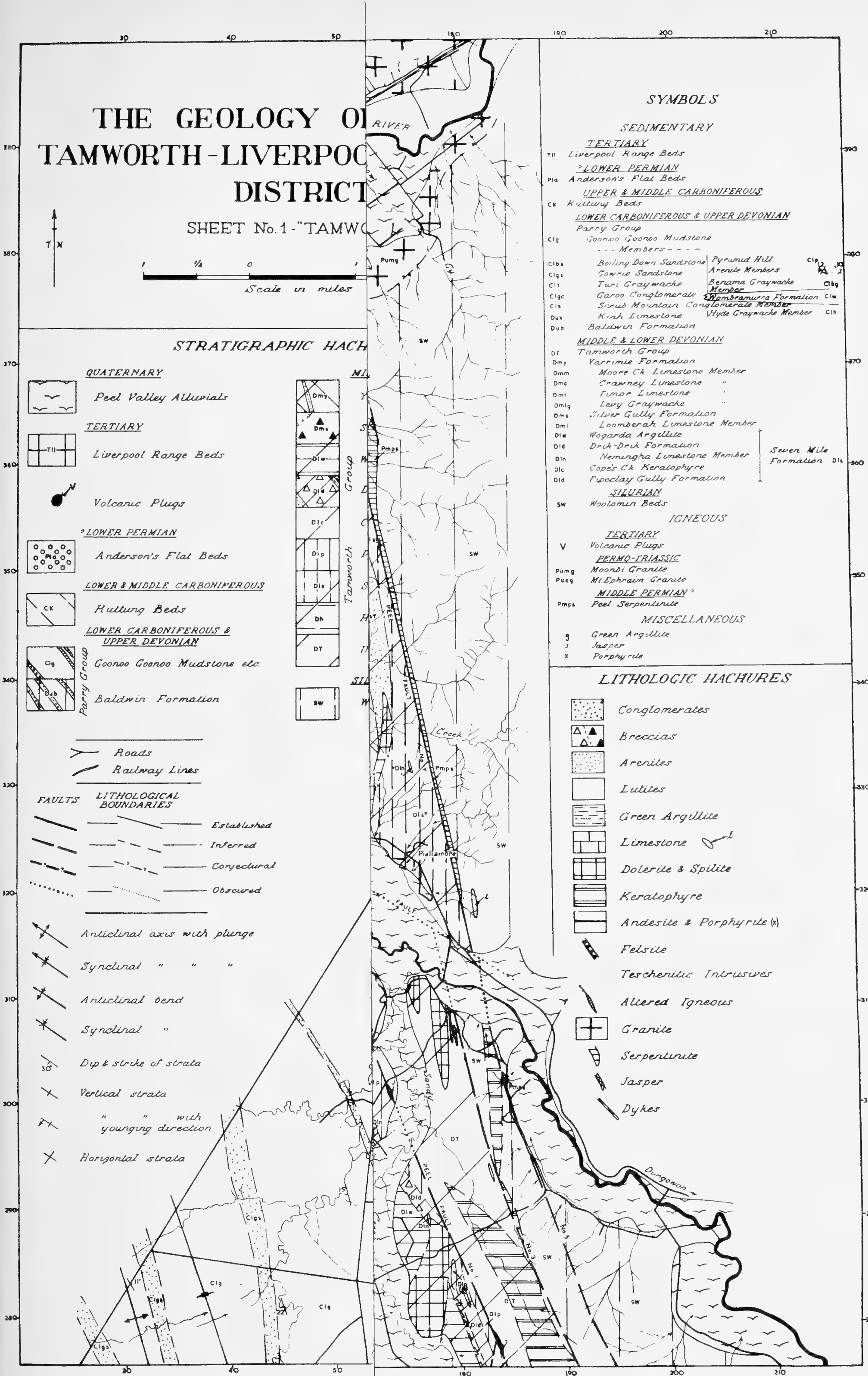
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Volcanic Plugs
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Anderson's Flat Beds
LOWER & MIDDLE CARBONIFEROUS
Kullung Beds
LOWER CARBONIFEROUS & UPPER DEVONIAN
Parry Group
Goonoo Goonoo Mudstone etc.
Baldwin Formation
Tamworth Group
Roads
Railway Lines
FAULTS
LITHOLOGICAL BOUNDARIES
Established
Inferred
Conjectural
Obscured
Anticlinal axis with plunge
Synclinal " " "
Anticlinal bend
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Dip & strike of strata
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SYMBOLS
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Tll Liverpool Range Beds
?LOWER PERMIAN
Pla Anderson's Flat Beds
UPPER & MIDDLE CARBONIFEROUS
CK Kullung Beds
LOWER CARBONIFEROUS & UPPER DEVONIAN
Parry Group
Clg Goonoo Goonoo Mudstone
--- Members ----
Clbs Boiling Down Sandstone
Clgs Gowrie Sandstone
Clt Turi Graywacke
Clgc Garoo Conglomerate
Cls Scrub Mountain Conglomerate Member
Duk Kirk Limestone
Dub Baldwin Formation
Pyramid Hill Arenite Members Clp
Benama Graywacke Member Clbg
Wombramurra Formation Clw
Hyde Graywacke Member Clh
MIDDLE & LOWER DEVONIAN
DT Tamworth Group
Dmy Yarrimie Formation
Dmm Moore Ck Limestone Member
Dmc Crawney Limestone "
Dmt Timor Limestone "
Dmlg Levy Graywacke "
Dms Silver Gully Formation
Dml Loomberah Limestone Member
Dlw Wogarda Argillite
Dld Drik-Drik Formation
Dln Nemingha Limestone Member
Dlc Cope's Ck Keratophyre
Dld Pipeclay Gully Formation
Seven Mile Formation Dls
SILURIAN
SW Woolomin Beds
IGNEOUS
TERTIARY
V Volcanic Plugs
PERMO-TRIASSIC
Pumg Moonbi Granite
Pueg Mt Ephraim Granite
MIDDLE PERMIAN?
Pmps Peel Serpentinite
MISCELLANEOUS
g Green Argillite
J Jasper
x Porphyrite
LITHOLOGIC HACHURES
Conglomerates
Breccias
Arenites
Lutites
Green Argillite
Limestone
Dolerite & Spilite
Keratophyre
Andesite & Porphyrite (x)
Felsite
Teschenitic Intrusives
Altered Igneous
Granite
Serpentinite
Jasper
Dykes
RIVER
Creek
Sandy
PEEL FAULT
FAULT
Piallamore
Dungowan
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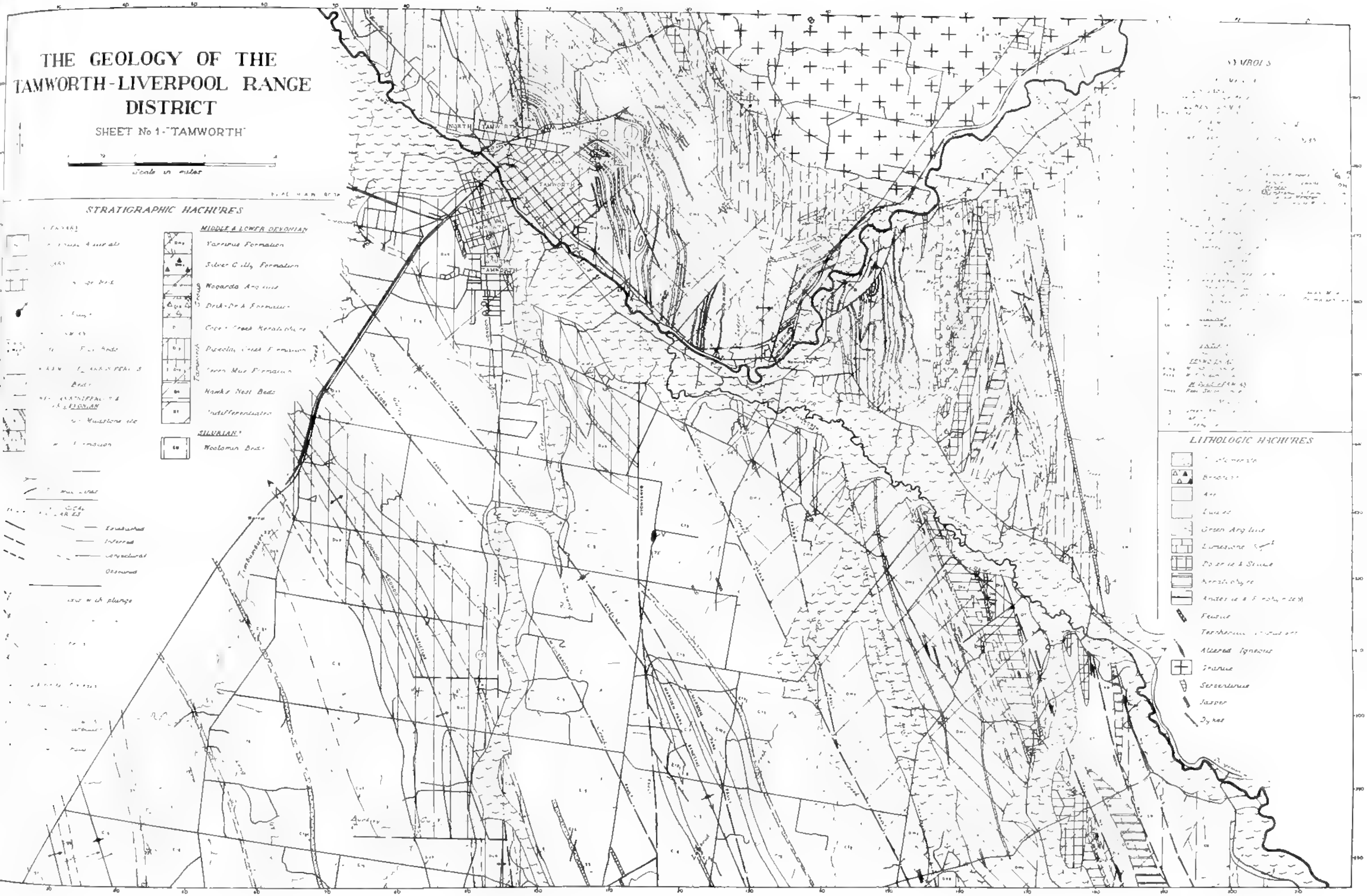

THE GEOLOGY OF THE
TAMWORTH-LIVERPOOL RANGE
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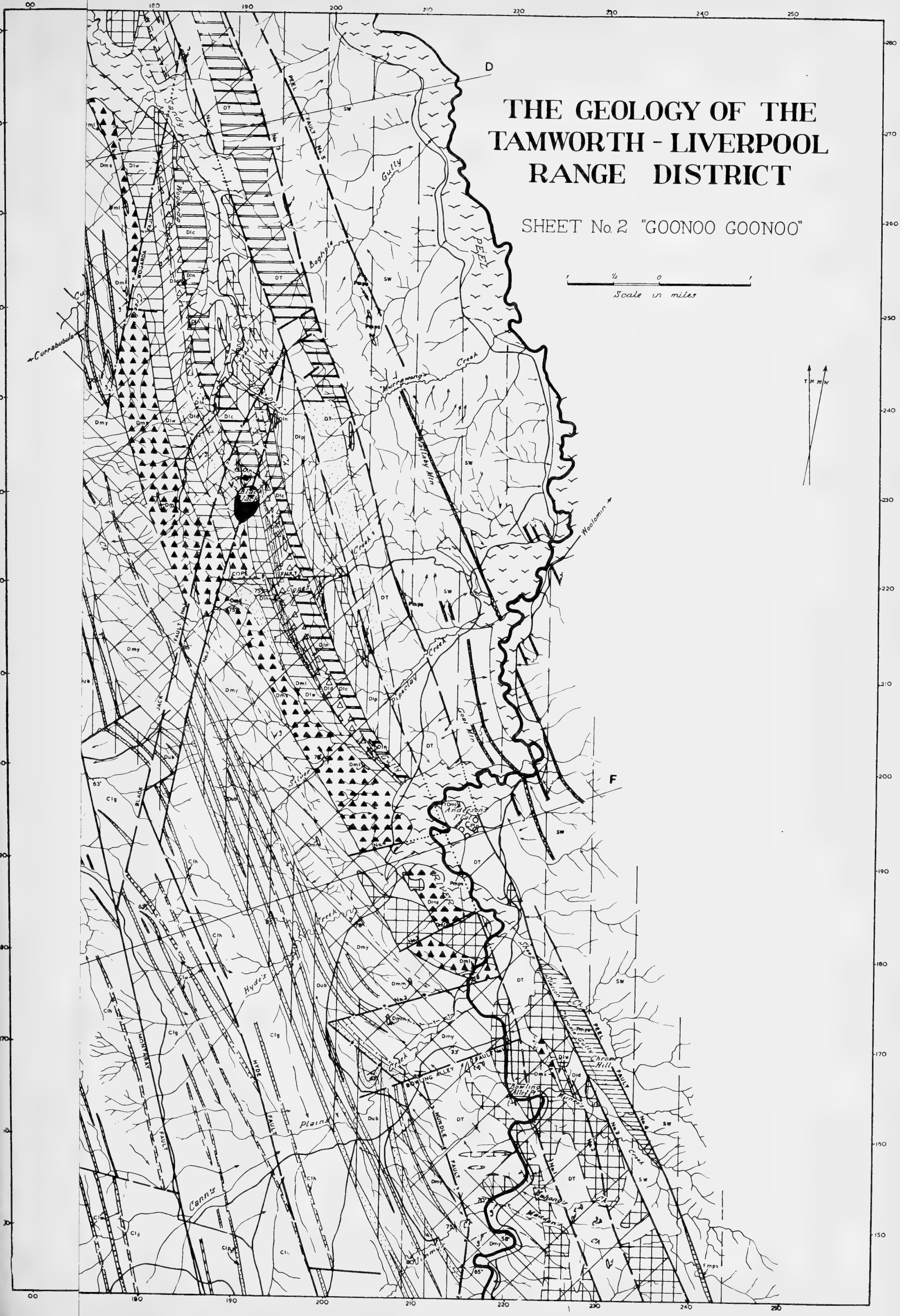

THE GEOLOGY OF THE TAMWORTH - LIVERPOOL RANGE DISTRICT

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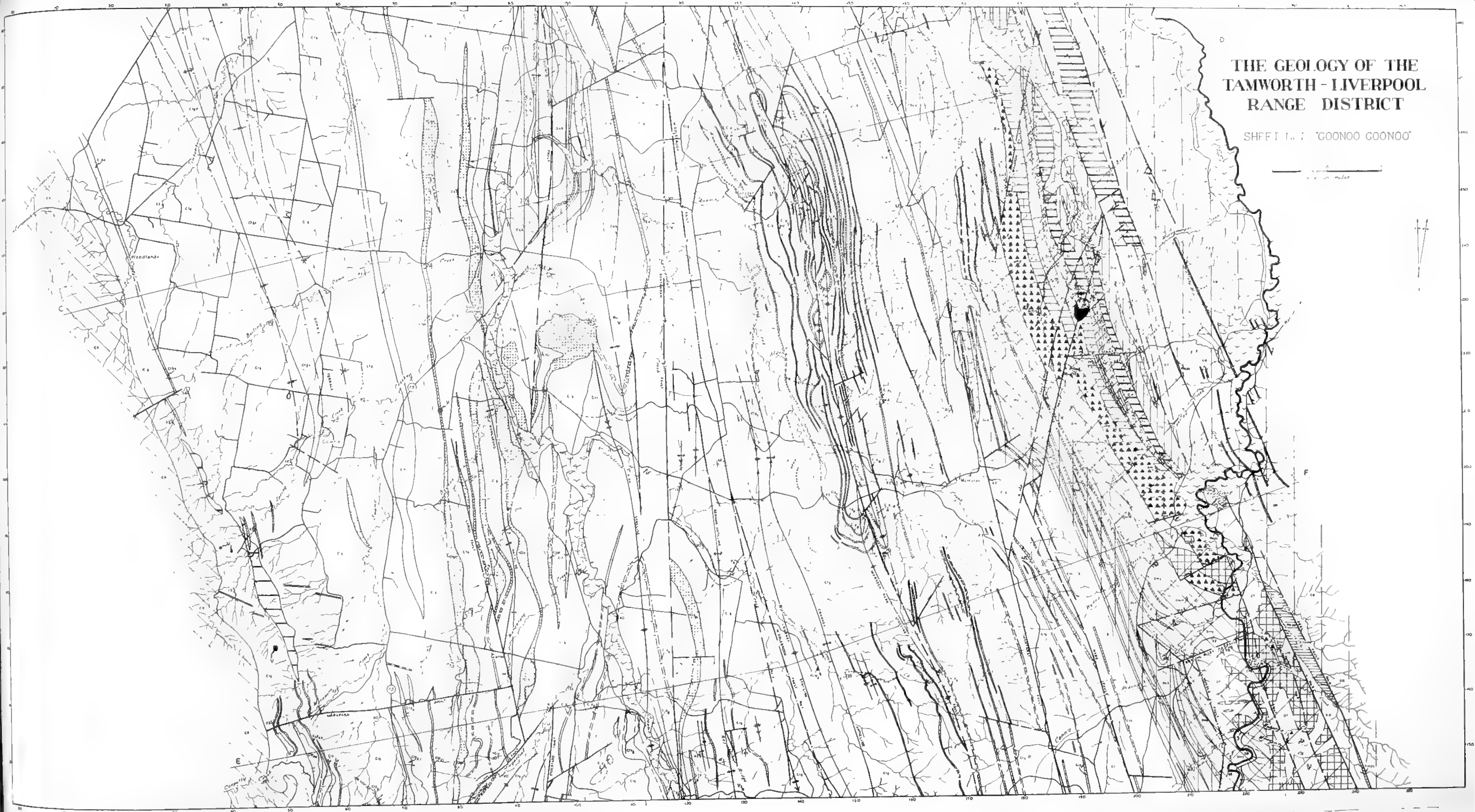

THE GEOLOGY OF THE TAMWORTH - LIVERPOOL RANGE DISTRICT

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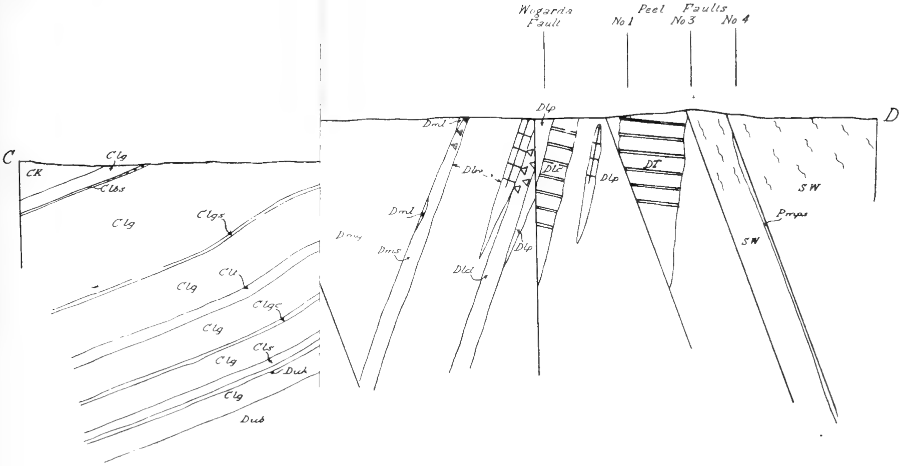
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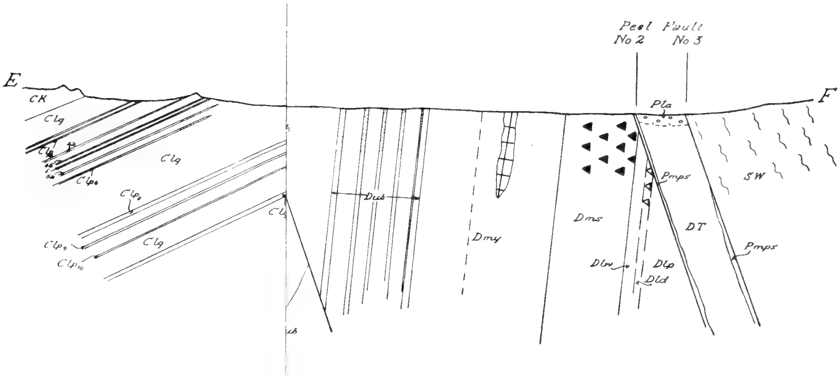
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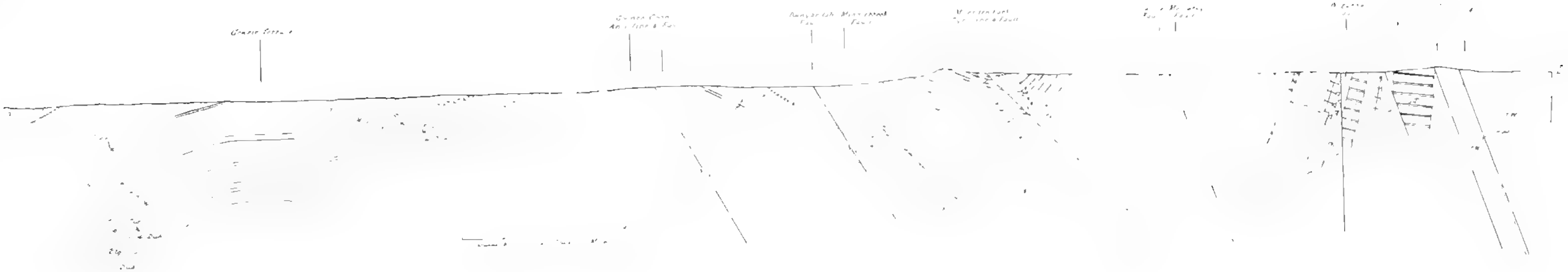
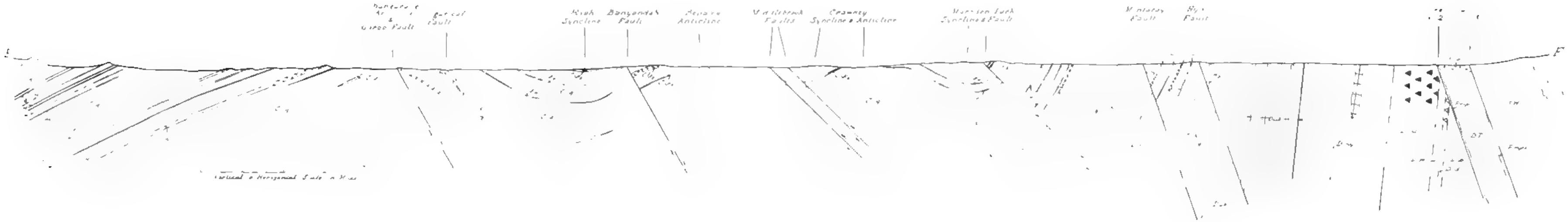
Section 2 WOODLANDS — DUNGOWAN C–D on Sheet 2



Section 3 TAMARANG — ANDERSON'S FLAT E–F on Sheet 2



Journal and Proceedings, Royal Society of New South Wales, Vol. 94, pp. 189–207, 1961

Stratigraphy of the Parry Group (Upper Devonian-Lower Carboniferous), Tamworth-Nundle District, N.S.W.

KEITH A. W. CROOK

(*Received February* 12, 1960)

ABSTRACT—The Parry Group, which is defined and described, conformably overlies the Tamworth Group in the Tamworth Trough sequence of western New England. It contains three formations, which are defined, the Baldwin Formation, Goonoo Goonoo Mudstone and Wombramurra Formation. Several members are recognized and defined within the Goonoo Goonoo Mudstone. The group thickens markedly as it is traced eastwards, attaining a maximum of 18,700 feet. Most of the variation occurs in the Goonoo Goonoo Mudstone, which has a maximum thickness of 15,600 feet. Data are presented.

The group is largely a deepwater deposit, consisting dominantly of olive-green mudstones accompanied by lithic labile graywackes and sandstones, polymictic conglomerates and minor amounts of siltstone, feldspathic graywacke, and argillaceous limestone.

As defined, the Parry Group is a synonym of the Lower Burindi Series (or Group) plus the Barraba Series (or Manilla Group) of authors. This new terminology is introduced because the junction between these two " series " or groups is not definable throughout the greater part of the district discussed herein.

Introduction

The Parry Group, herein defined, is a major unit in the Tamworth Trough sequence of western New England, N.S.W. In the foregoing paper the author has defined the Tamworth Trough and discussed one of its constituent units, the Tamworth Group, which conformably underlies the Parry Group. The introductory remarks, cartographic notes, and terminology given therein (Crook, 1961) apply also to this paper.

To obtain a true perspective of the stratigraphic nomenclature proposed herein it is necessary to discuss first the nomenclatural history of the sequence overlying the Tamworth Group. The various schemes which have been proposed are shown in Table 1, and as synonymies in the text.

Table 1. Relation between the new nomenclature and older systems

Benson, 1912-1920		Carey & Browne, 1938	Voisey 1952-1958		Herein	
Burindi Series		Upper Burindi Series = Lower Kuttung Series	Upper Burindi Group = Lower Kuttung Group		"Lower Kuttung Group"	
		—?—?—?—	—?—?—?—			
		Lower Burindi Series	Lower Burindi Group		Parry Group	Goonoo Goonoo
—?—?—?—?—		—?—?—?—?—?—	—?—?—?—?—			Kiah Limestone
Barraba Series	Barraba Mudstone Estimated thickness 13,000 feet		Manilla Group	Barraba Mudstone		Mudstone Estimated maximum thickness 1150 feet
	Baldwin Agglomerate			Baldwin Formation		Baldwin Formation
Tamworth Series			Tamworth Group		Tamworth Group	

—?—?—?— = junction not specifically defined.

In the Tamworth-Nundle district and westwards, the sequence above the Tamworth Group consists of an upper coarse unit of pink sandstones, polymictic conglomerates and some shales, and a lower unit consisting dominantly of olive-green mudstones which contain some coarse green arenites and polymictic rudites. Coarse beds are rather prominent in the 3000 feet of sequence immediately overlying the Tamworth Group.

The upper coarse unit has been termed the Lower Kuttung Group (or Series) (Carey, 1934, 1937; Voisey, 1952). Its junction with the lower unit is readily mappable throughout the area examined in this study. Whilst there is a nomenclatural problem inherent in this coarse unit when it is considered regionally (see Table 1 and Voisey, 1958*a*, pp. 175–7), this will not be discussed in this paper.

The lower unit has been subdivided (Table 1) as follows:

(A) *BALDWIN FORMATION:* The lowest subdivision, the Baldwin Formation (Voisey, 1958*b*, p. 209) contains that part of the sequence with prominent coarse beds, immediately overlying the Tamworth Group.

Synonymy: Baldwin Agglomerate (Benson, 1913*a*, p. 499); Baldwin Series, Beds (Benson); Baldwin Stage (Brown (in David, 1950, p. 251)); Baldwin Formation (Voisey, 1958*b*, p. 209).

Facies variant according to Benson: Scrub Mountain Conglomerate (Benson, 1918*a*, p. 338).

Benson erected the term Baldwin Agglomerate to cover the " tuffaceous agglomerates (which) consist of fragments . . . up to a foot in diameter . . . included in a matrix of andesitic or spilitic tuffaceous character " developed on Mount Baldwin near Manilla, where the basal beds are not exposed. He considered that similar rocks near Tamworth belonged to this unit (1913*a*, p. 500). These rested conformably on his Tamworth Series (i.e. the Tamworth Group). Voisey (1958*b*) modified the name to " Baldwin Formation " because of the large amount of mudstone within the unit in the Manilla district. A type section has not yet been designated.

(B) *BARRABA MUDSTONE:* Overlying the Baldwin Formation is a dominantly mudstone sequence, which contains *Leptophloeum* [*Lepidodendron*] *australe** in the lower portions, and Carboniferous marine fossils with *Lepidodendron* in the upper portions, although in many areas considerable thicknesses are unfossiliferous. The lower portion of this mudstone unit is known as the Barraba Mudstone. No type section has been designated.

Synonymy: Nundle Series (Benson, 1912, p. 106); Nundle Beds (Benson); Barraba Series (Benson, 1913*a*, p. 502); Barraba Beds, Shales, Nundle-Barraba Series (Benson); *not* Barraba Series (Benson, 1915*b*, p. 577 and subsequently); Barraba Mudstone (Benson, 1915*b*, p. 577).

Facies variant, according to Benson: Pyramid Hill Tuff (Benson, 1918*a*, p. 339).

In 1912 Benson introduced the term " Nundle Series " for the beds conformably above his Bowling Alley (Tamworth) Series in the Nundle district, where he considered that his Baldwin Agglomerate was not developed. This unit he described (1912, p. 101) as " a succession of fine-grained andesitic tuffs and soft laminated clay-shales and mudstones . . . in places . . . cherty; elsewhere there are bands of conglomerate containing granitic pebbles, and frequently there are thin limestone lenses ". In 1913*a*, p. 502, he uses the term Barraba Series for " banded shales and mudstones " lying conformably above his Baldwin Agglomerate. The identity of the Barraba Series with the Nundle Series is noted in several places (e.g. 1913*a*, p. 495). Later (1918*a*, p. 256) he states: " The rock of the Barraba district is the type for the Barraba mudstones, fine-grained, olive-green flaggy rocks containing thin layers of whitish felsitic tuff, and numerous casts of *Lepidodendron australe*; and, in the finer portions, numerous radiolaria. There are also a few bands of conglomerate, sometimes of a normal character, more often with a strongly tuffaceous base."

In 1915 Benson altered his usage of the term Barraba Series, extending it to include his Baldwin Agglomerate. Thereafter he referred to the mudstones previously termed the " Barraba Series " as the " Barraba Mudstone ". In his later usage " Barraba Series " is synonymous with Voisey's " Manilla Group ".

(C) *LOWER BURINDI GROUP:* The upper portion of the mudstone unit is at present known as the Lower Burindi Group (Voisey, 1952, p. 50). Its nomenclature has undergone several changes which have been discussed by Voisey (1958*a*, p. 175–7). No constituent formations have been defined.

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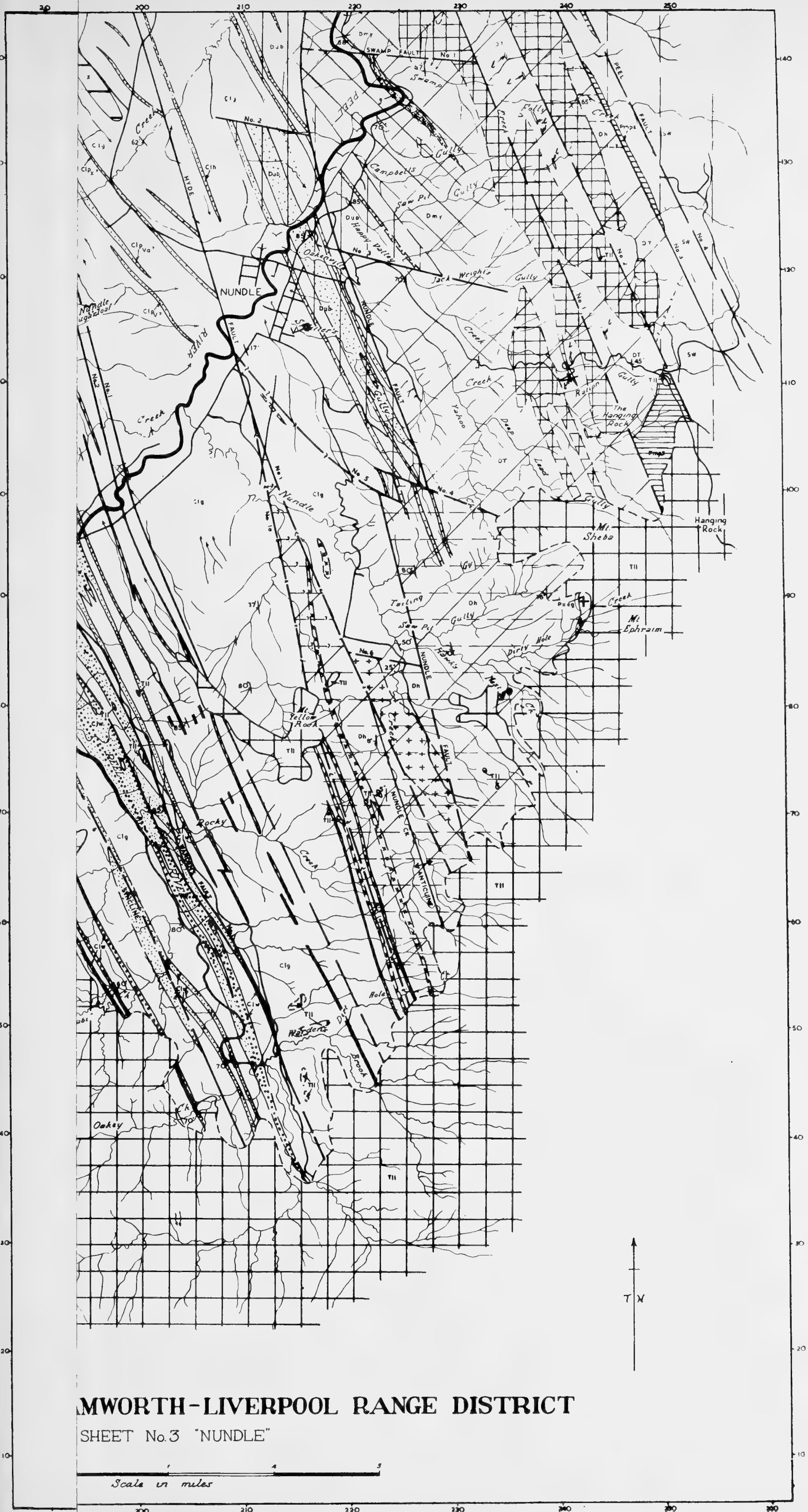
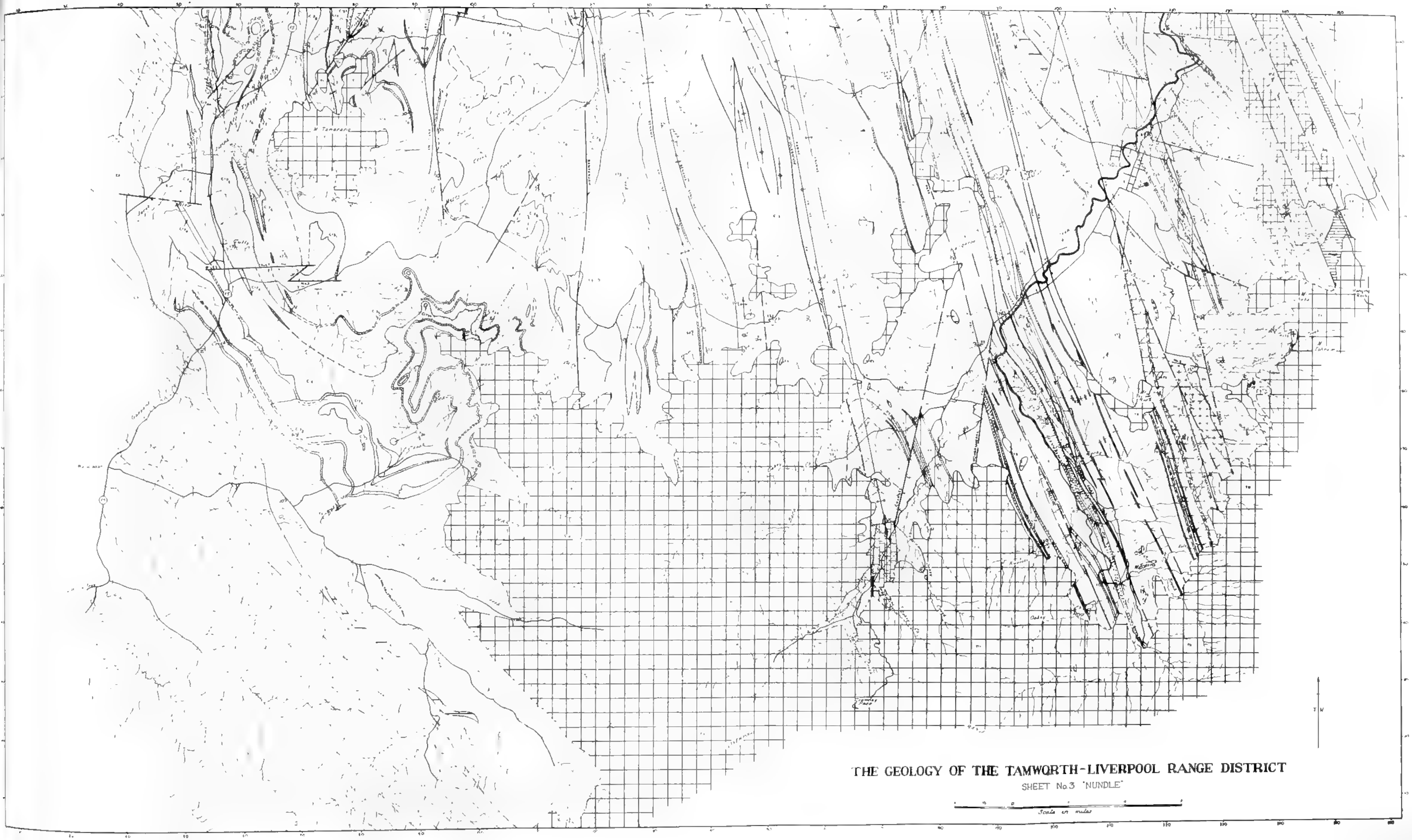
* The author follows Walton (1926) in referring the form *L. australe* McCoy to the genus *Leptophloeum*. As Benson notes (1922, p. 204) the genus *Lepidodendron* is considered by many workers to be restricted to the Carboniferous.



MWORTH-LIVERPOOL RANGE DISTRICT

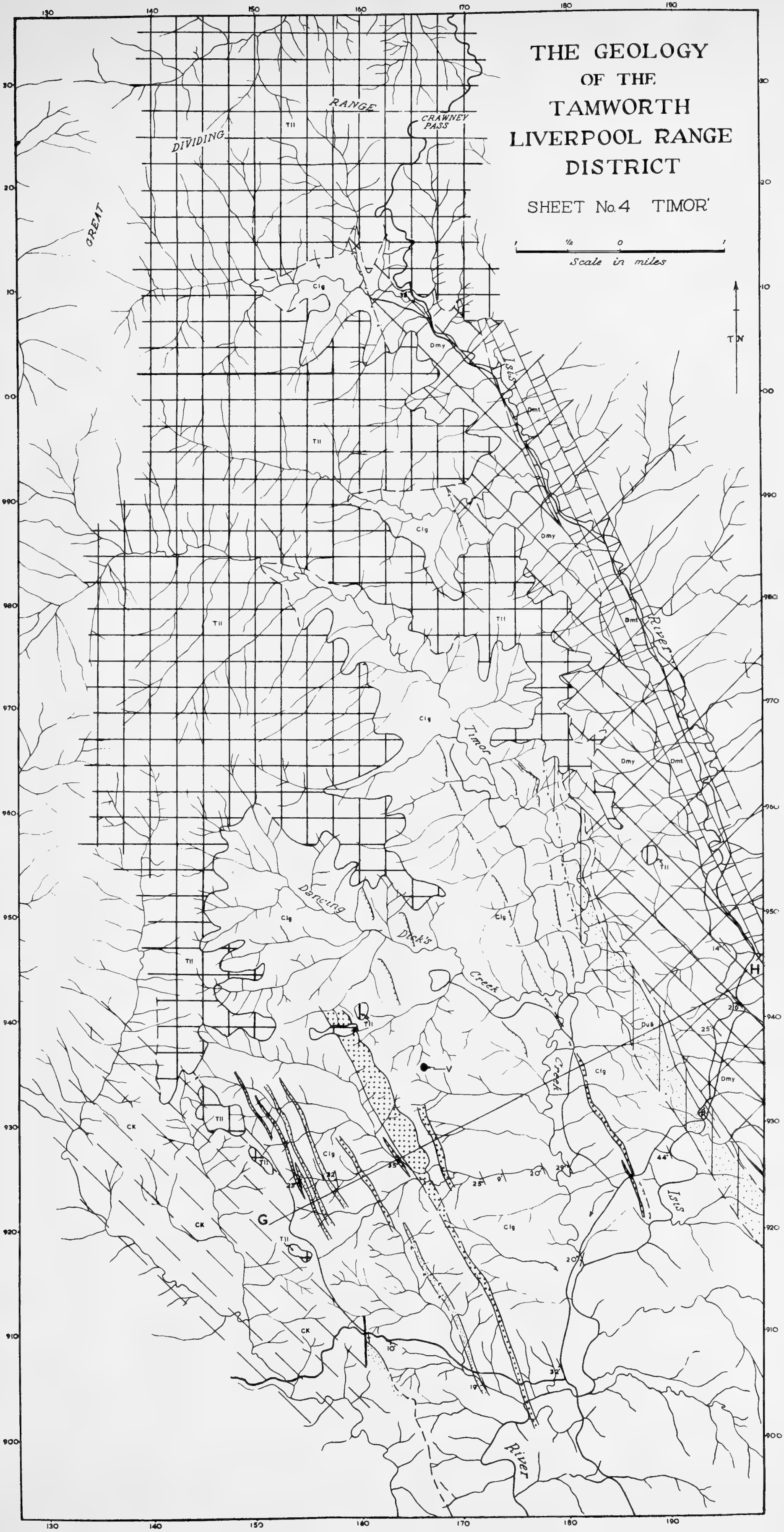
SHEET No. 3 "NUNDLE"



THE GEOLOGY OF THE TAMWORTH-LIVERPOOL RANGE DISTRICT

SHEET No.3 'NUNDLE'

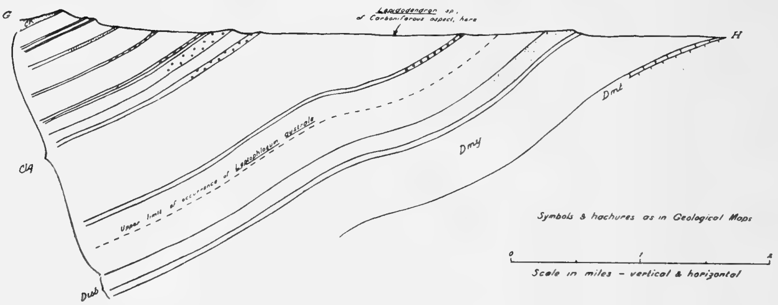
Scale in miles



THE GEOLOGY OF THE TAMWORTH LIVERPOOL RANGE DISTRICT

SHEET No. 4 'TIMOR'

Section 4. Geological Section G to H, Sheet 4



Synonymy: Burindi Series (in part) (Benson, 1913*a*, p. 503); Burindi Series (Benson, 1920, p. 292); Burindi Series (Carey, 1937); Lower Burindi Series (Carey and Browne, 1938, p. 592); Lower Burindi Group (Voisey, 1952, p. 50).

This is the Lower Burindi Series of authors. Benson (1913*a*, p. 503) introduced the term Burindi Series (or Burindi Mudstone) for "fine dark grey, fissile mudstone, with bands of tuff of an andesitic nature and occasionally a rather coarsely grained, tuffaceous breccia. Here and there are thin bands of limestone, composed almost entirely of crinoid ossicles, and other beds largely oolitic", which overlay his Barraba Series. These beds did not contain *Leptophloeum* [*Lepidodendron*] *australe* (see Benson, 1913*a*, p. 502).

(D) *MANILLA GROUP:* In the Manilla district the Barraba Mudstone and Baldwin Formation are together recognized as a fourth stratigraphic unit, the Manilla Group (Voisey, 1958*b*, p. 209). The term "Manilla Group" has not been applied to the sequence within the present area.

Synonymy: Barraba Series (Benson, 1915*b*, p. 577, and subsequently); *not* Barraba Series (Benson, prior to 1915); Manilla Group (Voisey, 1958*b*, p. 209).

Status of these units—From the foregoing it will be apparent that the base of the Baldwin Formation is defined. Its top, although not formally defined, is readily identifiable throughout the area mapped and also in the Manilla district (Voisey, 1958*b*, p. 209). The unit only requires designation of a type section to be completely acceptable under the Australian Code of Stratigraphic Nomenclature (1959).

With the definition of a top to the Baldwin Formation, the base of the Baraba Mudstone is automatically fixed. The top of the Barraba Mudstone—which is the base of the Lower Burindi Group (Voisey, 1958*a*, p. 175)—is not satisfactorily defined. The unit thus requires further definitive work, in addition to the designation of a type section, preferably in the Barraba district, for it to be acceptable under the Code, and fully useful in the field.

The Lower Burindi Group has, within the area mapped, a clearly defined top—the base of the "Lower Kuttung Group"—but lacks a satisfactorily defined base. Its name is unsatisfactory, in that the word 'Lower' is included, and its status as a group is prejudiced by a lack of defined formations. It therefore requires considerable definitive work before it can be considered acceptable, and completely useful in the field.

Problem of the Burindi-Barraba junction—Any attempt to utilize the substance of the existing terminology for an adequate description of the stratigraphy of this sequence is clearly dependent on a satisfactory definition of the junction between the "Lower Burindi Group" and the Barraba Mudstone. If this proves impossible, some more or less radical departure will be necessary, at least for the areas in which the junction cannot be defined.

Benson's statements—Examination of the statements of the original proposer of the Burindi Series and Barraba Mudstone, make it clear that he at no time felt able to map clearly a junction between them. He states (Benson, 1913*a*, p. 503): "The Burindi Series lies conformably above these [Barraba] mudstones, and it has not yet been possible to draw a sharp distinction between them." And later (1913*a*, p. 508): "The thickness of the fossiliferous marine beds [Burindi] at Burindi is about

1000–1500 feet, but it is not yet possible to define their lower limit." Some years later (1917*a*, p. 265) he is still of the same opinion: " Other evidence mentioned below (p. 269) indicates that we cannot yet be sure where the line of demarkation should be drawn between the Devonian and Carboniferous Series."

Not only was Benson unable to map the junction between his two Series; he experienced some difficulty in distinguishing the mudstones of one from those of the other. He states (1913*c*, p. 719): " The [Burindi] mudstones are indistinguishable from the coarser type of the Barraba Series, until the fossil-bearing horizons are reached, where the rock becomes finer grained and darker green in colour . . . "

It is evident from other statements that Benson's criteria for distinguishing the mudstones were paleontological, not lithological. For example (1913*a*, p. 502), " Indeed, the distinction between the Barraba Series and the Burindi Series, lies largely in the absence of *L. australe* (and radiolaria) from the latter ". His later statement (1917*a*, p. 269): " It may be, therefore, that the true base of the Carboniferous system lies at some unrecognizable horizon in the Barraba mudstone. For the purpose of mapping, however, the base of the Burindi beds is the lowest recognizable horizon in the Carboniferous that can be traced ", suggests that the base of Burindi Series was recognized on paleontological grounds.

Although Benson realized that the Middle Devonian-Lower Carboniferous sequence was conformable, his stratigraphic column (1922, pl. XIVA) shows a distinct break in the hachuring between the Burindi and Barraba Series, together with the words " Thickness of intervening beds not determined ". This is his last statement on the problem.

Benson therefore left the junction between his two Series unsatisfactorily defined, and it became the practice to refer mudstones with *Leptophloeum australe* to the Barraba Series and those with Carboniferous marine fossils to the Burindi Series.

Carey's contribution—Working on the western side of the axis of the Werrie Syncline at Piallaway, Carey (1937, p. 349) found a sequence—the Merlewood Section—containing marine fossils of very early Carboniferous aspect, with massive arenite and conglomerate containing *Leptophloeum australe* a short distance below. He placed the top of the Barraba Series at the top of this coarse unit, but did not attempt to trace the horizon across the axis of the syncline. This work of Carey's is the only case to date in which the Barraba-Burindi junction has been specifically defined. If applicable to the region as a whole this would constitute a satisfactory solution to the problem.

The new data—To proceed further it is necessary to consider the new data obtained by the author during the course of the present study. This is presented in the form of a series of stratigraphic columns in Fig. 1, together with a reinterpretation of data from Carey (1937) and Williams (1954).

It will be seen, from Fig. 1, that the sequence thickens rapidly coming eastward from Merlewood, and therefore Carey's junction horizon is difficult to identify. The author's interpretation is one of several possibilities. Furthermore, Carey's junction horizon is not known to cross the axis of the syncline, so that the chances of tracing it into the thicker sequence east of Merlewood are not good. Finally, there is a distinct possibility, and the author subscribes to this view, that the massive arenite and conglomerate taken as the top of the Barraba Series by Carey is, in fact, the top of the Baldwin Formation. This possibility arises from the unexpected thinness of the *Leotophloeum*-bearing mudstones overlying the Baldwin Formation in areas where the total sequence is quite thick (Fig. 1, cols. 3, 9). With regular thinning of all parts of the mudstone sequence going westward, the thickness of *Leptophloeum*-bearing mudstones at Merlewood would be negligible.

It must therefore be concluded that Carey's contribution cannot solve the problem satisfactorily so far as the present area is concerned.

Remembering that, by usage, ' Barraba Mudstone ' has been the term applied to the *Leptophloeum australe*-bearing portions of the mudstone sequence, and that ' Lower Burindi Group ' has been applied to Carboniferous portions of the sequence, the problem could be solved satisfactorily by defining the junction between the two units in accordance with the following criteria.

(1) The junction should be placed at, or not far above, the top of the *Leptophloeum australe*-bearing mudstones, and as close to the Devonian-Carboniferous junction as practicable.

(2) The junction should be marked by (a) a change in the character of the mudstones, or (b) by a bed of distinctive lithology.

(3) The horizon taken as the junction should be readily identifiable throughout the region under discussion, or the greater part of it.

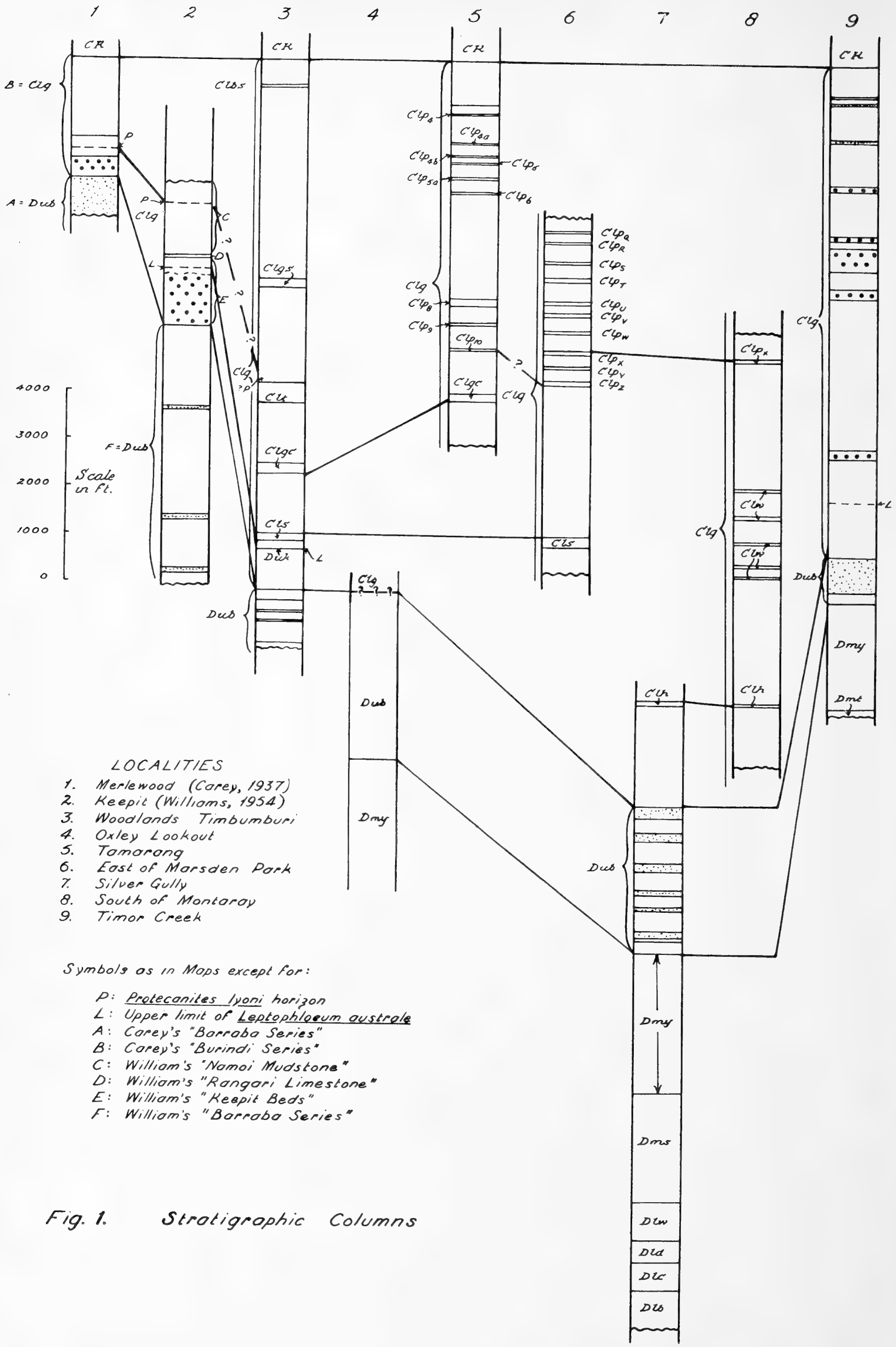


Fig. 1. Stratigraphic Columns

Consideration of the stratigraphic columns in Table 1 indicates that, from criterion (1), the junction horizon must be at least 850 feet above the top of the Baldwin Formation throughout most of the region, and should probably be within the succeeding 2000 feet of strata.

Criterion 2 (a) cannot be fulfilled, as no obvious changes occur within the mudstones in this region of the sequence. Turning to criterion 2 (b), the following marker horizons are available: the Kiah Limestone Member (*Duk*), the Hyde Graywacke Member (*Clh*), and the Scrub Mountain Conglomerate Member (*Cls*). (These units are defined below.)

Testing these three possible horizons on criterion 3, it is found that none of them meet this requirement. In fact, a further examination of Fig. 1 will reveal that it is not possible to find any horizon between the top of the Baldwin Formation and the base of the " Lower Kuttung Group " which will fulfil the three criteria.

Accordingly it must be concluded that, for the area under consideration, the existing Barraba-Burindi subdivision cannot be satisfactorily employed, as it is without an objective basis. This does not necessarily apply to other areas: indeed, the Kiah Limestone Member is known to extend northward from the present area for some distance, and in this region it may fulfil the three criteria. If the criteria are thus fulfilled in this other area, it is to be greatly regretted that the Kiah Limestone Member is not more extensively developed in the present area, for this unit marks the point, based on the paleontological grounds used by Benson, at which the junction should be placed. As mentioned below, the Kiah Limestone marks the upper limit of *L. australe* and lies very close to the Devonian-Carboniferous boundary.

The author's solution—The absence of any mappable junction between the Barraba Mudstone and " Lower Burindi Group " in most of the area under discussion has forced the author to choose between discarding the Barraba-Burindi subdivision, or defining a junction which is not objective, or is based on paleontological grounds alone.

He has chosen the first course, rather than the adoption of what he considers to be unsatisfactory stratigraphic practice, and has been reinforced in his decision by the following factors.

(1) The relative insignificance of the *L. australe*-bearing mudstones in the area examined. The following thicknesses have been obtained:

Timbumburi district ..	850 feet
Crawney-Middlebrook Creek	probably less than 1000 feet
Timor Creek district ..	1150 feet.

Assuming that Benson would have placed the top of his Barraba Mudstone at the upper limit of distribution of *L. australe*, it becomes clear from Fig. 1 and the geological maps that his figure of 13,000 feet for the thickness of the Barraba Mudstone west of Nundle (1913*a*, p. 495) is a gross overestimate. The sequence he measured includes much of his Burindi Mudstone, and is repeated by faulting.

(2) The lithogenetic unity of the sequence between the top of the Tamworth Group and the base of the " Lower Kuttung Group ". This unity is suggested by the difficulty in finding suitable horizons for use in subdivision, and it becomes apparent when the petrology of the rocks is considered. Arenites and mudstones from near the top of the sequence are often indistinguishable from those near the base.

The author therefore considers that, within the area under discussion, the sequence should be considered as a single group, the Parry Group, which contains two main formations, the Baldwin Formation and, overlying it, the Goonoo Goonoo Mudstone. The latter formation comprises the Barraba Mudstone and " Lower Burindi Group ". This subdivision is shown in Table 1, and in detail in Table 2.

In view of the possibility that a satisfactory junction between the Barraba Mudstone and " Lower Burindi Group " may be definable outside the present area, the author does not wish to discuss the future usage of these units or of the terms " Burindi " and " Barraba ", except to reiterate that they have no objectivity throughout most of the area discussed herein.

Other units erected by Benson—In a previous paper (Crook, 1961) the author has mentioned Benson's correlation of the lower part of his Nundle Series with the upper part of his Tamworth Series, and has indicated that this correlation is in error. It remains to show this.

In 1918 Benson, having mapped the area south of Loomberah, recognized two new units, the Scrub Mountain Conglomerate and the Pyramid Hill Tuff. The former he thought coeval with his Baldwin Agglomerate (Benson, 1918*a*, pl. XXXII); the latter he considered equivalent to part of his Barraba Mudstone. Remembering that Benson considered there was no development of his Baldwin Agglomerate

Table 2. Stratigraphic Subdivision of the Parry Group

			Western Region	Eastern and Southern Regions
	Visean		"Lower Kuttung Group" (CK)	(not preserved)
Lower Carboniferous	Tournaisian	PARRY GROUP	-Boiling Down Sandstone Member (Clbs) -Gowrie Sandstone Member (Clgs) -Turi Graywacke Member (Clt) -Garoo Conglomerate Member (Clgc) -Scrub Mountain Conglomerate Member (Cls) -Kiah Limestone Member (Dlk) Goonoo Goonoo Mudstone (Clg)	Goonoo Goonoo Mudstone (Clg) Pyramid Hill Arenite Members (Clp) -1 -2 -3 -4 -4a -5 -6 -7 P- Q- R- S- T- U- V- Va- W- -8 X- -9 Y- -10 Z- -Benama Graywacke Member (Clbg) -Wombramurra Formation (Clw) -Scrub Mountain Conglomerate Member (Cls) -Hyde Graywacke Member (Clh)
Upper Devonian			Baldwin Formation (Dub)	Baldwin Formation (Dub)
Middle Devonian			not exposed	Tamworth Group

near Nundle, it followed from his correlation of the Scrub Mountain Conglomerate with his Baldwin Agglomerate that there was a considerable thickness of mudstone between his Scrub Mountain Conglomerate and the recognizable top of his Tamworth Series near Nundle. Since this mudstone formed part of his Nundle (Barraba) Series, and seemed much thicker than elsewhere, he correlated the lower part of his Nundle Series with the upper part of his Tamworth Series at Tamworth.

The initial error in this lies in the equating of the Scrub Mountain Conglomerate Member and the Baldwin Formation. Examination of Fig. 1 (especially column 3) and the geological maps shows that the Scrub Mountain Conglomerate Member overlies the Baldwin Formation in the Timbumburi region. It is further apparent from Fig. 1 (columns 5, 6 and 8) and the maps that the Pyramid Hill Arenite Members (Benson's Pyramid Hill Tuff) are above the *L. australe*-bearing portions of the sequence, and therefore outside the units of what Benson would have termed Barraba Mudstone. In the Tamarang district, the Pyramid Hill Arenite contains occasional Carboniferous marine fossils.

These observations destroy much of the basis for Benson's correlation involving his Nundle and Tamworth Series. The conclusive observation, however, is that the Baldwin Formation is developed at Nundle, passing through the northern end of the township (see map). This confirms Benson's earlier correlation of his Nundle Series with his Barraba Series.

Definitive and Descriptive Stratigraphy Parry Group

Synonymy—Manilla Group (Voisey, 1958*b*) plus Lower Burindi Group (Voisey, 1952).

Derivation—County of Parry.

Lithology—Olive-green to olive-brown mudstones, frequently with silty bands and small argillaceous limestone lenses. Numerous labile arenite and conglomerate units, and one thin bed of lithographic limestone, are contained within the mudstones.

Thickness—Maximum observed 18,700 feet (obtained by addition of partial sections).

Age and Relations—Early Upper Devonian to late Tournaisian (Lower Carboniferous). Conformably overlies the Tamworth Group, and is conformably overlain by the " Lower Kuttung Group ".

The subdivisions of the Parry Group are shown in Table 2. Recognition of the three constituent formations does not involve any problems, as the junction between the Baldwin Formation and Goonoo Goonoo Mudstone is easily recognizable, and the limits of the Wombramurra Formation, which intertongues with the Goonoo Goonoo Mudstone, are marked by the change in lithology from conglomerate to mudstone.

The nomenclature of units within the Goonoo Goonoo Mudstone, however, is rather more complicated. All units are sheet-like but ultimately lenticular, and wedge out into the surrounding mudstones. The problems involved in applying the Stratigraphic Code to this sequence have already been discussed (Crook, 1959*b*) from a theoretical viewpoint. In view of these problems, each sheet-like unit has been termed a member, and in cases where several lithologically similar members occur close together in a collection they have been given a common geographic name and the individuals differentiated by means of letters or numerals.

Goonoo Goonoo Mudstone

Synonymy—Lower Burindi Group, plus Barraba Mudstone (Benson, 1915*b*).

Derivation—Goonoo Goonoo village (084228 Goonoo Goonoo).

Type Section—Timor Creek and tributaries (153923.5 to 191.5;929 Timor).

Lithology—As for Parry Group.

Thickness—Maximum observed (obtained by addition of partial sections, and extrapolation on drawn cross-section), 15,600 feet. Type Section, 10,350 feet.

Age and Relations—Late U. Devonian to L. Carboniferous (late Tournaisian). Lies conformably on the Baldwin Formation. The base of the formation is placed at the top of the first major arenite bed in the arenite rich portion of the Parry Group which occupies the 3000 feet odd immediately overlying the Tamworth Group. The Formation is overlain conformably by the " Lower Kuttung Group ". The junction is placed at the top of the last recognizable mudstone of the type common in the Goonoo Goonoo Mudstone, and is generally marked by a passage into polymictic conglomerate or sandstone. From a genetic viewpoint the junction lies at the point where marine sedimentation gives way to the fluviatile sedimentation characteristic of the " Lower Kuttung Group ".

The unit consists dominantly of mudstone with conglomerate, arenite and minor limestone. The mudstones are usually olive-green to olive-brown, but unweathered exposures are dark green. They are typically poorly fissile with alternating bands of silt (or fine sand) and clay (Plate 1, fig. 1). The coarser bands are often paler than the finer, the contrast being very marked above and below the Garoo Conglomerate on Spring Creek (075.4;222.9 Goonoo Goonoo).

Bedding is usually prominent, but is obscured if fracture cleavage is well developed. The rocks are poorly fissile along the junction of bands, and parting is rare within a band.

There is considerable variation in the grain-size, colour, and relative and absolute thicknesses of the bands, and the degree of fissility of the rocks. The variation in appearance does not appear to fall into any coherent pattern stratigraphically, and is apparently due largely to variations in degree of weathering, intensity of jointing and incidence of fracture cleavage.

In the core of the Benama Anticline at 134084.5 Nundle, and possibly also on upper Leura Creek, there occur pinkish muddy arenites with gray poorly fissile claystone interbeds. Relationships to the adjacent mudstones are obscure. On Middlebrook Creek at 157.2;099 Nundle black shales with arenite interbeds, possibly less weathered equivalents of the Benama Anticline lithology, occur adjoining the Middlebrook Fault No. 1. Relationships to the adjacent mudstones are again obscure.

Unfossiliferous argillaceous limestone in lenses up to two feet thick is common throughout the sequence (Plate 1, fig. 2). Occasionally it forms continuous beds up to 18 inches thick. Pyrite cubes and ripple lamination occur occasionally.

Beds of dark green siltstone are locally dominant, but are restricted stratigraphically. They are poorly fissile, laminated, and break into rectangular blocks. They occur below the Benama Graywacke Member (129.5;086.3 Nundle), on Spring Creek between Members U and W of the Pyramid Hill Arenite (153198.5 Goonoo Goonoo), on Boiling Down Creek immediately above the Scrub Mountain Conglomerate Member (082239 Goonoo Goonoo), below Member 9 of the Pyramid Hill Arenite on Benama Creek (123.8;117 Nundle), on Sugarloaf Creek (078140 Nundle) above the Garoo Conglomerate Member, above Member 5 of the Pyramid Hill Arenite on Wiles Gully (052.5;109.5 Nundle) and below Member X ? of the same on Yuruga Creek (192.5;137 Nundle).

A characteristic feldspathic labile graywacke in graded beds up to 4 inches thick, at times containing pyrite, occurs sporadically. Where it possesses calcite cement it simulates limestone in outcrop. Typically it occurs as isolated prominent beds, at times with shale pebbles (Plate 1, fig. 3).

Green lithic labile arenite beds up to five feet thick appear occasionally in areas where mappable arenite members are absent. Where thicker arenites are developed they increase in frequency, all arenites being closely related in composition and sedimentary structures. They may be mottled, locally contain pyrite, and high in the sequence occasionally show lustre mottling.

Pebbly mudstones are developed locally, usually associated with conglomerate members, to which they are lithologically similar.

Southeast of Gowrie, at 048.5;190 Goonoo Goonoo, a 2 ft. band of sparsely fossiliferous calcarenite outcrops on a private roadway. This is similar to those described by Carey (1937).

On Boiling Down Creek, immediately above the Turi Graywacke Member (064.7;236.5 Goonoo Goonoo), is a 1 ft. bed of large limestone masses intimately mingled with mudstone. It contains abundant large lamellibranchs, small gastropods and fossil wood. A specimen of a goniatite close to *Gattendorfia minusculum* was obtained. Along the strike the limestone decreases in abundance and the bed becomes a much-disrupted silty unit. It is clearly the result of a submarine slide, which has removed lime mud with enclosed organic remains from shallow to deeper water.

Sedimentary structures—The most prominent structure of the mudstones is their bedding. The surfaces of sedimentation units are usually parallel and extend for long distances along the strike. Graded bedding and ripple-cross-stratification are frequent in the coarser layers. Current ripple-marks and current lineations are occasionally observed.

Rarely arenite beds up to 6 inches thick show curved planar cross-stratification. Such units have parallel bounding surfaces, and are traceable for many yards without change in thickness. Other arenite and coarse silt beds may show flow and flute casts.

Convolute bedding (Plate 1, fig. 4), at times truncated, and minor slumps, are not uncommon. Cases of possible large-scale slumping have been noted beneath the Garoo Conglomerate at 081.5;225 Goonoo Goonoo on Spring Creek, and again at 074.6;237.1 Goonoo Goonoo, on Boiling Down Creek. Below Member 8 (?) of the Pyramid Hill Arenite on Stockyard, Burra, and Goonoo Goonoo Creeks (098117.5, 101125, and 110.5;115 Nundle) there are large disrupted masses of unsheared mudstone, some of which are recumbent. Shale breccias are associated.

Arenite interbeds within the mudstone may contain abundant shale pebbles and, high in the sequence, spherical mud balls occur in both the arenites and the siltstones.

On Wiles Gully (057104.5 Nundle) the mudstones show a discontinuous banding which is similar to the discontinuous curved lamination of the arenites (see Plate 1, fig. 5).

Fossils—These occur sporadically throughout. Obscure plant remains are fairly common, and are frequently of value as current-directional indicators. *Lepidodendron* spp. occur, and *Leptophloeum australe* is common low in the sequence, with occasional *Sigillaria*. A solitary specimen of *Rhacopteris* was observed near the top of the sequence.

Marine fossils are uncommon, except in the first few hundred feet below the Kuttung Beds, where they may be abundant. In a quarry beside Highway 15 (053086.5 Nundle) argillaceous limestone containing abundant brachiopods and bryozoa occurs. These and crinoids, solitary corals, gastropods and lamellibranchs occur in the mudstones. Cephalopods and trilobites, recorded by Benson (1921), have not been observed. A list of localities and forms is incorporated in the author's Ph.D. thesis (Crook, 1959*a*).

Worm burrows, serrated and plain tracks, and *Chondrites*-like structures have been encountered.

The Formation in the Timor district—Arenite and conglomerate members occur throughout but have not been named. The arenites, which occur in the top 3000 ft., are indistinguishable from the Pyramid Hill Arenite. The conglomerates are very similar to the Garoo Conglomerate. Pebbly mudstones are associated, e.g. at 163926.5 Timor. At 168925.5 Timor the lower boundary of a conglomerate bed sharply transgresses the bedding of the underlying mudstone.

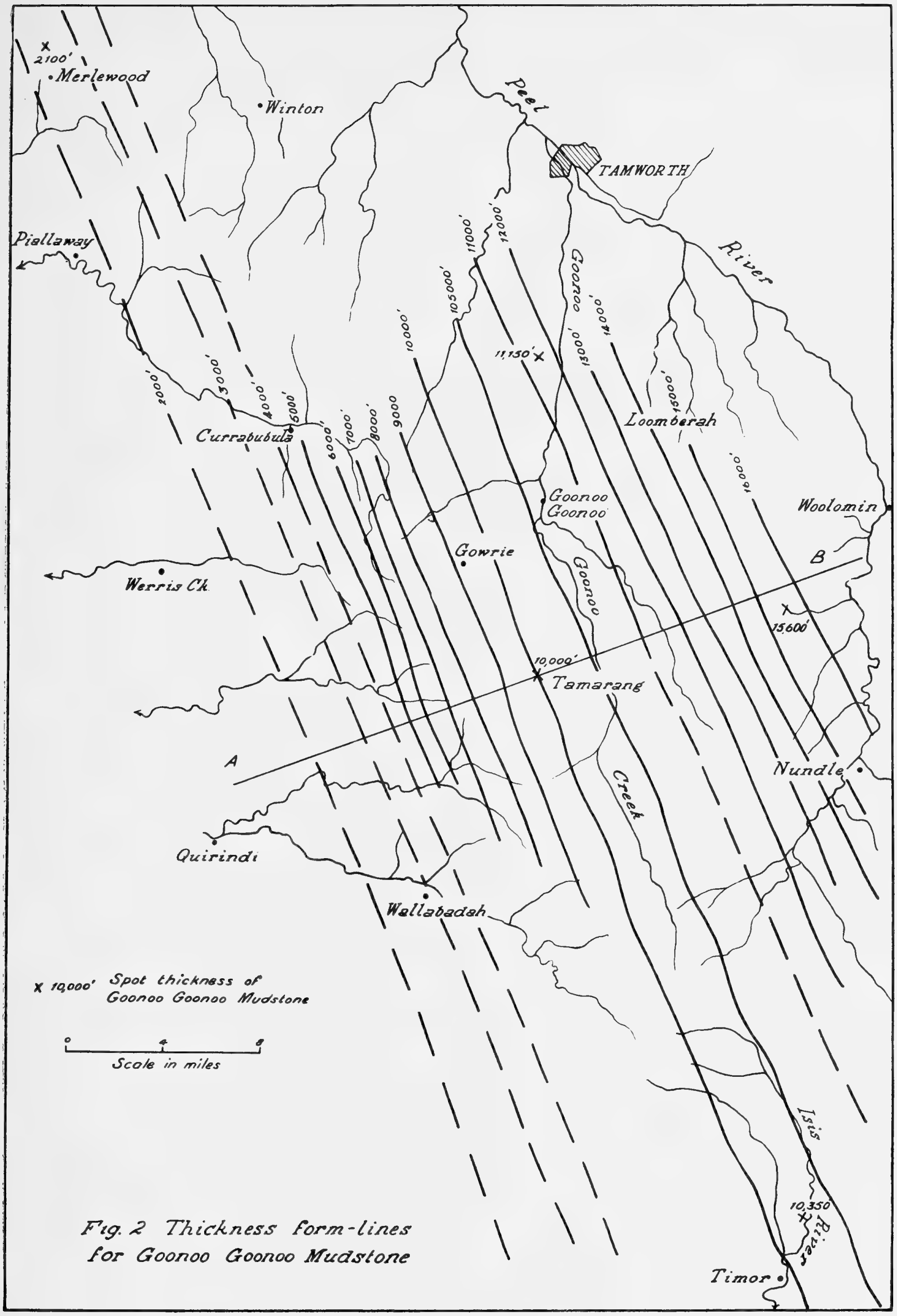


Fig. 2 Thickness form-lines for Goonoo Goonoo Mudstone

Leptophloeum australe is restricted to the bottom **1150** ft. of the sequence. Higher, on Timor Creek (180925.8 Timor) *Lepidodendron* sp. occurs. Nearby (178.4;925 Timor), argillaceous limestone shows cone-in-cone structure.

Intrusives—In the southeast of the area the Goonoo Goonoo Mudstone contains felsite intrusions, generally concordant, but transgressive locally. A prominent series of sills runs southeastward from Square Top to Rocky Creek, and others occur to the east.

Porphyrite occurs on Yuruga Creek beside the Lindsay's Gap road, and is probably intrusive. It was described by Benson (**1913***a*)

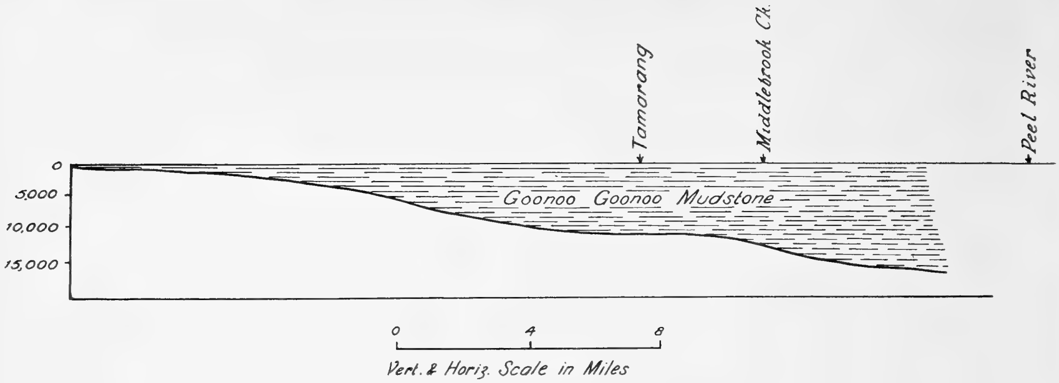


Fig. 3. Section A-B from Fig. 2. showing lateral thickening of Goonoo Goonoo Mudstone to the east.

as plagioclase porphyry. South of Mt. Tamarang there occur at various points, sills of a mottled and much altered finely phaneritic rock, which has not been closely examined.

High in the sequence in two areas—south-west of Gowrie, and in the upper Quirindi Creek valley—pyroxene andesite sills occur. These are generally concordant, but locally transgress the mudstones. Those in the former area have poorly exposed contacts with no noticeable metamorphism. A similar intrusive mass, the Minarooba Sill, has been recorded north of the present area (Benson, 1920, p. 293; Carey, 1937, p. 345). Porphyrite dykes are common in the Gowrie district, some being mappable. Occasional Tertiary teschenitic plugs are encountered, and will be dealt with elsewhere.

Variations in lateral thickness—Estimates of thickness have been made at four localities, and a further estimate from Merlewood (Carey, 1937) is also available. These are shown in Fig. 2. A cross-section from Fig. 2 is shown in Fig. 3, which gives the shape of the Goonoo Goonoo Mudstone assuming a horizontal base to the overlying "Lower Kuttung Group". There is a marked thickening eastwards from 2100 ft. at Merlewood to 15,600 ft. near Woolomin.

The form-lines shown on Fig. 2 trend approximately 340° (true reading), indicating the local trend of the depositional basin, termed the Tamworth Trough (Crook, 1961).

Several members are recognized within the Goonoo Goonoo Mudstone. In the Western Region of the area these are, in descending order :

Boiling Down Sandstone Member

Derivation—Boiling Down Creek (030.8;212.3 Goonoo Goonoo).

Type Section—Boiling Down Creek (locality cited above).

Lithology—Green lithic sandstones.

Thickness—Maximum observed, ca. 100 feet.

Age and Relations—Tournaisian. A Member 500 feet below the top of the Goonoo Goonoo Mudstone, wedging out to the south of Woodlands. The top and base are marked by the passage from sandstone into mudstone.

The unit consists of massive green lithic labile sandstone and minor polymictic conglomerate, containing fossils beside the Currabubula-Tamworth road. Sedimentation units tend to be lenticular and current lineation has been observed.

Gowrie Sandstone Member

Derivation—Village of Gowrie (053.5;207.5 Goonoo Goonoo).

Type Section—Spring Creek (054.7;207.4 to 056208 Goonoo Goonoo).

Lithology—Green labile sandstones with discontinuous bedding and shale breccias.

Thickness—Maximum observed, ca. 200 ft.

Age and Relations—Tournaisian. A unit about 4600 ft. below the top of the Goonoo Goonoo Mudstone, wedging out south of Gowrie. The top and base are marked by a passage from sandstone into the surrounding mudstone.

The unit consists of pale green sandstones, some mottled, and minor conglomerates, all labile. Sedimentation units average 2 feet in thickness, tend to be wedge-shaped, and exhibit scour and fill structure. Shale breccia is abundant, and crinoid stems are locally present in the sandstones. Straight or curved planar cross-stratification in sets up to 18 inches thick is common.

South of Spring Creek near Gowrie the unit appears to wedge out rapidly. Northward it appears to be better developed, but outcrops are poor north of Boiling Down Creek.

The small lens of sandstone on Swamp Creek (065214 Goonoo Goonoo) is similar to the Gowrie Sandstone.

Turi Graywacke Member

Derivation—Parish Turi, County Parry.
Type Section—Spring Creek (069.7;216 to 070.5;216.8 Goonoo Goonoo).
Lithology—Mottled green labile graywacke with some interbedded mudstone.
Thickness—Maximum observed, ca. 400 feet.
Age and Relations—Early Tournaisian. Developed about 6800 feet below the top of the Goonoo Goonoo Mudstone. Wedges out abruptly near Garoo. The top and base are placed at the point where the interbedded mudstones and graywackes are replaced by a mudstone sequence.

The unit consists of thin beds of mottled green lithic labile graywacke and dark greenish-black mudstones, with some thick mottled coarse graywackes and polymictic conglomerates locally. Sedimentation units are tabular and extensive, with parallel bounding surfaces. Graded bedding is common and shale breccias are present. Discontinuous curved lamination occurs in the arenites.

Garoo Conglomerate Member

Derivation—Parish Garoo, County Parry.
Type Section—Boiling Down Creek (075236.5 Goonoo Goonoo).
Lithology—Polymictic conglomerate with argillaceous matrix, and some graywacke.
Thickness—Type Section, 250 feet.
Age and Relations—Early L. Carboniferous. A very persistent unit on the western side of the Goonoo Goonoo Anticline, some 8450 ft. below the top of the Goonoo Goonoo Mudstone. The base and top are marked by a passage from conglomerate and arenite into the surrounding mudstone sequence.

The unit is dominantly polymictic conglomerate with an argillaceous matrix. Boulders are well rounded, up to 2 ft. in diameter, and are dominantly of andesite and other volcanics, although granite has been noted. Mottled coarse lithic and feldspathic labile graywackes may be associated. Locally pebbly mudstones occur, and the mudstones underlying the unit may be contorted.

The unit is one of the most extensive in the area along the strike, but seems to have little extent across the strike, as it is scarcely developed on the eastern limb of the Goonoo Goonoo Anticline.

Scrub Mountain Conglomerate Member
(Benson, 1918)

Derivation—Scrub Mountain (166219 Goonoo Goonoo).
Type Section—Tributary of Goonoo Goonoo Creek (080.1;249.3 to 081.8;248.5 Goonoo Goonoo).
Lithology—Similar to the Garoo Conglomerate Member.
Thickness—Type Section, 200 feet.
Age and Relations—Early Lower Carboniferous. A unit of considerable east-west extent developed beneath the Garoo Conglomerate Member, some 10,000 ft. below the top of the Goonoo Goonoo Mudstone. Top and base are marked by the appearance of a continuous mudstone sequence.

Lithologically similar to the Garoo Conglomerate, this unit contains a variety of pebbles, including granite, with volcanics dominant, together with blocks of mudstone. One of the last, on Kiah Creek (104225 Goonoo Goonoo) appears to be 50 yards in length and 25 feet thick, suggesting that the conglomerate may be a submarine slide deposit. Pebbly mudstone and contorted mudstones occur below the conglomerate at several points. The upper part of the unit is often green graywacke which may show load casts.

Along the Wangarang Anticline the unit appears to split into several beds separated by mudstone, but relationships are obscure away from creek beds. The unit is extensive across the strike, but of limited extent along the strike. It wedges out about 5 miles north of Goonoo Goonoo, and further east its southern limit is 7 miles south of Loomberah Public School.

Kiah Limestone Member

Derivation—Kiah Creek.
Type Section—Kiah Creek (100233.7 Goonoo Goonoo).
Lithology—Fine-grained, gray, bedded, lithographic limestone with pseudomorphs of carbonate after ? albite.
Thickness—3 feet.
Age and Relations—Etroeungtian or very late U. Devonian. An important marker horizon, marking the top of the local teil-zone of *Leptophloeum australe*. It occurs some 850 ft. above the base of the Goonoo Goonoo mudstone. The top and base of the unit are placed at the points where the lithographic limestone gives way to a mudstone sequence.

This unit is a thin marker bed on the western side of the Goonoo Goonoo Anticline. Its maximum observed thickness is 3 feet, yet it has been traced for some 15 miles along the strike, and is known for another 30 miles to the northwest of the present area. It is massive, gray and poorly bedded, and typically contains euhedral pseudomorphs of carbonate after ? albite, which weather in relief.

Near Kiah Creek, in a field at 102.5;233.7 Goonoo Goonoo, outcrops of a rather silty limestone with abundant plants preserved in-the-round have been provisionally referred to this unit. The unit marks the upper limit of *Leptophloeum australe* in the Goonoo Goonoo Anticline area, but has not been found south of Goonoo Goonoo, nor east of the Goonoo Goonoo Anticline.

In the eastern region of the area, the members are, in descending order :

Pyramid Hill Arenite

(Benson, 1918 emend.)

Synonym—Pyramid Hill Tuff, Benson, 1918*a*, p. 339.

Derivation—Pyramid Hill Range (147236 Goonoo Goonoo).

Type Section—Tributary of Reedy Creek and Anembo Creek (144.8;243.4 to 141.8;241.3 Goonoo Goonoo).

Lithology—Green lithic labile sandstones (in the south-west) and graywackes (in the north-central) with minor conglomerate, siltstone and mudstone.

Thickness—The arenite members grouped in this unit occur throughout the top 6800 ft. of the Goonoo Goonoo Mudstone, and rarely exceed 50 ft. in thickness individually.

Age and Relations—L. Carboniferous. The unit consists of a collection of arenite members developed at frequent intervals throughout the upper part of the Goonoo Goonoo Mudstone. The individual members are of limited extent, wedging out into the surrounding mudstones. The top and base of each is marked by the appearance of a mudstone sequence.

The term " tuff " is rejected as inappropriate, " arenite " having been used in its place to indicate the mixture of rock-types which occur.

This unit consists of a variable number of arenite members. It is developed in the south-west about Mt. Tamarang, and in the north-central region along the Marsden Park Syncline. Fourteen members, given numerical suffixes, are recognized in the former district. In the latter, 11 members are given letter suffixes, and others of very limited extent are also present.

Lithologically the various members are similar, consisting mainly of green lithic labile arenites. They vary from fine to coarse, and frequently show discontinuous curved lamination (Plate 1, fig. 5). Mottling occurs in Members 9 and 10 on Goonoo Goonoo Creek (105.8;180.5 and 107.7;175.5 Goonoo Goonoo), Member 9 on Middlebrook Creek (121190 Goonoo Goonoo) and locally in Member 5 on Wiles Gully (060100 Nundle) (Plate 1, fig. 6).

Minor polymictic conglomerate, usually with an arenaceous matrix, occurs in the southwest. It contains a wide variety of pebbles, including granite and andesite, with volcanics dominant. Occasional conglomerates consisting almost exclusively of andesite fragments (Plate 2, fig. 1) occur, as at 118145.5 Goonoo Goonoo on Benama Creek, and on Burra Creek at 095.8;121.3 Nundle where there is a block of andesite 2½ ft. in diameter.

Minor amounts of siltstone and mudstone occur. The former is frequently pale and is usually well laminated.

Sedimentation units in the arenites average 2 feet in thickness. In the south-west they tend to be wedge-shaped, although those in Member 6 and lower tend to be tabular and extensive, particularly in the case of the finer beds. In the north-central area the sedimentation units of all arenites tend to be tabular and extensive. Throughout the sequence in all areas the siltstones and mudstones exhibit extensive thin tabular sedimentation units.

Shale breccias are common, and may form closely-packed masses at the base of arenite units. They are more frequent in the south-western area than the north-central (Plate 2, figs. 2 and 3).

Sedimentary structures—The arenites and siltstones exhibit an unusual range of structures. Ripple-cross-stratification occurs in the siltstones, with graded and convolute bedding. Ripple marks are occasionally seen. In the north-central area the associated arenites also show ripple-cross-stratification, but graded bedding is usually not apparent.

In the southwest, particularly high in the sequence, the associated arenites show tabular, trough, or wedge-shaped cross-stratified sets with curved cross-strata, sets ranging to 1 foot thick. Occasionally the cross-strata are themselves graded, due presumably to competency variation (see Pettijohn, 1957, p. 171). Lower, below Member 7, this medium-scale cross-stratification has not been observed, and the arenites may show graded and convolute bedding.

Load casts (Plate 2, fig. 4), and pseudo-intrusive relationships between beds of mudstone and arenite (Plate 2, fig. 5) occur in Member 5 on Wiles Gully 060100 Nundle.

The associations of sedimentary structures suggest that Members 8–10 and P–Z are labile graywackes, whilst Members 1–7 consist of labile graywackes and labile sandstones, the latter becoming dominant in the higher members.

Fossils—Fossil remains are uncommon. Crinoid ossicles and shell fragments are present in arenites in the southwest. Member 4*a* at 052.5;133 Nundle contains marine fossils. Occasional specimens of *Lepidodendron* spp. have been seen. Excellent examples of cf. *Chondrites* (Simpson, 1957) occur in Member 5 on Wiles Gully (060100 Nundle) (Plate 2, fig. 6).

Distribution—In the west all members wedge out just north of the Marapana Fault. Tracing the unit eastwards, as far as the structural complexity will permit, it extends further and further northwards before wedging out. Thus many of the lower members extend to within 6 miles of Tamworth along the Marsden Park Syncline.

In the north-central region the lower beds wedge out southwards of Spring Creek, but apparently reappear slightly further south and continue south of Lindsay's Gap until they disappear due to erosion.

Benama Graywacke Member

Derivation—Benama Creek (130106.2 Nundle).

Type Section—Tributary of Goonoo Goonoo Creek (125.5;088 to 127087.3 Nundle).

Lithology—Green lithic labile graywacke and minor polymictic conglomerate.

Thickness—Maximum observed, 100 ft.

Age and Relations—L. Carboniferous, probably roughly coeval with the Turi Graywacke Member. Developed locally in the south, below the Pyramid Hill Arenite. Top and base marked by appearance of continuous mudstone sequence.

The unit is lenticular and of limited extent, consisting of dark green lithic labile graywackes with crinoid ossicles and minor shale breccia. Locally polymictic conglomerate with a restricted range of volcanic pebbles occurs. North of the Type Section the unit thins rapidly, passing into a bed of feldspar-rich graywacke before reaching the Nundle road.

Hyde Graywacke Member

Derivation—Hyde's Creek (191175.3 Goonoo Goonoo).

Type Section—Tributary of Hyde's Creek (188179.2 Goonoo Goonoo).

Lithology—Green lithic labile graywacke.

Thickness—Type Section, 30 feet.

Age and Relations—Probably U. Devonian, possibly L. Carboniferous. Developed low in the sequence, some 2,100 ft. above the top of the Baldwin Formation. Top and base marked by the appearance of a mudstone sequence.

This is a typical dark green lithic labile graywacke with graded bedding. It is not easily accessible, and has been examined only in the Type Section.

Wombramurra Formation

Derivation—Wombramurra Creek (160040 Nundle).

Type Section—Kurrabi Creek (197053 to 200053.3 Nundle).

Lithology—Polymictic conglomerate and green lithic labile graywacke with minor interbedded siltstone-mudstone.

Thickness—Maximum observed, 1700 ft., but tongues of the unit may occur through 2000 ft. of sequence.

Age and Relations—Early Lower Carboniferous. Its top, marked by the appearance of massive conglomerate, lies approximately 9000 ft. below the top of the Goonoo Goonoo Mudstone. It extends for some 15 miles along the strike, splitting up northwards into separate beds which intertongue with the Goonoo Goonoo Mudstone and finally wedge out into it. Its base, marked by the appearance of a mudstone sequence without further conglomerate, lies some 2450 ft. above the Hyde Graywacke Member. It is a tongue-shaped unit extending into the Goonoo Goonoo Mudstone, appearing from beneath a Tertiary sequence in the south.

The unit is well developed in the southeast on the upper part of the Peel River, and extends northwest along the east limb of the Marsden Park Syncline almost to Montaray, thinning and splitting into several distinct beds between which mudstones, referred to the Goonoo Goonoo Mudstone, are developed. On the western limb the unit extends briefly along the strike, disappearing before reaching the Nundle-Wallabadah road.

The unit is typically coarse polymictic conglomerate with a wide range of pebbles up to 1 ft. in diameter. Andesite is common, and granite and argillite (not Tamworth Group varieties) fragments have been noted. Labile graywackes indistinguishable from those of the Pyramid Hill Arenite are associated. Shale breccias and pebbles are common, and the graywackes may exhibit discontinuous curved lamination.

The finer beds are either siltstones or mudstone-siltstone-fine graywacke successions. All have extensive tabular sedimentation units. Graded bedding is common in the formation, and graywackes and finer types may show ripple-cross-stratification. Fossils are absent, save for an occurrence of cf. *Chondrites* in siltstones on Kurrabi Creek (197.2;053.5 Nundle).

Baldwin Formation

(Benson, 1913, emend. Voisey, 1958)

Synonym—Baldwin Agglomerate, Benson, 1913*a*, p. 499.

Derivation—Mount Baldwin, north of Manilla.

Type Section—Silver Gully and hills behind (191200.6 to 186198 Goonoo Goonoo.)

Lithology—Massive green labile graywackes and minor rudites in several distinct beds, with olive-green mudstones between.

Thickness—Type section, 3100 ft.

Age and Relations—U. Devonian. The top of the Formation is defined as the top of the last major arenite bed in the basal portion of the Parry Group. A break of some 2100 ft. ensues between it and the Hyde Graywacke Member. The base of the unit is the top of the Tamworth Group (Crook, 1961), on which it is conformable.

The formation consists of olive-green mudstones similar to the Goonoo Goonoo Mudstone, and green graywackes, more indurated and brighter but lighter green than those higher in the sequence. Locally there are polymictic conglomerates, e.g. near Calala (107348 Tamworth), and on Goonoo Goonoo Creek (096.3;259.5 Goonoo Goonoo).

Detritus is dominantly andesitic, with some sedimentary material. On Wombramurra Creek a large block of black and white banded argillite, typical of the Yarrimie Formation beneath, is included in the graywacke. As explained elsewhere (Crook, 1959*c*), this need not imply subaerial erosion of the Yarrimie Formation. Locally there are shale pebbles surrounded by white halos. The graywackes are occasionally mottled on weathered surfaces.

The mudstones may be silty, and occasionally contain argillaceous limestone lenses. Well-laminated siltstone beds are abundant north of Goonoo Goonoo and on the Cleary's Hill road northeast of Tamworth.

In West Tamworth (092.6;368.6 Tamworth) black and white banded argillites occur in the mudstones, suggesting that the Passage Beds of the Yarrimie Formation may have been reached, or that there is a recurrence of the dominant Yarrimie Formation lithology above its defined top. Poor exposures in this region do not permit resolution of this problem.

Minor banded argillites occur interbedded with the mudstones in various places. They are silty and have pale and dark bands, but are gray-black and off-white rather than black and white.

The graywackes and siltstones have extensive tabular sedimentation units and show good ripple-cross-stratification, graded bedding and flute casts. An example of the last occurs on Cann's Plains Creek (203.2;161.9 Goonoo Goonoo). Slump structures and indefinite ripple-marks are occasionally seen. Organic remains, apart from worm-tracks, are restricted to *Leptophloeum australe* which is locally abundant except in the north of the area.

The thickness of the unit is fairly constant at about 3100–3400 ft. over much of the area, but thins southward towards Timor, where it is 950 ft. thick.

Near Nundle (221.7;110 Nundle) the formation contains a probably intrusive mass of porphyrite, similar to that in the Goonoo Goonoo Mudstone on Yuruga Creek.

"Lower Kuttung Group"

A few observations on this unit are included here for completeness.

From between Quirindi Creek and Highway 15 north to just north of the Marapana Fault the basal unit of the Kuttung is a heavy polymictic conglomerate, apparently exclusively of volcanic detritus. North and south of this region the basal unit is sandstone, at times pebbly, with cross-stratification in trough-shaped sets up to four feet thick with curved cross-strata.

On upper Spring Creek (037.8;177 Goonoo Goonoo) the arenites are green, but rapidly become maroon as the sequence is ascended. This typical Kuttung sandstone colour is apparently due to a zeolitic cement. Above these sandstones is a little impure coal, carbonaceous shale and red mudstone.

On Gaspard Creek (050082 Nundle) a small area of fossiliferous mudstone, identical with the Goonoo Goonoo Mudstone close by, occurs within the Kuttung. This is either faulted in, or represents a very local marine incursion.

Relationships between Members of the Goonoo Goonoo Mudstone

Figure 1 shows a series of stratigraphic columns, and the correlations on which the stratigraphic subdivision of the sequence is based. These are further explained by Sections 1–4 accompanying the maps.

Concerning the correlation of members of the Goonoo Goonoo Mudstone, the following points are clear from field relations :

(i) The Boiling Down Sandstone Member is on approximately the same horizon as Member 4*a* of the Pyramid Hill Arenite.

(ii) The Gowrie Sandstone Member lies on a horizon somewhere between Members 6 and 8 of the Pyramid Hill Arenite.

(iii) The horizon of the Turi Graywacke Member is below that of Member 10 of the Pyramid Hill Arenite.

(iv) There appear to be less strata between Member 10 and the Turi Graywacke Member than between Member 10 and the Benama Graywacke Member.

(v) The Scrub Mountain Conglomerate Member appears to lie beneath the Wombramurra Formation.

Probably Member 10 of the Pyramid Hill Arenite is the equivalent of Member Z of the same, but this cannot be confirmed from field evidence.

The remainder of the correlations are based on petrographic evidence, which will be published elsewhere.* The following summary indicates the features which have been utilized.

(1) In correlating the two sets of Members of the Pyramid Hill Arenite :

(a) Members 1–6 and 10 are characterized by a granite-rhyolite component, lacking in Members R–Y. Equating Z and 10, Members R–Y must lie below Member 6.

(b) Members 4–6 lack octahedral skeletal sphene-chlorite fragments, which occur in Members 8–10 and R–Z. Again Members R–Z lie below Member 6.

(c) Members 1–7 contain a bright red vitric volcanic, lacking in Members R–Z. This again points to the same conclusion.

(2) The relation between the Garoo and Scrub Mountain Conglomerate Members and the Wombramurra Formation and Hyde Graywacke Member :

(a) Skeletal sphene-chlorite is absent from the Hyde Graywacke Member, but common in the Wombramurra Formation and above and the Scrub Mountain Conglomerate and above. This is therefore the lowest of the four units.

(b) There is a strong affinity in composition between the Scrub Mountain Conglomerate Member and the Wombramurra Formation, and also several similarities between the last and the Garoo Conglomerate Member. The Wombramurra Formation occupies some 2000 feet of strata, and appears to lie above the Scrub Mountain Conglomerate Member. It has therefore been placed between the two Conglomerate Members.

In constructing the stratigraphic columns it is assumed, without direct evidence, that the bed shown on the map as Hyde Graywacke Member on upper Hyde's Creek west of the Montaray Fault is identical with the type Hyde Graywacke east of the Hyde Fault. Any other assumption would complicate the stratigraphy of that region.

Recognition of the Age of the Sequence

In determining the age of various parts of the Parry Group the following fossils are the most important.

(a) A fauna, high in the Goonoo Goonoo Mudstone, which appears to have close affinities with that described by Campbell (1957) from Watts, Babinboon. It contains *Eucladocrinus* sp., and is high in the Tournaisian.

(b) The occurrence of a goniatite close to or identical with *Gattendorfia minusculum* Miller and Collinson, 1951, immediately above the Turi Graywacke Member. Weller (1948) gives the range of this species as middle Easley Group (early Upper Kinderhookian) of the North American sequence. Associated forms in U.S.A. include *Protocanites lyoni*. This horizon is probably close to the Lower Tournaisian *P. lyoni* horizon at Merlewood (Carey, 1937).

(c) From immediately below the Kiah Limestone Member on Kiah Creek the author collected a *Leptophloeum australe* preserved in-the-round in limestone. The specimen has since been destroyed by fire. The pith cavity contained petioles of another plant, identified by Assoc. Prof. G. L. Davis as *Kalymma* Unger, 1856. The form was a new species, showing affinities with those described by Read (1937) from the New Albany Shale of central Kentucky, which lies on the Devonian-Carboniferous boundary, and is the equivalent of the European Etroeungtian.

The Devonian-Carboniferous boundary is placed by the author on the horizon of the Kiah

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* Journal of Sedimentary Petrology, **30**, 1960.

Limestone, and this may be considered a first approximation. Data which have led to this decision are:

(a) The horizon marks the upward limit of *Leptophloeum australe*, and can therefore be recognized in the field.

(b) *L. australe* has not been found associated with Carboniferous marine fossils at any point in N.S.W., and is presently presumed to be restricted to the Devonian.

(c) The presence of a flora suggestive of the Etroeungtian very close to this horizon.

(d) The occurrence of *Cymaclymenia*, a high Devonian goniatite, in the Kiah Limestone west of Manilla (Pickett, 1959).

The Tournaisian-Visean boundary falls at or above the top of the Parry Group.

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PARRY GROUP


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PARRY GROUP

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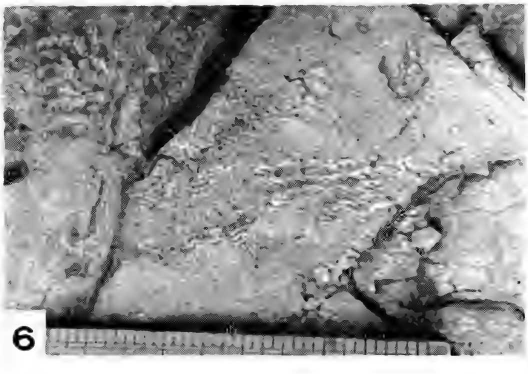

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Explanation of Plates

PLATE 1

Fig. 1 : Banded mudstone, Goonoo Goonoo Mudstone above Hyde Graywacke Member, Spring Creek, 166.8;196 Goonoo Goonoo.

Fig. 2 : Argillaceous limestone lenses in Goonoo Goonoo Mudstone above Kiah Limestone Member, Kiah Creek, 101232.3 Goonoo Goonoo.

Fig. 3 : Feldspathic labile graywacke with shale pebbles, Goonoo Goonoo Mudstone above Member 7 of Pyramid Hill Arenite, Wiles Gully, 070099.5 Nundle.

Fig. 4 : Convolute bedding (?) in fine graywacke bed in Goonoo Goonoo Mudstone below Member 9 (?) of the Pyramid Hill Arenite, Merri Creek, 104.7;106 Nundle.

Fig. 5 : Discontinuous curved lamination in labile graywacke, Pyramid Hill Arenite, Member 8 (?), Stockyard Gully Creek, 071.2;137 Nundle.

Fig. 6 : Mottled labile arenite, Pyramid Hill Arenite, Member 5, Wiles Gully, 060100 Nundle.

PLATE 2

Fig. 1 : Andesite pebble conglomerate in Pyramid Hill Arenite, Member 8 (?), Burra Creek, 095.8;121.3 Nundle.

Fig. 2 : Shale breccia (view of top surface of bed). Note contortion of shale blocks. Pyramid Hill Arenite, Member 5, Wiles Gully, 060100 Nundle.

Fig. 3 : Shale breccia, Pyramid Hill Arenite, Member 8, 112.8;149 Goonoo Goonoo.

Fig. 4 : Load cast structure (? flow-cast) in base of fine arenite bed, Pyramid Hill Arenite, Member 5, Wiles Gully, 060100 Nundle.

Fig. 5 : Bed of arenite transgressing underlying mudstone. Pyramid Hill Arenite, Member 5, Wiles Gully, 060100 Nundle.

Fig. 6 : *Chondrites* on bedding surface of siltstone, Pyramid Hill Arenite, Member 5, Wiles Gully, 060100 Nundle.

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Post-Carboniferous Stratigraphy of the Tamworth-Nundle District, N.S.W.

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ABSTRACT—Definitions and descriptions of post-Carboniferous units in the Tamworth-Nundle district are given. Units dealt with are : Anderson's Flat Beds, (? L. Permian), a block within the Peel Fault System ; Peel Serpentinite, (? M. Permian) ; Moonbi and Mt. Ephraim Granites, (U. Permian), post-orogenic batholiths ; Liverpool Range Beds and related teschenitic intrusives, (Tertiary), fluviatile sediments, basalts, and boles unconformable on older units ; Peel Valley Alluvials, (Quaternary), still forming.

The Liverpool Range Beds rest on an uneven surface of Paleozoic rocks, extensively reddened below the unconformity. This is presumed to be due to weathering under acid oxidizing conditions, such as produce soils of the upland humid red type.

Introduction

In addition to the Paleozoic units already described from the Tamworth-Nundle district (Crook, 1961*a*, *b*) younger rocks also occur. In the east a small patch of Permian occurs within the Peel Fault System. Serpentinite intrusions, considered to be Permian, occur in the fault planes of this system. A post-orogenic granitic batholith intrudes the Paleozoics east of Tamworth, and a small granite mass occurs southeast of Nundle.

In the south, Tertiary fluviatile deposits and basalts form the Liverpool Range and its foothills. Isolated plugs are scattered northwards. Along the courses of the major streams alluvials are prominent, and are still forming. These units are named and described.

Maps of the area, showing these units, are incorporated in the Paleozoic stratigraphy papers (Crook, 1961*a*, *b*). Terminology herein follows that in these papers, and map references refer to these maps.

Anderson's Flat Beds

This unit takes its name from the district of Anderson's Flat (216195 Goonoo Goonoo). It outcrops in the grounds of Westaway's (formerly Reichel's) homestead, Portion 11, Parish Dungowan, County Parry, here designated the Type Area.

The unit consists of an indeterminable thickness of black, well-indurated lithofeldspathic arenite with a calcareous cement. Outcrops are poor, being obscured by grass and soil cover. On the southern margin of the area of outcrop is a poorly indurated rudite consisting largely of sub-rounded chert fragments. This is considered to be part of the unit.

The rudite (R962, University of New England Collections) is oligomictic and well sorted with minor chloritic cement. The detritus is dominantly chert but contains some quartz and indeterminable weathered volcanics. The chert consists of a fine quartz mosaic, occasionally with chalcedony and quartz veins, and contains recrystallized radiolarian tests which are abundant in some fragments. Detrital quartz occurs as simple unstrained grains with abundant fluid inclusions and transverse streaks.

The lithofeldspathic arenite (R961, University of New England Collections), is poorly sorted and medium to fine grained. The average apparent sphericity of fragments is 0·6 (visual estimation), and most are angular to subangular. Quartz, feldspar, rock-fragments and chlorite are the major detrital constituents and a matrix is present. Modal analysis gives :

Quartz	16·4%
Chert	4·8%
Feldspar	30·6%
Chlorite	0·2%
Volcanic rock fragments ..	21·3%
Sedimentary rock fragments ..	3·5%
Granite fragments..	0·4%
Heavies	0·4%
Matrix	22·4%

Quartz—Strained simple grains with trails of fluid inclusions and epidote, calcite, and indeterminate high relief inclusions. Some grains have orthoclase associated. Others are composite and strained, with similar trails of inclusions. Chlorite may occur along the margins of the components in composite grains.

Feldspar—Clear, strained, occasionally with multiple twinning, locally clouded by sericite and at times veined by albite. Probably andesine.

Another type is perthitic, clouded and at times replaced by carbonate in part. A similar type occurs, extensively replaced by a carbonate with strong absorption. Rarely chequer-board-twinned feldspar is seen.

Chlorite—Irregular deep yellow-green patches without inclusions. D.R. 0·010, optically negative.

Accessories—Zircon, opaques, biotite (pleochroic from deep red-brown to pale yellow-brown), ? amphibole, ? spinel (isotropic, pale brown), and organic carbonate.

Rock Fragments—Volcanics dominant, comprising the following textural types: fluidal, spherulitic, arabesquitic, and trachytic (porphyritic in plagioclase and biotite). Pilotaxitic andesite and rhyolite occur, together with granite, meta-quartzite, chlorite schist, siltstone, radiolarian chert and vitric tuff.

Diagenesis—Local carbonate cement, and quartz-chlorite cement.

Benson (1913*b*, p. 586–7) has recorded several fossils from the arenites, including *Glossopteris* and " *Martiniopsis* ". The fauna is undescribed, but is probably of Lower Permian age.

The relationships of the unit to the Tamworth Group and Woolomin Beds are obscured by soil cover. The eastern and western boundaries are thought to be faults, and the northern and southern boundaries are either faults or unconformities.

Little can be added to previous structural interpretations of the unit (see Benson, 1912, p. 102; 1913*a*, p. 513; 1913*b*, pp. 586–7; 1913*c*, p. 721; 1918*a*, p. 360). Its topographical position on the floor of the Peel valley surrounded on all sides by hills of older rocks presents a problem, and Benson considered that it was preserved by down-faulting. It appears to be a block between two planes of the Peel Fault System.

Peel Serpentinite

This name, derived from the Peel River, is applied to the pods, lenses, and elongated sill-like masses of serpentinite up to ½ mile wide which occur in the planes of the Peel Fault System between Kootingal and Hanging Rock. They form part of the Great Serpentine Belt of Benson (1913*a*), and are thought to be of Permian age (Voisey, 1939, p. 252; Osborne, 1950). The masses consist of serpentinized harzburgite and dunite immediately mingled with schistose serpentinite, with local magmatic segregations of chromite.

Moonbi Granite

(Benson, 1915*b*, p. 586)

This name, derived from the township of Moonbi on the New England Highway 3 miles north of Kootingal, was applied by Benson to the granitic mass east and northeast of Tamworth.

The mass is practically unexamined petrographically: Card (in Andrews and Mingay, 1907, p. 210) and Benson (1915*b*, p. 616) have noted some features. It intrudes the Woolomin Beds, the Peel Serpentinite and the Tamworth Group, with transgressive boundaries.

The batholith is unstressed, and subsequent, post-dating the Hunter-Bowen orogeny. It is therefore late Permian or possibly early Triassic.

The contact aureole has been examined in a few places. On the upper tributaries of Seven Mile Creek (125391 Tamworth) it is 0·2 mile wide. Metamorphic effects are first seen in the limestones, which are recrystallized. Approaching the contact the argillites become hornfelsed and are locally phyllitic. In some places they contain small masses of silica and calc-silicate hornfels which represent altered radiolarian limestone lenses.

The contact has also been examined near the granite apophysis at 163.5:375 Tamworth. Here the adjoining limestone is extensively recrystallized with some development of calc-silicates. Excellent developments of calc-silicates occur further east at 169376 Tamworth.

Mount Ephraim Granite

This name is derived from Mt. Ephraim, a peak south of Nundle (246087 Nundle). The mass, first noted by Benson (1913*b*, p. 586), has been scarcely examined petrographically (see Benson, 1913*c*, p. 694). It intrudes the Hawk's Nest Beds and is overlain unconformably by the Liverpool Range Beds which almost obscure it. Its age is unknown, but it may be coeval with the Moonbi Granite.

Liverpool Range Beds

Derivation—The Liverpool Range, a portion of the Great Divide.

Representative Sections — Snowden Creek (097.5;088 Nundle); Mt. Yellow Rock (216080.7 Nundle).

Lithology—Fluviatile conglomerates with minor quartz-rich sandstones and ferruginous shales, overlain by basalts with interbedded boles and fluviatile sediments, locally intruded by coarse teschenitic sills.

Thickness—Unknown, but greater than 1000 ft. The fluviatile beds at the base aggregate 340 ft. on Mt. Yellow Rock (Benson, 1913*b*, p. 590).

Age and Relations—Tertiary, epoch unknown. Essentially horizontal and unconformable on all older units.

Description—The basal portions of the Liverpool Range Beds, consisting of fluviatile sediments, are well developed south and southeast of Nundle. They extend eastwards under the overlying volcanics with decreasing thickness, wedging out between Goonoo Goonoo and Ranger's Valley Creeks. A small outcrop also occurs beneath the volcanics on Mt. Tamarang, some 7 miles northwest of this.

The dominant rock type is conglomerate. On Mt. Yellow Rock it is coarse, with well rounded pebbles up to 9 inches in diameter. Jasper and chert pebbles are very abundant, and the quantity of labile constituents is small. Some quartz-rich sandstone interbeds show obscure cross-stratification dipping southeast. The outcrops on Mt. Yellow Rock form prominent cliffs, and the beds appear to dip ENE at a low angle. To the west at 209.8;079.4 Nundle the conglomerates pass up into ferruginous shales with abundant plant remains. These are overlain by basalt.

To the east, in the upper part of Dirty Hole Creek (241.5;086.7 Nundle), good exposures of the fluviatile sediments are seen resting on the Mt. Ephraim Granite. Here weathering of the granite has produced a gradational contact. The sequence follows (descending) : gray pebbly shale ; red pebbly shale ; red clayey sandstone ; arkose (barely transported) ; weathered granite ; fresh granite. All changes are gradual. This is probably the " maladie du granite " of Benson (1913*b*, p. 590).

Nearby, and above, are sandstones with sets of straight planar cross-stratification (see Crook, 1957, p. 158 and Fig. 1) up to 5 ft. thick. These rocks are quartz-rich and contain indeterminable plant remains. They are overlain by basalt. Benson (1913*b*, p. 589) has given the name " Mt. Sheba Series " to these sediments where they outcrop on Mt. Sheba nearby.

The Liverpool Range Beds consist mainly of volcanics and their derivatives. However, two beds of fluviatile sediments outcrop between the basalt flows along the cliffs southwest of Hanging Rock, on horizons well above the sediments already discussed. Benson (1913*b*, p. 587) noted one of these beds and suggested the possibility of a second.

A good section through the lower part of the volcanics is exposed on the upper part of Snowden Creek. Here the lowest basalt flow, which is underlain by a pink bole, has a weathered (purple) upper surface on which is developed a red bole with gray cherty nodules. The base of the flow above is also altered, and passes up into fresh basalt. Vesicles in the altered and weathered basalts contain an assemblage of secondary minerals, probably of zeolitic and chloritic affinities.

The junction between the Liverpool Range Beds and the underlying Paleozoics is exposed on Ryan's Oakey Creek (177.5;047.5 Nundle), where the presence of an inlier of Paleozoic rocks suggests an uneven pre-basalt surface. This is supported by the relations between the basalt and Paleozoics on Oakey Creek (207043 Nundle).

On Ryan's Oakey Creek a basal breccia is developed, the angular fragments of argillite having scarcely moved, and being set in a red clay matrix. This breccia is overlain by a fine conglomerate dipping NE at 19°. This dip is presumably depositional rather than tectonic.

Nearby, on a tributary of Wombramurra Creek (166054.3 Nundle), greybilly is developed beneath the basalt. An adjacent gully (166057.6 Nundle) shows poorly indurated sandstones and dark red to purple vesicular claystones with lineated shear planes, apparently caused by expansion on hydration. The last are probably tuffaceous.

At many points the Paleozoics are coloured for some distance below the unconformity. This is particularly noticeable on Leura Creek (144082.7 Nundle), where bright red and dull yellow colours are prevalent. Immediately below the unconformity the mudstones are bright pink, and are overlain by a bright pink bole.

These reddened beds seem to belong to the " complete oxidation " type of Trotter (1953), the colour apparently being secondary, and due to weathering of the pre-Liverpool Range Beds surface. They are very similar to the reddened beds beneath the Permian of Durham, England, which have been discussed by Anderson and Dunham (1953). These are attributed to weathering of the pre-Permian surface under acid, oxidizing conditions, giving rise to soils of the upland humid red type. A similar explanation may hold for these Australian occurrences.

Tectonically there seems to have been little disturbance of the Liverpool Range Beds. Faulting has been mentioned by Benson (1913*b*, p. 589), but evidence for this has not been found. The northern extensions of the basalt on Mt. Tamarang form smooth-topped ridges which dip northwards at approximately 5°. This, and others (e.g. Mt. Yellow Rock), are probably original dips.

Additional information, including petrographic notes on the basalts, is to be found in Benson (1913*b*, pp. 587–593; 1913*c*, pp. 699–701).

Tertiary Intrusives

Benson (1911, 1913*c*, p. 702) mentioned the occurrence of a coarsely porphyritic teschenitic rock as boulders in Wombramurra Creek, and possibly in situ near Crawney Pass. This probably forms a sill which intrudes the Liverpool Range Beds.

A series of plugs are scattered over the area north of the Liverpool Range. Several of these are small knobs of basalt, but some contain coarser rocks of teschenitic affinities. Four are noteworthy. Black Jack (190230 Goonoo Goonoo), the largest mass in the area (Benson, 1918*a*, p. 357), is composed of basalt. One and a half miles south of Goonoo Goonoo (076.5;211.5 Goonoo Goonoo) is a small plug, with chilled margins, described by Benson (1911, 1913*c*, p. 703). Some 3½ miles northeast of this, near Kiah Creek (108227.5 Goonoo Goonoo), is a similar plug. Another, somewhat larger, occurs southwest of Farrar (106326 Tamworth), and is doleritic in appearance.

Square Top, west of Nundle (190116 Nundle), is capped by one of these teschenitic masses, probably a sill. It has been described by Benson (1911; 1913*b*, p. 593; 1913*c*, p. 701).

The exact age of these masses is not known, but is probably Lower Tertiary. They form part of the New South Wales Tertiary teschenitic province.

Peel Valley Alluvials

Derivation—Peel River Valley, along which the unit is best developed.

Representative Sections—Tamworth railway viaduct bores (Benson, 1915*b*, p. 591).

Lithology—Unindurated fluviatile clays, loams, sands and gravels.

Thickness—A maximum of 50 ft. near Tamworth (Benson, *op. cit.*).

Age and Relations—Late Neogene, probably post-Pleistocene, and a product of the present cycle of erosion.

Description—These alluvials form wide flood plains along the Peel and Cockburn Rivers and several of their tributaries, particularly Goonoo Goonoo Creek. The boundaries of the unit are marked by a truncation of the sloping valley sides, and are clearly visible on aerial photographs.

Brown (rarely red) loams are dominant in the unit, although some prominent gravel lenses occur. Both high- and low-level alluvials are included in the unit, the former occurring somewhat away from present streams and the latter forming the banks of the streams. The former type is seen on the Farrar-Calala road where it approaches Calala Creek.

Cross-stratification in tabular sets with curved cross-strata, is developed occasionally. Sets may be 3 ft. or more in thickness.

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Resonance Absorption in a Cylindrical Fuel Rod with Radial Temperature Variation

A. Reichel and A. Keane

(*Received April* 11, 1960)

Abstract—When calculating the effective resonance integral for a cylindrical fuel rod in which allowances must be made for a radial temperature variation, it has been found that the appropriate average temperature to use is $T_s+0{\cdot}44(T_c-T_s)$ where T_s and T_c are the surface and central temperatures respectively.

1. Introduction

For the design of high temperature gas cooled reactors, it is important to know the average temperature to be used in calculating the Doppler coefficient since allowance must be made for a radial temperature variation across the fuel rods. The treatment herein for cylindrical fuel rods, which depends to some extent on a result due to one of the authors (Keane, 1958) and previous work on the Doppler coefficient for fuel rods containing Thorium 232 (Keane et al., 1960), gives the average temperature to be taken on any neutron path as

$$T_{\mathrm{av}}=\tfrac{1}{4}\left\{\sqrt{T_s}+\frac{T_s+\frac{2}{3}(T_c-T_s)}{\sqrt{\frac{2}{3}(T_c-T_s)}}\sin^{-1}\sqrt{\frac{\frac{2}{3}(T_c-T_s)}{T_s+\frac{2}{3}(T_c-T_s)}}\right\}^2$$

where T_s is the surface temperature and T_c the temperature at the centre of the cylinder. This value of T_{av} does not differ significantly from $T_{\mathrm{av}}=T_s+0{\cdot}44(T_c-T_s)$ which is the recommended average.

2. Assumption Underlying the Calculation

The radial temperature variation in the cylinder is assumed to be parabolic. The actual temperature variation given by equation (3.6) is approximately parabolic for fuel rods of practical size and is exactly parabolic if the assumptions of uniformly distributed thermal source and constant thermal conductivity are made. The analytic treatment of the problem is vastly simplified by assuming the parabolic temperature distribution. The cylinder is assumed to be long in comparison to the diameter so that there is no appreciable axial temperature variation.

If the temperature were uniform throughout the fuel rod the effective resonance absorption cross section would depend on the function $\psi(x, \xi)$ (equation 5.1). When there is a radial parabolic temperature distribution, the resonance absorption cross section depends on the function $\chi(x, \xi, \tau')$, defined in section 5. In obtaining this function, scattering in the fuel rods is neglected, and the use made of this function depends on results found for the almost identical function $\chi(x, \xi, \tau)$ by Keane (1958), where a slab was considered. Within the framework of the simplified model discussed in that paper it is felt that the recommendations made as to the correct mean temperature to be used in calculating the resonance absorption cross sections is not in error by more than 5 per cent.

The values of the fractional increase in the effective resonance integral relevant to this paper (section 7) have been obtained from the empirical formulae given by Keane et al. (1960). In that paper a statistical model of Thorium 232 resonances was considered and scattering was taken into account. Some changes in the recommendations may be made when the resonances of Thorium 232 have been better resolved experimentally.

3. Temperature Distribution in a Cylindrical Fuel Rod

The thermal flux at a point in a cylinder of radius a distant r from the axis is given by

$$\varphi(r)=\varphi_0\frac{I_0(\mu r)}{I_0(\mu a)} \quad \ldots\ldots \quad (3.1)$$

where φ_0 is the flux incident on the cylinder, I_0 is the zero order modified Bessel function and μ is the solution of the equation

$$\frac{\mu}{\Sigma}=\tanh\frac{\mu}{\Sigma_s} \quad \ldots\ldots \quad (3.2)$$

where Σ_s is the thermal scattering cross section and Σ is the total thermal cross section (Murray, 1959).

Since the number of fissions occurring at a point in the cylinder is proportional to the flux at the point, the volumetric heat source distant r from the axis is given by

$$Q(r)=Q_0\frac{I_0(\mu r)}{I_0(\mu a)} \quad \ldots\ldots \quad (3.3)$$

(assuming heat is produced at the point of fission).

The temperature T at any point in the cylinder is given by $-k\Delta^2 T=Q(r)$, where k is the thermal conductivity, considered constant.

Since we have cylindrical symmetry,

$$\frac{d^2T}{dr^2}+\frac{1}{r}\frac{dT}{dr}=-\frac{Q_0 I_0(\mu r)}{kI_0(\mu a)} \quad \ldots\ldots \quad (3.4)$$

On solving equation (3.4), using the boundary conditions

$$\left.\begin{array}{ll} \dfrac{dT}{dr}=0 & \text{when } r=0 \\ T=T_s & \text{when } r=a \end{array}\right\} \quad \ldots\ldots \quad (3.5)$$

and eliminating $\frac{Q_0}{k}$ using the result $T=T_c$ when $r=0$ we obtain

$$T=T_s+\frac{T_c-T_s}{I_0(\mu a)-1}[I_0(\mu a)-I_0(\mu r)] \quad \ldots\ldots \quad (3.6)$$

If x is small, $I_0(x)\approx 1+\frac{x^2}{4}$ so that

$$T\approx T_s+\frac{T_c-T_s}{a^2}(a^2-r^2) \quad \ldots\ldots \quad (3.7)$$

which is the same result as would be obtained if instead of (3.3) we assumed that the volumetric heat source was constant. In the interests of analytic simplicity, equation (3.7) is taken to represent the temperature distribution within the cylinder.

4. Temperature Distribution Along a Chord of the Cylinder

The temperature at a point distant z along a chord of length L is the same as the temperature at a point distant y along the projection of the chord on a diametral plane. The distance r from the centre of the circle in the diametral plane is given by

$$r^2=a^2-Yy+y^2.$$

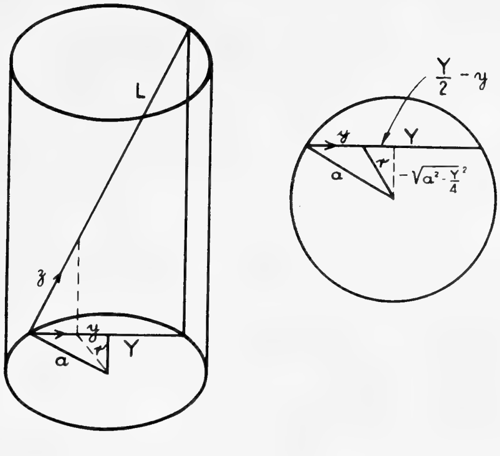

FIG. 1

Thus from equation (3.7), and putting $y=\frac{z}{L}Y$, we have

$$T_z=\frac{T_c-T_s}{a^2}Y^2\left(\frac{\tau a^2}{Y^2}+\frac{z}{L}-\frac{z^2}{L^2}\right) \qquad \text{(4.1)}$$

where $\tau=\dfrac{T_s}{T_c-T_s}$ .... (4.2)

5. The Average Doppler Broadened Capture Cross Section

In the neighbourhood of an isolated Breit-Wigner resonance the effective resonance absorption cross section is

$$\sigma_a=\sigma_0\psi(x,\ \xi)$$

$$\text{where}\ \ \psi(x,\ \xi)=\frac{\xi}{2\sqrt{\pi}}\int_{-\infty}^{\infty} e^{\frac{\xi^2}{4}(x-y)^2}\frac{dy}{1+y^2}\,; \qquad \text{(5.1)}$$

$$\xi=\frac{\Gamma}{\left(\frac{4E_rkT}{M}\right)^{\frac{1}{2}}}\ ;\ x=\frac{E_r-E}{\Gamma/2} \qquad \text{(5.2)}$$

where σ_0=peak cross section at the centre of the resonance,

E=energy of neutron,

E_r=energy of neutron at the centre of the resonance,

Γ=the width of the resonance at half maximum,

M=ratio of nuclear mass to neutron mass,

k=Boltzmann's constant,

T=absolute temperature.

When account is taken of the resonance broadening due to a temperature variation along the path of a neutron (i.e. along a chord of the cylinder), $\psi(x,\ \xi)$ must be replaced by its average value along a chord of length L, the temperature along which is given by (4.1). The evaluation of this average is given in Appendix 1, and is almost identical with the evaluation carried through by Keane (1958) where a parabolic temperature distribution in a slab was investigated. It is found that

$$\frac{1}{L}\int_0^L \psi(x,\ \xi)dz=\chi(x,\ \xi_{\max},\ \tau') \qquad \text{(5.3)}$$

where $\chi(x,\ \xi,\ \tau')=\frac{\xi}{2}\sqrt{\tau'+1}\int_0^\infty e^{-p^2}\left\{\tan^{-1}\left(x+\frac{2p}{\xi}\right)-\tan^{-1}\left(x-\frac{2p}{\xi}\right)\right\}\operatorname{erf}\frac{p}{\sqrt{\tau'}}dp$ (5.4)

where $\xi_{\max}$ in (5.3) is given by

$$\xi_{\max}=\frac{2C}{\sqrt{\tau'+1}} \qquad \text{(5.5)}$$

and $\tau'=\frac{4a^2\tau}{Y_2}$, τ being given by (4.2).

When τ' is replaced by τ, equation (5.4) becomes identical with the function $\chi(x,\ \xi,\ \tau)$ discussed by Keane (1958). In that paper (section 8) it was shown that for low energy resonances the uniform temperature T_1, to be taken in the slab, giving the same absorption as the parabolic distribution of temperature, is given approximately by

$$\frac{6}{\xi_1^2}=\frac{4}{\xi_{\max}^2}\left(\frac{\tau}{2(\tau+1)}+1\right) \qquad \text{(5.6)}$$

where ξ_1 is the value of ξ corresponding to T_1. For the slab, equation (5.6) gives

$$T_1=T_s+\tfrac{2}{3}(T_c-T_s) \qquad \text{(5.7)}$$

which is the arithmetic mean temperature through the slab. It was shown also that for high energy resonances the corresponding uniform temperature does not vary significantly from (5.7). The same analysis applies to equation (5.4). In this case the uniform temperature T_1 along a chord (length L) of the cylinder giving the same absorption as the parabolic temperature distribution (4.1) along L is given approximately by

$$\frac{6}{\xi_1^2}=\frac{4}{\xi_{\max}^2}\left(\frac{\tau'}{2(\tau'+1)}+1\right) \qquad \text{(5.8)}$$

so that

$$T_1=T_s+\frac{Y^2}{6a^2}(T_c-T_s) \qquad \text{(5.9)}$$

and this value of T_1 is the arithmetic mean temperature along L.

Numerical calculations (Keane, 1958) would appear to indicate that when $\psi(x,\ \xi_1)$, where ξ_1 corresponds to the mean temperature T_1, is used instead of $\chi(x,\ \xi_{\max},\ \tau)$ to calculate the absorption per resonance as a function of resonance energy, the error involved is less than 5 per cent. Thus, in calculating the effective resonance integral in the idealized case when scattering is neglected, the error involved using $\psi(x,\ \xi_1)$ as against $\chi(x,\ \xi_{\max},\ \tau')$ is not expected to exceed 5 per cent. This applies only to the contribution to the effective resonance integral for neutrons travelling the path L. Since T_1 given by (5.9) is a function of Y, the effective resonance integral (and the fractional Doppler increase in the effective resonance integral) must be averaged over all projections Y of all chords L.

6. Distribution of the Projections of All Chords of a Cylinder on a Diametral Plane

Let L be a chord of the cylinder, taken to represent any neutron path, and let Y be the projection of L on a diametral plane. Suppose Y subtends an angle $\pi-\varphi$ at the centre of the circular cross section of the cylinder. As shown in Appendix II (equation 1), if $\varphi(Y)dY$ is the probability that a projection chord has length between Y and $Y+dY$, then

$$\varphi(Y)dY=\frac{1}{4}\cos\frac{\varphi}{2}d\varphi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.1)$$

Also, from Appendix II, the average value of Y is $\frac{\pi a}{2}$. Thus, if we define an average chord of the cylinder as one having a projection of $\frac{\pi a}{2}$ on a diametral plane, the average temperature on an average chord is (from 5.9)

$$T_1=T_s+\frac{\pi^2}{24}(T_c-T_s) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6.2)$$

7. The Fractional Doppler Increase in the Effective Resonance Integral

Theoretical investigations have shown that the effective resonance integral for a heterogeneous lattice is equal to that in a homogeneous system for which the scattering cross section per fertile atom, σ_m, is given by

$$\sigma_m=\sigma_p+\frac{1}{N\bar{l}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7.1)$$

where σ_p is the potential scattering cross section per fertile atom for the material in the fuel rods of the lattice, $\bar{l}$ is the mean chord length of the fuel rod and N is the number of fertile atoms/cm^3 of the fuel rods (Chernick and Vernon, 1958; Keane, McKay and Cox, 1959).

By considering a model absorber whose resonance structure approximates that of Thorium 232, Keane et al. (1960) were able to calculate the Doppler increase in the effective resonance integral as a function of σ_m, for absolute temperatures of 300°, 600° and 900°. In that paper, empirical formulae were given for the Doppler increase ΔI as a function of temperature and also for the effective resonance integral $I(0)$ of Th^{232} at 0° A as a function of σ_m. Using these results and equation (7.1) above, Table 1 has been compiled giving the fractional Doppler increase in the effective resonance integral, $\Delta I/I(0)$ as a function of chord length $\bar{l}$ and of σ_m, for temperatures of 300° A, 600° A and 900° A. The last column in the table gives the ratio

$$\frac{\Delta I(300)}{I(0)}:\frac{\Delta I(600)}{I(0)}:\frac{\Delta I(900)}{I(0)},$$

and from this ratio for different chord lengths the overall temperature variation law for $\Delta I/I(0)$ can be obtained.

The last row in the table sets the limiting values for very long chords.

TABLE 1

$\bar{l}$ cms	σ_m barns	$\frac{\Delta I(300)}{I(0)}$	$\frac{\Delta I(600)}{I(0)}$	$\frac{\Delta I(900)}{I(0)}$	$\frac{\Delta I(300)}{I(0)}$	:	$\frac{\Delta I(600)}{I(0)}$	:	$\frac{\Delta I(900)}{I(0)}$
0·25	149	0·553	0·706	0·803	1	:	1·28	:	1·45
0·5	80	0·465	0·613	0·715	1	:	1·32	:	1·54
1	46	0·398	0·538	0·641	1	:	1·35	:	1·61
2	29	0·355	0·491	0·598	1	:	1·38	:	1·68
3	23	0·333	0·469	0·575	1	:	1·41	:	1·73
4	21	0·328	0·462	0·568	1	:	1·41	:	1·73
∞	12	0·293	0·424	0·542	1	:	1·44	:	1·85

These table entries must be studied in conjunction with Appendix III where an expression is given and a graph drawn for the fraction of neutron paths in a cylinder less than or equal to any fraction δ of the diameter.

For convenience we consider these results as they apply to a 4-cm diameter cylinder.

The inferences are that for the fuel rod as a whole,

(i) the value of $\Delta I/I(0)$ can be taken as being independent of the path length and
(ii) $\Delta I/I(0)$ behaves with temperature like $T^{\frac{1}{2}}$.

These assertions may be argued as follows:

(i) From Appendix III we see that about 90 per cent. of chords of the cylinder have lengths above 2 cms, and for these chords $\Delta I/I(0)$ is reasonably constant. Suppose we choose $0{\cdot}33$ as the constant value of $\Delta I(300)/I(0)$. This estimate is too low for the short chords (the $2\frac{1}{2}$ per cent whose length is less than 1 cm) and slightly too high for the 42 per cent. of chords whose length is greater than 4 cms. Indeed if we take moments about $0{\cdot}33$, the moments being weighted in accordance with the percentage of chords having lengths in a suitable range around each value of $\bar{1}$, we see that the overall error involved in taking $0{\cdot}33$ as the constant value of $\Delta I(300)/I(0)$ is almost negligible. Similar arguments apply to $\Delta I(600)/I(0)$ and $\Delta I(900)/I(0)$. The error estimate actually improves for cylinders of diameter greater than 4 cm, but increases for smaller cylinders. For cylinders down to 2 cm in diameter the overall error is not expected to exceed 2 per cent.

(ii) In order that $\Delta I/I(0)$ behave like $T^{\frac{1}{2}}$, the ratio

$$\frac{\Delta I(300)}{I(0)} : \frac{\Delta I(600)}{I(0)} : \frac{\Delta I(900)}{I(0)}$$

should be $1 : \sqrt{2} : \sqrt{3}$. Clearly this is almost true for the large majority of chords which have lengths from about $2\frac{1}{2}$ cm upwards. For the $0{\cdot}25$ cm chords, $\Delta I/I(0)$ obeys a $T^{0{\cdot}35}$ law, the $0{\cdot}5$ cm chords a $T^{0{\cdot}40}$ law and so on. The very long chords approach a $T^{0{\cdot}53}$ law. Thus in taking the overall temperature law as $T^{\frac{1}{2}}$, the error involved in the small percentage of chords for which the index $\frac{1}{2}$ is too large is compensated by an error in the opposite direction from those chords for which the index $\frac{1}{2}$ is too small. The moment weighting process used in (i) for cylinders of 4-cm diameter, indicates that the overall error is very small. The error improves for larger diameter rods and for rod diameters down to 2 cm the overall error is less than 2 per cent.

Thus from (i) and (ii) we see that a constant A can be found which best fits all results, such that

$$\frac{\Delta I}{I(0)} = A T^{\frac{1}{2}} \qquad \text{.........................} \quad (7.2)$$

where A is independent of path and T is the temperature on the path. A conservative estimate of the overall error in (7.2) is 5 per cent. In the cylinder the temperature varies along the path and equation (5.9) gives the constant temperature on any path for which the absorption is the same as the actual temperature distribution.

8. Average Temperature for Computing Fractional Doppler Increase in the Effective Resonance Integral

Section 7 shows that for any neutron path in the cylinder, we may take

$$\frac{\Delta I}{I(0)} = A\left(T_s + \frac{Y^2}{6a^2}(T_c - T_s)\right)^{\frac{1}{2}} \qquad \text{....................} \quad (8.1)$$

where A is a constant for all paths. Since from equation (6.1), $\varphi(Y)dY = \frac{1}{4}\cos\varphi/2d\varphi$, and since $Y = 2a\cos\varphi/2$, the average value of $\Delta I/I(0)$ for all paths is given by

$$\begin{aligned}\left(\frac{\Delta I}{I(0)}\right)_{\mathrm{av}} &= 2A\int_0^{\pi} [T_s + \tfrac{2}{3}\cos^2\varphi/2(T_c - T_s)]^{\frac{1}{2}} \cdot \tfrac{1}{4}\cos\varphi/2d\varphi \\ &= A\int_0^1 (\alpha - \beta u^2)^{\frac{1}{2}} du\end{aligned}$$

where $\alpha=\frac{1}{3}T_s+\frac{2}{3}T_c$, $\beta=\frac{2}{3}(T_c-T_s)$

whence
$$\left(\frac{\Delta I}{I(0)}\right)_{\text{av}}=\frac{A}{2}\left\{\sqrt{\alpha-\beta}+\frac{\alpha}{\sqrt{\beta}}\sin^{-1}\sqrt{\frac{\beta}{\alpha}}\right\} \qquad \text{(8.2)}$$

Therefore, by analogy with equation (8.1) the appropriate average temperature to use when calculating the average fractional Doppler increase in the effective resonance integral is

$$T_{\text{av}}=\frac{1}{4}\left\{\sqrt{T_s}+\frac{T_s+\frac{2}{3}(T_c-T_s)}{\sqrt{\frac{2}{3}(T_c-T_s)}}\sin^{-1}\sqrt{\frac{\frac{2}{3}(T_c-T_s)}{T_s+\frac{2}{3}(T_c-T_s)}}\right\}^2 \qquad \text{(8.3)}$$

To obtain some indication of the trend in T_{av}, we consider some special values of T_c and T_s.

If $T_s=0$, $\quad T_{\text{av}}=\frac{1}{4}(\sqrt{\tfrac{2}{3}T_c}\sin^{-1}1)=\frac{\pi^2}{24}T_c$.

If $T_s=100$, $\quad T_c=550$, we find $T_{\text{av}}=T_s+0\cdot425(T_c-T_s)$.

For $T_s=600$, $T_c=900$, $T_{\text{av}}=T_s+0\cdot437(T_c-T_s)$.

Various other combinations of T_s and T_c have been taken, and the calculations show that if $(T_c-T_s)/T_s$ is not too large, say <2, we may take

$$T_{\text{av}}=T_s+0\cdot44(T_c-T_s). \qquad \text{(8.4)}$$

9. Conclusion

In recommending the formula $T_{\text{av}}=T_s+0\cdot44(T_c-T_s)$ as the temperature to use in evaluating the Doppler increase in the effective resonance integral for cylindrical fuel rods containing Thorium 232, it is expected that within the framework of the assumptions made, the error involved will be less than 5 per cent. More precise numerical calculations may show some error in the recommendation but the error will be far less than that involved in the suggestion that the surface temperature T_s should be used in calculating the Doppler increase. This suggestion is based on an erroneous interpretation of the surface and volume terms appearing in Wigner's treatment of resonance absorption.

To minimize the error, the function $\chi(x, \xi, \tau')$ would need to be tabulated. This laborious task may not be warranted unless $\chi(x, \xi, \tau')$ can be modified so as to make allowance for scattering and for the actual temperature variation given in equation (3.6). The possibility of allowing $\Delta I/I(0)$ to have a variation with path length must not be overlooked, as well as the possibility of a temperature variation law slightly different from $T^{\frac{1}{2}}$.

APPENDIX 1

Derivation of the Average Doppler Broadened Function on a Chord

From equations (5.2) and (4.1)

$$\xi(z)=\frac{C}{\{\tau a^2/Y^2+z/L-z^2/L^2\}^{\frac{1}{2}}}$$

where
$$C=\frac{Aa}{(T_c-T_s)^{\frac{1}{2}}\cdot Y} \qquad \text{(1)}$$

and A is a constant.

The value of ξ corresponding to maximum temperature at $z=L/2$ is given by

$$\xi_{\text{max}}=\frac{C}{\{\tau a^2/Y^2+\frac{1}{4}\}^{\frac{1}{2}}}, \qquad \text{(2)}$$

and
$$\xi_{\text{min}}=\frac{C}{\{\tau a^2/Y^2\}^{\frac{1}{2}}} \qquad \text{(3)}$$

corresponds to minimum temperature at $z=0$. Note that $\xi_{\text{max}}<\xi_{\text{min}}$.

Now $\int_0^L \psi(x, \xi)dz$

$$=\frac{C}{2\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{dy}{1+y^2}\int_0^L\frac{\exp\left\{\frac{-C^2(x-y)^2}{4(\tau a^2/Y^2+z/L-z^2/L^2)}\right\}dz}{\{\tau a^2/Y^2+z/L-z^2/L^2\}^{\frac{1}{2}}}$$

$$=\frac{CL}{2\sqrt{\pi}}\int_{-\infty}^{\infty}\frac{dy}{1+y^2}\int_0^1\frac{\exp\left\{\frac{-C^2(x-y)^2}{4(\tau a^2/Y^2+u-u^2}\right\}du}{\{\tau a^2/Y^2+u-u^2\}^{\frac{1}{2}}}\ .$$

Thus $\frac{1}{L}\int_0^L \psi dz$ is independent of L but is a function of Y, the projection of L on a diametral plane.

Denoting by I the integral with respect to u, we write

$$B=\{\tau a^2/Y^2+\tfrac{1}{4}\}^{\frac{1}{2}}=\frac{C}{\xi_{\max}}$$

and making in turn the substitutions $u-\frac{1}{2}=B\sin\theta$, $t=\tan\theta$, we find

$$I=2\int_0^{Y/2a\sqrt{\tau}} e^{-\frac{c^2(x-y)^2(1+t^2)}{4B^2}}\frac{dt}{1+t^2}\ .$$

Since $\int_0^{\alpha} e^{-K^2(1+t^2)}\frac{dt}{1+t^2}=\sqrt{\pi}\int_{|K|}^{\infty} e^{-p^2}\operatorname{erf}\alpha p\,dp$

we find

$$I=2\sqrt{\pi}\int_{\left|\frac{c(x-y)}{2B}\right|}^{\infty} e^{-p^2}\operatorname{erf}\frac{Yp}{2a\sqrt{\tau}}dp$$

whence

$$\int_0^L \psi dz=CL\int_0^{\infty} e^{-p^2}\operatorname{erf}\frac{Yp\,dp}{2a\sqrt{\tau}}\int_{x-\frac{2Bp}{C}}^{x+\frac{2Bp}{C}}\frac{dy}{1+y^2}\ .$$

We have finally

$$\frac{1}{L}\int_0^L \psi(x, \xi)dz=\chi(x, \xi_{\max}, \tau)$$

$$=\{\tau a^2/Y^2+\tfrac{1}{4}\}^{\frac{1}{2}}\xi_{\max}\int_0^{\infty} e^{-p^2}\left\{\tan^{-1}\left(x+\frac{2p}{\xi_{\max}}\right)-\right.$$

$$\left.-\tan^{-1}\left(x-\frac{2p}{\xi_{\max}}\right)\right\}\operatorname{erf}\frac{Yp}{2a\sqrt{\tau}}dp \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

If in equation (4) we write $\tau=\frac{Y^2}{4a^2}\tau'$, we find

$$\chi(x, \xi_{\max}, \tau')=\frac{\xi_{\max}}{2}\sqrt{\tau'+1}\int_0^{\infty} e^{-p^2}\left\{\tan^{-1}\left(x+\frac{2p}{\xi_{\max}}\right)-\tan^{-1}\left(x-\frac{2p}{\xi_{\max}}\right)\right\}\operatorname{erf}\frac{p}{\sqrt{\tau'}}dp$$

$$\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where

$$\xi_{\max}=\frac{2C}{\sqrt{\tau'+1}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

APPENDIX II

Average Length of the Projection of All Undeflected Neutron Paths in a Cylinder on to a Diametral Plane (Cylinder Infinite in Length)

Let 0 be a point on the cylinder and $\underset{\sim}{\Omega}$ a direction from a surface element ds at 0 such that the chord in the direction $\underset{\sim}{\Omega}$ is of length R. Referring to Figure 2

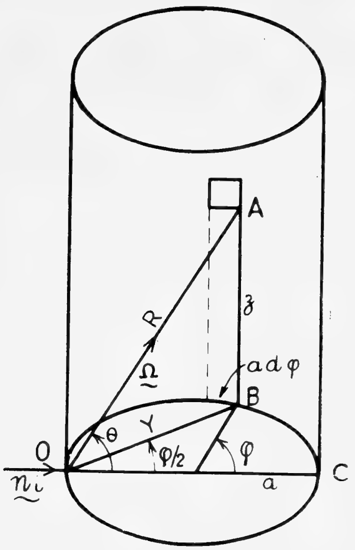

FIG. 2

$$d\Omega = \frac{\cos\theta \cdot a d\varphi dz}{R^2}$$

where $\cos\theta = \underset{\sim}{\Omega}.\underset{\sim}{n}_i$ and $d\Omega$ is an element of solid angle around the direction $\underset{\sim}{\Omega}$. The number of undeflected neutron paths of lengths between R and $R+dR$ from dS is proportional to $\underset{\sim}{\Omega}.\underset{\sim}{n}_i d\Omega dS$ (Case, de Hoffman and Placzek (1953)), i.e. to

$$\frac{\cos^2\theta . a d\varphi dz dS}{R^2}.$$

Let Y be the length of the projection of R on the diametral plane through 0, and $Y+dY$ the length of the projection of a chord of length $R+dR$. The number of projection chords of lengths between Y and $Y+dY$ (corresponding to the angle between φ and $\varphi+d\varphi$) is proportional to

$$\frac{2\cos^2\theta . a d\varphi dz dS}{R^2}.$$

(There will be an equal number of projection chords from the solid angle about A', the image of A in the diametral plane.)

Now $Y = 2a\cos\varphi/2$ and $R^2 = 4a^2\cos^2\varphi/2 + z^2$. The geometry of the figure then gives

$$\cos\theta = \frac{2a\cos^2\varphi/2}{R}.$$

Therefore the number of projection chords of lengths between Y and $Y+dY$ is proportional to

$$\frac{2.4a^2\cos^4\varphi/2}{z^2+4a^2\cos^2\varphi/2} . \frac{a d\varphi dz dS}{z^2+4a^2\cos^2\varphi/2} = \frac{8a^3\cos^4\varphi/2 d\varphi ds dS}{(z^2+4a^2\cos^2\varphi/2)^2}.$$

The total number of projection chords is proportional to

$$\int \underset{\sim}{\Omega}.\underset{\sim}{n}_i d\Omega dS = \pi S \text{ where } S \text{ signifies the total surface area.}$$

Therefore if $\varphi(Y)dY$ is the probability that a projection chord is of length between Y and $Y+dY$ we have

$$\varphi(Y)dY=\frac{1}{\pi S}\int_{Y=\text{const}}\frac{8a^3\cos^4\varphi/2d\varphi dzdS}{(z^2+4a^2\cos^2\varphi/2)^2}$$

$$=\frac{8a^3\cos^4\varphi/2d\varphi}{\pi}\int_0^\infty\frac{dz}{(z^2+4a^2\cos^2\varphi/2)^2}.$$

Thus

$$\varphi(Y)dY=\tfrac{1}{4}\cos\frac{\varphi}{2}d\varphi \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Therefore the average value of Y is

$$\int Y\varphi(Y)dY=\tfrac{1}{4}\int_0^{2\pi}2a\cos^2\varphi/2d\varphi$$

$$=\frac{\pi a}{2} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

APPENDIX III

Fraction of Neutron Paths in a Cylinder Less than any Fraction of Diameter

All chords of the cylinder less than or equal to $2a\delta$, where $0<\delta<1$, starting from 0, will end on the cylinder at a point between or on the curves of intersection of the cylinder with a sphere of radius $2a\delta$, centre 0.

Referring to the diagram, and from Appendix II, the number of chords of lengths $R\rightarrow R+dR$ is proportional to

$$\frac{2\cos^2\theta . ad\varphi dzdS}{(z^2+4a^2\cos^2\varphi/2)}$$

i.e. to

$$\frac{8a^3\cos^4\varphi/2d\varphi dzdS}{(z^2+4a^2\cos^2\varphi/2)^2}.$$

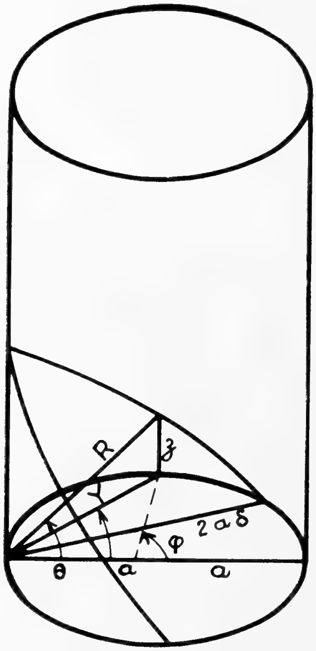

FIG. 3

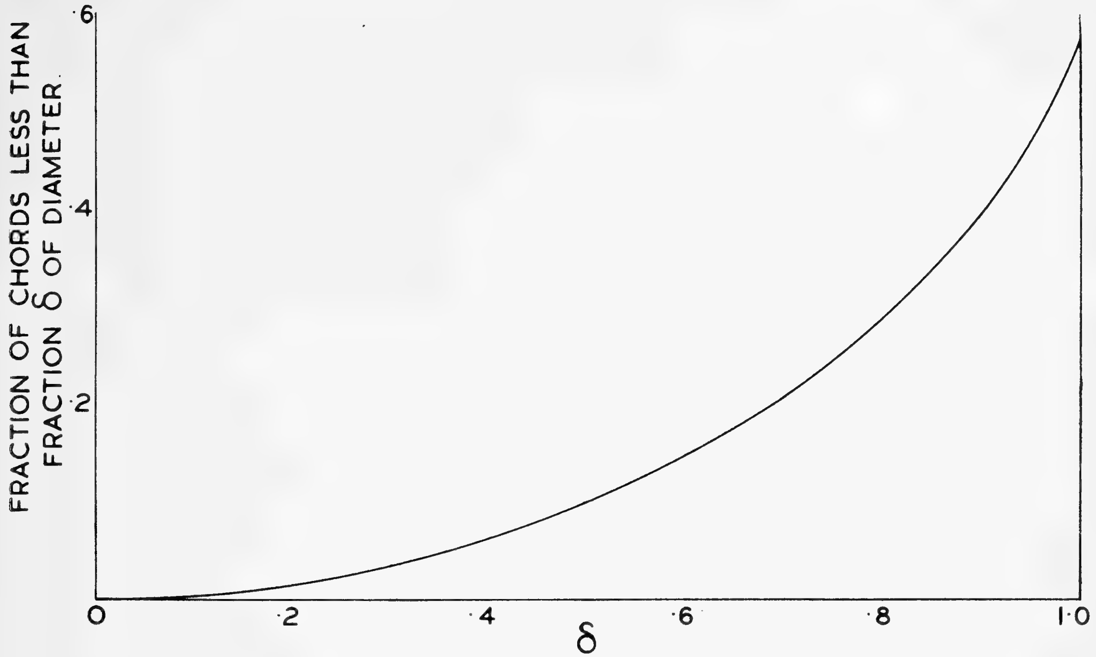

Fig. 4

The total number of chords is proportional to πS so that the fraction of chords of length less than or equal to $2a\delta$ is given by

$$\frac{16a^3S}{\pi S}\int_{2\cos^{-1}\delta}^{\pi}\cos^4\varphi/2\,d\varphi\int_0^{2a(\delta^2-\cos^2\varphi/2)^{\frac{1}{2}}}\frac{dz}{(z^2+4a^2\cos^2\varphi/2)^2} \qquad \ldots\ldots \ (1)$$

$$=1-\frac{4}{3\pi}\left\{\frac{1-\delta^2}{\delta^2}K-\frac{1-2\delta^2}{\delta^2}E\right\} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ (2)$$

where $K=K(\delta)$ and $E=E(\delta)$ are the complete elliptic integrals of the first and second kinds respectively.

As $\delta\to 1$, the fraction approaches $1-\frac{4}{3\pi}$.

As $\delta\to 0$, the fraction approaches 0 $\left(\text{since } \lim_{\delta\to 0}\frac{K-E}{\delta^2}=\frac{\pi}{4}\right)$.

The fraction of chords less than any fraction of the diameter can be read from the graph (Figure 4).

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The Palaeomagnetism of some Igneous Rock Bodies in New South Wales

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Introduction

The directions and intensities of magnetization of rock specimens from four igneous bodies in eastern New South Wales have been measured. These are labelled A, B, C and D in Figure 1. To ensure freshness samples were taken from as far below the natural surface as practicable, all specimens being taken from road cuttings and quarries. The bodies studied do not appear to have suffered any appreciably post-consolidation tilting. The collecting sites are located by map references which are taken from the one-inch-to-the-mile military series and are given by the sheet title followed by the six-figure grid reference. The results indicate a Mesozoic age for these bodies which is older than had been previously supposed.

A. *Prospect Intrusion*—This is a dish-shaped sheet of teschenitic dolerite convex downwards, intruded discordantly (at least in part) into the upper beds of the Liverpool Subgroup (Lovering, 1954) of the Wianamatta Group, which is of Upper Triassic age. It has a chilled envelope enclosing a main mass which is variable in texture and composition. David (1950, p. 578) states that on petrological grounds this dolerite, among other basic hypabyssal intrusives in eastern Australia, is usually regarded as Tertiary. Samples taken from three quarries (Liverpool 920215, 914205, 916216), included specimens from the chilled envelope and the more pegmatitic facies.

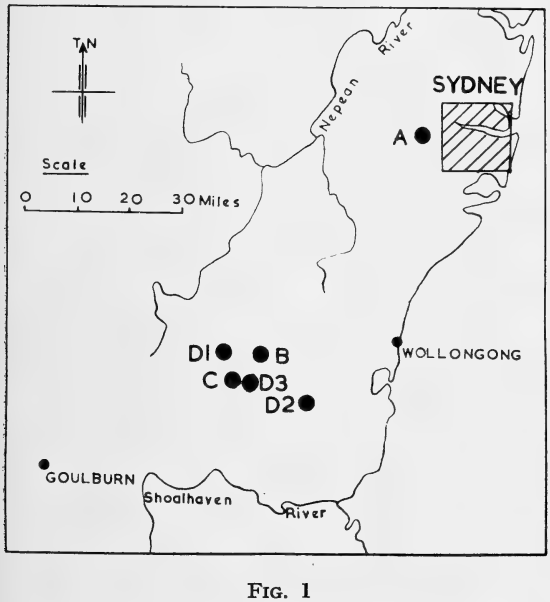

FIG. 1

Locality sketch-map. The localities are labelled as follows: A, Prospect Dolerite; B, Gibraltar Syenite; C, Gingenbullen Dolerite; D, Tertiary Basalts (D1 Berrima, D2 Robertson, D3 Moss Vale)

B. *Gibraltar Syenite*—This is thought to be an asymmetric laccolith and is intruded into Hawkesbury Sandstone (Stevens, 1956). It is composed of an aegerine-augite microsyenite with deuterically altered phases and narrow pegmatitic veins. On petrological grounds it is regarded as probably early Tertiary (David, p. 581; Stevens, 1956). The samples were obtained from the two operating quarries on the southern face (Mittagong 426426, 427424). Another disused quarry a little east of these (Mittagong 431421) and much nearer the roof showed signs of weathering and was not sampled.

C. *Gingenbullen Dolerite*—This is a 350 ft thick horizontal tabular body composed of columnar dolerite. The mass is either a denuded sill or a dyke. It lies on the uppermost beds of the Liverpool Subgroup and is thus of post-Upper Triassic age. Samples were taken at various heights in the exposed face of the disused quarry on the northern side of the body (Moss Vale 317347).

D. *Some Tertiary Basalts*—These have been sampled from the Berrima, Moss Vale and Robertson areas. At Berrima the basalt occurs as a horizontal sheet overlying shales of the lower part of the Liverpool Subgroup. It probably represents a residual of a now extensively dissected flow. Fresh rock was found in only one road cutting which was sampled at regular intervals over a distance of about fifty yards (Mittagong 370473). The rock is a

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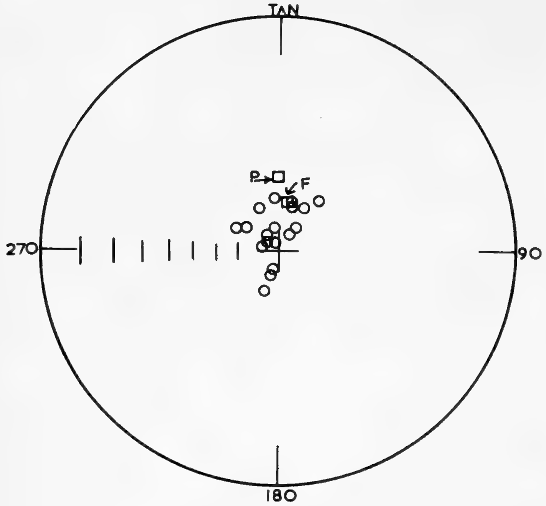


FIG. 2
Directions of NRM in the Prospect Dolerite
North-seeking directions of magnetization are plotted as circles on the upper hemisphere. In this, and all subsequent figures, polar stereographic projections are used, and the dipole (**P**) and present (**F**) field directions are marked

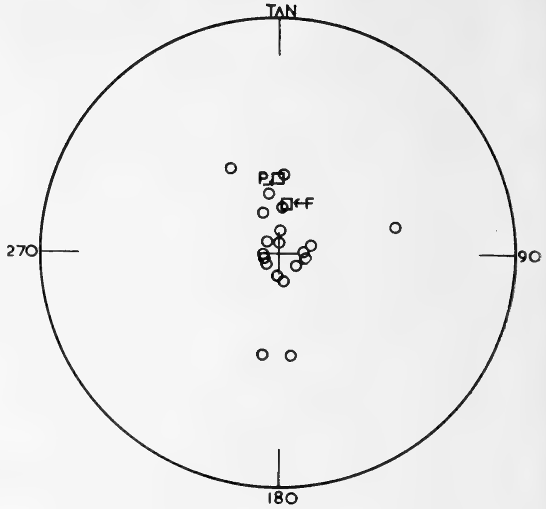
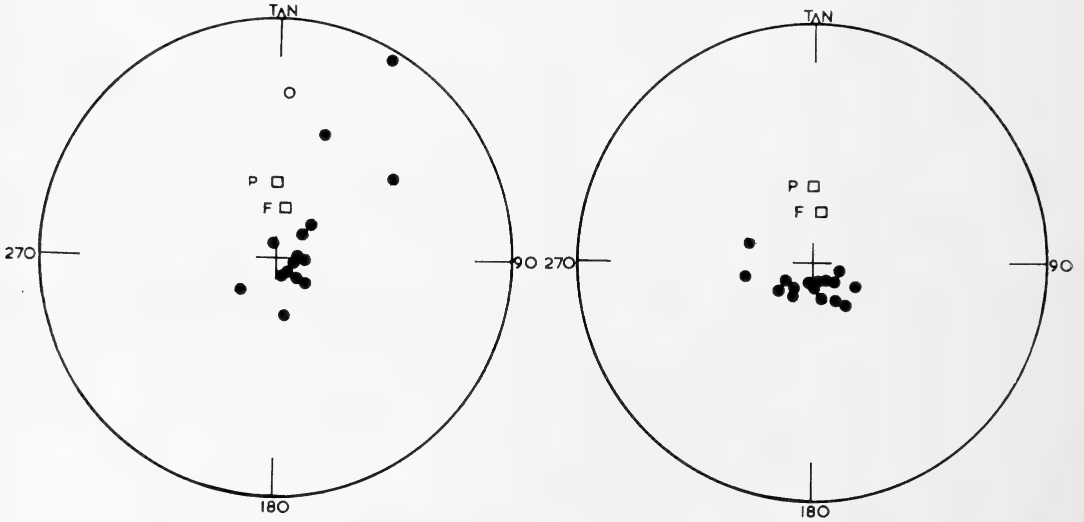


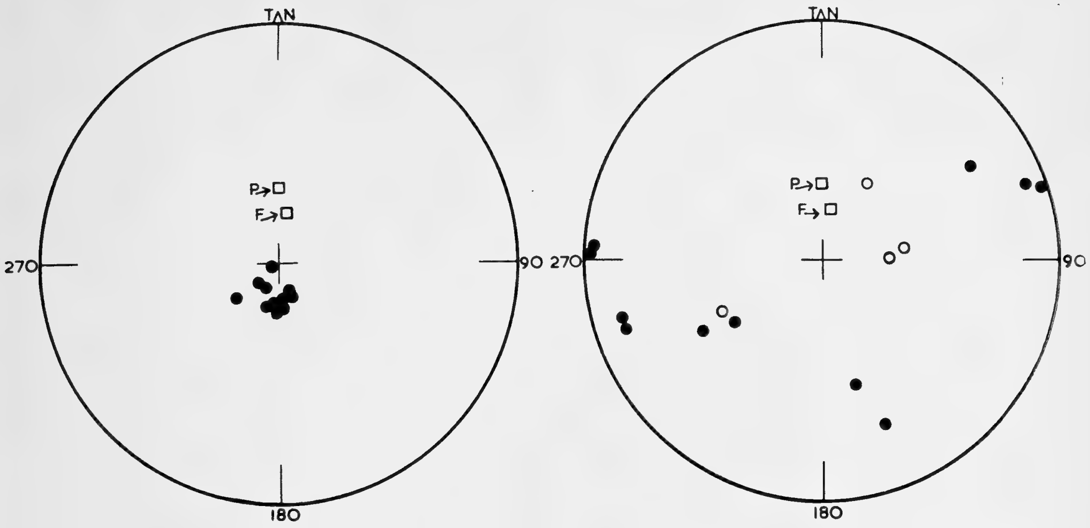
FIG. 3
Directions of NRM in the Gibraltar Syenite
North-seeking directions are plotted as circles on the upper hemisphere

porphyritic olivine basalt, variable in texture and containing phenocrysts of olivine in a groundmass of microlitic plagioclase, augite, magnetite, and occasional glass. The basalt of the Robertson flow is petrographically very similar to the Berrima rock. Samples were taken from road cuttings (Kiama 627294, 594275, 560284). The weathering in most exposures was severe but large unweathered nodules could be obtained in some exposures. The samples from Moss Vale were taken from a disused quarry (Moss Vale 364337). In addition to these localities



(*a*) (*b*)

FIG. 4
Directions of magnetization in the Gingenbullen Dolerite
North-seeking directions are plotted as circles on the upper and dots on the lower hemisphere. (*a*) NRM, the spread of points towards the dipole field (**P**), is due to partial instability in some specimens. (*b*) Directions after treatment in an alternating peak field of 150 oersteds which removes this instability



(*a*) (*b*)

FIG. 5

Direction of magnetization in some Tertiary basalts

(*a*) Berrima basalt, stable magnetization. (*b*) Robertson and Moss Vale flows, randomly directed unstable magnetization

other basalts in the Robertson-Exeter-Mittagong district were examined, but were found to be extensively weathered. Similarly on the Illawarra scarp and adjoining highlands exposures of the Cordeaux teschenitic dolerite, the Bong Bong basalt on and near Saddleback Mountain (Kiama 817516 west to 787163, and 783155 west to 773159), and the whole of the exposed Kangaroo Mountain basanite, were visited but found to be too decomposed to be of use.

Remanent Magnetization

The hand specimens were oriented prior to extraction from the rock face. Cylinders were machined from these with non-magnetic tools. The directions of magnetization were measured using an astatic magnetometer. The experimental error involved throughout all these operations is about 5° in the determined direction.

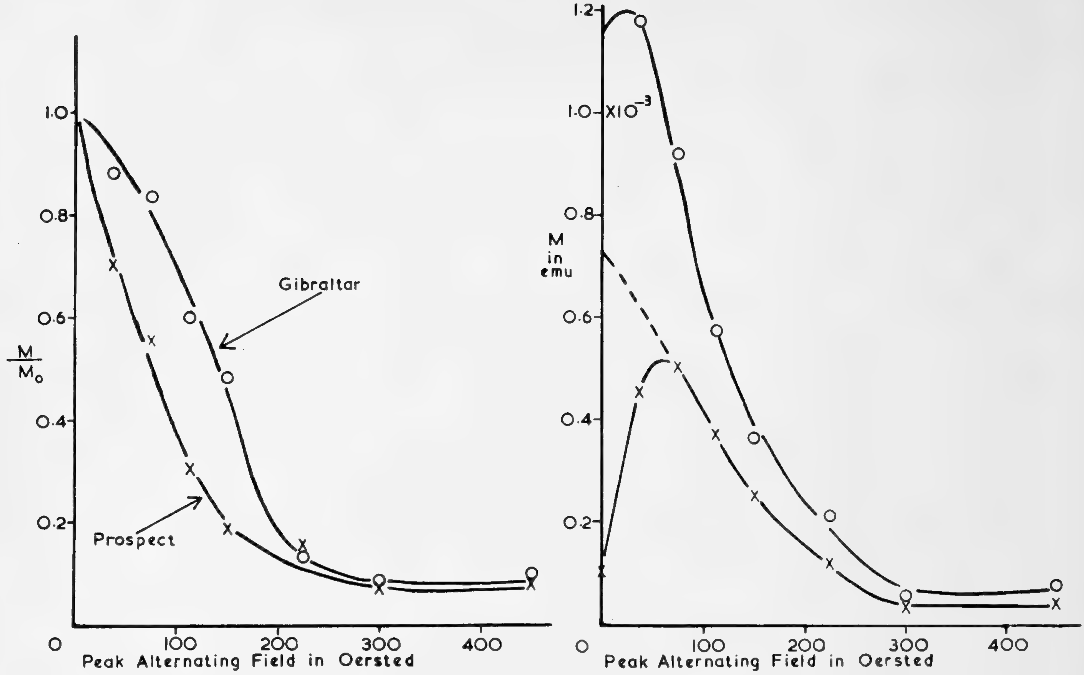
The directions of natural remanent magnetization (NRM) are plotted in Figures 2 to 5 on

TABLE 1

Mean Directions of N.R.M.

The values given refer to the four igneous occurrences listed in the first column. In the case of the Gingenbullen Dolerite the values obtained after removal of the unstable magnetization by treatment in 150 oersteds peak alternating field are also given. S is the number of oriented rock samples, N is the number of specimens cut from these samples, D and I are the declination and inclination of the mean direction, R is the resultant giving each specimen unit weight, α is the 95% error in the mean direction (Fisher, 1953) and k is Fisher's precision parameter. ΔP and ΔF are the angular distances between the mean directions and the dipole and present field respectively

	S	N	D	I	R	α ($P=0\cdot05$)	k	ΔP	ΔF	Pole Positions
A. Prospect Dolerite (33° 49′ S, 150° 49′ E)	10	18	359	—81	17·40	6·8	28	27	16	51 S, 151 E
B. Gibraltar Syenite (34° 28′ S, 150° 26′ E)	10	20	27	—86	17·94	11·7	9	32	22	41 S, 146 E
C. Gingenbullen Dolerite (34° 22′ S, 150° 20′ E)	8	16								
1. N.R.M.			56	+71	12·89	19·6	5	147	165	— —
2. After treatment			191	+80	15·33	8·0	23	154	166	53 S, 144 E
D1. Tertiary Basalt, Berrima	7	11	187	+76	10·78	6·9	44	158	169	— —



(*a*) (*b*)

FIG. 6

Alternating field demagnetization

(*a*) Prospect Dolerite and Gibraltar Syenite specimens, M/M_0 is plotted against peak alternating field; M is the intensity of magnetization after treatment and M_0 is the intensity of NRM.

(*b*) Gingenbullen Dolerite, M is plotted against alternating field. The upper curve is from a specimen with a predominantly stable magnetization and the lower curve is from a specimen in which the stable and unstable components are of comparable magnitudes.

stereographic projections, the convention adopted being to plot the north-seeking direction of magnetization as circles on the upper hemisphere and as dots on the lower hemisphere. The mean directions are given in Table 1. The directions in the Prospect Dolerite (Fig. 2) and Gibraltar Syenite (Fig. 3) are well grouped, the scatter being greater in the latter. Both have steep negative inclinations. The directions at Gingenbullen are for the most part almost vertical with positive inclination. There are, however, a few results with northerly declinations and less steep inclination which are strung out towards the geocentric axial dipole field. The directions in the Berrima basalt show a close grouping with steep positive inclinations. The directions of magnetization at Robertson and Moss Vale (Fig. 5*b*) show a wide scatter, the resultant R for 15 specimens being 1·32 and from the tables given by Watson (1956) the distribution is random at $P=0{\cdot}05$.

At Prospect the intensities of natural remanent magnetization (in emu/cc $\times 10^{-3}$) range from 1 to 8, at Gibraltar from **0·1** to **1·0**, at Gingenbullen from 0·1 to 1·2 and in the Tertirya Basalts from 1–10.

The saturation isothermal remanence ($M_{i(\mathrm{sat})}$) and the field required to saturate ($H_{(\mathrm{sat})}$) and the coercivity (H_c) of $M_{i(\mathrm{sat})}$ for specimens from the three intrusives are given in Table 2.

TABLE 2

Magnetic Properties

M is the intensity of the natural remanent magnetization, $M_{i(\mathrm{sat})}$ is the isothermal remanent magnetization both in emu/cc $\times 10^{-3}$. $H_{(\mathrm{sat})}$ is the field required for saturation and H_c is the back field needed to remove $M_{i(\mathrm{sat})}$ in oersted

	M	$M_{i(\mathrm{sat})}$	$H_{(\mathrm{sat})}$	H_c
A. Prospect Dolerite	6·3	263	1500	200
B. Gibraltar Syenite	0·5	208	2000	250
C. Gingenbullen Dolerite	0·1	62	1000	200

Stability

Remeasurement of the Robertson and Moss Vale specimens showed changes of direction of up to 20° outside the limits of experimental error, and this, together with the observed wide scatter of directions, shows that these basalts have a highly unstable magnetization. The mean directions of magnetization at Prospect, Gibraltar, Berrima and Gingenbullen differ from the directions of the present (ΔF) and dipole (ΔP) fields by amounts which exceed the errors by a factor of 2 or more (Table 1), indicating that for most of the specimens the magnetic directions have remained little changed in the Earth's field (0·6 oersted) for periods of the order of hundreds of years. However, the " strung " distribution observed at Gingenbullen is of a familiar type associated with partial instability, the vertical reversed magnetization being, in some specimens, substantially affected by a viscous component imposed by the present Earth's field during the past few hundreds of years.

Tests have been made by treating specimens in alternating magnetic fields in the absence of any steady field using the apparatus and methods described by Irving, Stott and Ward (1961). In fields up to 300 oersteds (peak) the effect in direction on specimens from Prospect is negligible. The effect in Gibraltar specimens is negligible up to 200 oersteds. All specimens in these two intrusions were treated in alternating fields of 150 oersteds with no important effects on the two distributions. The effect on intensity is illustrated in Figure 6.

In the specimens from Gingenbullen the viscous components due to the present earth's field are removed in fields of about 100 oersteds. All specimens have been treated at 150 oersteds and the results are plotted in Figure 4*b*. The associated changes of intensity are given in Figure 6*b* for two specimens ; one in which the initial direction is vertical and stable, being little changed in direction in fields up to 300 oersteds, and a second in which the initial direction has only a shallow dip, and is substantially affected by an unstable component. In the first case (upper curve) there is a very small increase of intensity due to the removal of a small unstable component, and in the second case the removal of the much larger unstable component causes an increase of intensity by a factor of four after treatment in low alternating fields.

The magnitudes S and U of the stable and unstable components $\mathbf{S}$ and $\mathbf{U}$ in this latter case may now be estimated. The NRM has a direction of (52, +18) and a magnitude 114×10^{-6} emu/cc. and is the vector sum $\mathbf{S}+\mathbf{U}$. $\mathbf{U}$ is directed along the dipole field (0, −54) and the direction of $\mathbf{S}$ (202, +75) is obtained after $\mathbf{U}$ is removed by treatment in low alternating fields ; in this case 75 oersteds was used. (The intensity measured after this treatment does not, of course, give S directly, since the latter is somewhat diminished by this treatment). The value obtained for S is 722×10^{-6} (see extrapolated dotted curve Fig. 6*b*) and for U is 727×10^{-6} emu/cc. It may be noted that S and U have each about half the magnitude of the NRM (1150×10^{-6}) of the stable specimen (upper curve in Fig. 6*b*).

Although the demagnetization characteristics of these specimens do not show the high stability which is associated with the NRM of some igneous rocks the results do, nevertheless, conform to the initial palaeomagnetic condition for stability, namely, that the directions, in most cases, have been little affected by a component due to the earth's field in recent times, and in those cases where a substantial unstable component is present its effect may be removed by treatment in low alternating fields.

The stability of the basalts of the Berrima, Moss Vale and Robertson areas has been studied as part of a general palaeomagnetic study of the Tertiary Basalts of New South Wales.

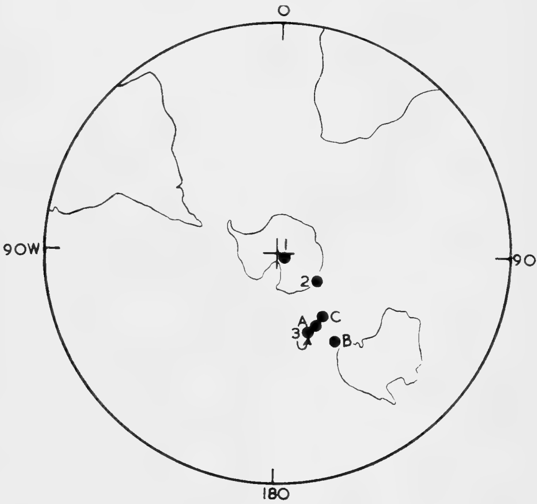


Fig. 7

Pole Positions

The pole positions for the three intrusions studied are labelled as in Table 1. The Cenozoic and Mesozoic poles previously obtained from Australia are numbered as follows : 1, Newer Volcanics of Victoria (Upper Pliocene, to Recent) ; 2, Older Volcanics of Victoria (Lower Tertiary) (Irving and Green 1958) ; 3, Tasmanian Dolerite Sills (Late Triassic, Jurassic or Cretaceous) (Irving 1956)

The results, which have been described by Irving, Stott and Ward (1961), are not discussed further in this paper.

Discussion

The directions of NRM in the Prospect Dolerite, the Gibraltar Syenite, and the directions in the Gingenbullen Dolerite after treatment in 150 oersteds are stable, and may be identified with the direction of the geomagnetic field at the time these intrusions cooled. On this assumption, and further assuming that the geomagnetic field at these times was on average that of a geocentric dipole, the pole positions (south) consistent with these directions may be calculated (Table 1). These poles are the points at which this geocentric dipole intersected the earth's surface. It has to be remembered that errors are present in these determinations since the time span of several hundreds of years necessary to average out the secular variation of the earth's magnetic field is not certainly represented in each case. In the larger bodies (Prospect and Gibraltar) this error is possibly quite small since these bodies may have taken a long time to cool.

The pole positions for the three intrusive bodies are plotted in Figure 7. They are in the region of Tasmania near the pole obtained for the Tasmanian dolerites (pole 3) but in a lower latitude than that obtained from the Older Volcanics of Victoria (pole 2). This suggests that these intrusions are older than the latter, and of an age comparable to the former, and are therefore Mesozoic.

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A Study of the Variation with Depth of the Magnetic Properties in a Dolerite Drill Core from Prospect, N.S.W.

S. A. A. Kazmi

(*Received February* 29, 1960)

Abstract—Using an astatic magnetometer the magnetic intensity, direction and susceptibility in a dolerite drill core were measured at intervals of five feet. Dip values mostly ranged between —70° and —80° except in the region 75 ft–140 ft where they ranged between —50° and —70°. The values of the intensity of magnetization (J) and susceptibility (k) were substantially uniform, but were somewhat higher in the region 5 ft to 80 ft than elsewhere.

The degree of fluctuation in values is very high in some regions. The ratio J/k has a mean value $0 \cdot 66$ and varies between $0 \cdot 2$ and $1 \cdot 1$. It is suggested that the rock has undergone a partial change in magnetization since this magnetization was first acquired, and that the observed intensity and direction of magnetization are the effective sum of thermo-remanent magnetization and isothermal remanent magnetization. Remeasurement after A.C. washing to eliminate I.R.M. would be necessary for the determination of true T.R.M.

Introduction

Igneous rocks are known to acquire most of their magnetism as they cool through the Curie temperature at the time of their formation. It is most probable that the present direction of magnetization of igneous rocks coincides in general with the direction of the geomagnetic field at the time the rocks solidified (provided we allow for any subsequent modification the rocks might have undergone physically, chemically and magnetically). By measuring changes in intensity and direction of magnetization through a continuous sequence of rocks the history of the geomagnetic field and of rock formation in the geologic past can be traced.

The variations of magnetic properties with depth in a dolerite drill-core from the intrusion at Prospect, N.S.W., have been studied and are described in this paper. The core came from a vertically drilled borehole 190 ft deep and $1\frac{1}{4}$ in. diameter. In a similar investigation Jaeger and Joplin (1954) studied the vertical distribution of magnetic properties in cores from Tasmanian tholeiites of Jurassic age.

The Measurements

The intensity and direction of magnetization and magnetic susceptibility were determined at five-foot intervals. Three cylindrical samples of length=diameter=$1\frac{1}{4}$ in were cut at each level and their mean values were taken to represent the dip (I), the intensity of magnetization (J) and susceptibility (k) at that depth. Measurements were made on a total of 100 samples. Since no horizontal orientation had been obtained for the core during its recovery from the borehole declinations could not be measured.

Intensity and direction of magnetization—The measurements were made on the astatic magnetometer constructed by the author in the Department of Geology and Geophysics, Sydney University (Kazmi, 1960). The instrument was set at a sensitivity of $9 \cdot 3 \times 10^{-7}$ emu per mm deflection. The specimen could be rotated beneath the magnet system around a vertical and two mutually perpendicular horizontal axes. When a minimum response was obtained from the magnet system the dip could

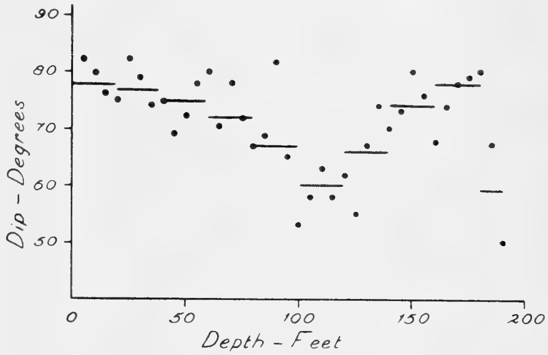

Fig. 1

Distribution of magnetic dip in dolerite core from Prospect. All values are negative (dip directed upwards).

- · mean value for three adjacent samples at each 5-ft level ;
- – mean value over 20-ft interval

be read directly from the calibrated circle at the base of the specimen holder. The intensity of magnetization was calculated from the magnitude of the deflection. The determination of dip is correct to about ±2° and of intensity of magnetization to about ±4%. The dip is reckoned negative when directed upwards and positive when directed downwards.

The vertical distribution of dip with depth is shown in Figure 1. The dots indicate the mean values at each 5-ft interval, and the dashes the mean values over 20-ft intervals. Between 5 and 75 feet and 140 and 180 feet the dip values are reasonably uniform, lying between —70° and —80°. In the ranges 75 to 140 feet and 180 to 190 feet the values are relatively low and fluctuating. The mean values over 20 ft intervals show a gradual decrease of dip from —78° to a minimum of —60° in the vicinity of the 120 ft level then increasing gradually to —78° at the 180 ft level. In the region 180–190 ft there is again a decrease of dip value.

The point and mean values for the intensity of magnetization are plotted in Figure 2. Between 5 and 80 feet the values are high and fluctuating; unusually large values exist between 20 and 30 feet, the greatest measured being $83 \cdot 6 \times 10^{-4}$ emu. In the regions 80–150 ft and 180–190 ft there is a general reduction in the level of the intensity of magnetization but apart from minor fluctuations the values were fairly uniform. Comparatively higher values occur in the region 150 to 180 ft.

Susceptibility—The volume susceptibility, k, of the samples was determined in a field of 0·46 Oe. The method of measurement involved the application of the magnetizing field while keeping the specimen at rest (Kazmi, 1960). As most of the samples were not uniformly magnetized this method was preferred over the conventional one. The determination of k is correct to about ±8%.

In Figure 3 is shown the variation of susceptibility with depth. Values of susceptibility at each five-foot sampling level are shown by a dot and the average value over a 20-ft interval by a dash. It will be observed that the susceptibility is high and fluctuating in the region 5 to 75 ft; thereafter the values are appreciably lower and apart from a few minor departures are relatively uniform.

All the measurements are summarized in Table 1. I_1 and I_2 denote the dip values for the same sample calculated by two independent methods. The last column of the table gives values of J/k, the ratio of intensity of magnetization to susceptibility.

Discussion of Results

If the magnetization of an igneous rock is due wholly to the thermo-remanent magnetization (T.R.M.), its direction of magnetization should be essentially uniform, although intensity may vary from point to point. Especially for palaeomagnetic studies the fluctuation of direction must be less than 10°. Long after their formation rocks may undergo changes in the direction in the intensity and direction of magnetization by the process of isothermal remanent magnetization (I.R.M.). Dolerite is well known to become greatly magnetized by this process even in a very weak field of the order of the Earth's field, so that the measured intensity and direction will be the effective sum of the primary and secondary magnetization.

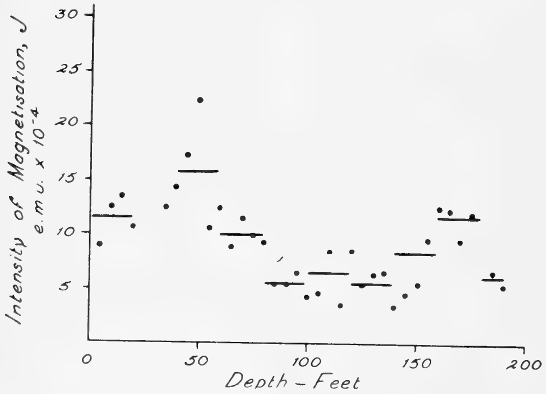

FIG. 2
Distribution of intensity of magnetization with depth in Prospect core. Symbols as for Fig. 1

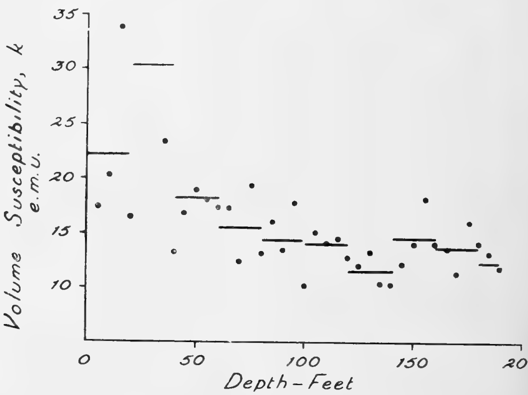

FIG. 3
Distribution of volume susceptibility in Prospect core. Symbols as for Fig. 1

Although the measured mean value of dip (—71°) is approximately in conformity with the present direction of the geomagnetic field at the site, the fluctuations in individual values is suggestive that the magnetic properties of the rock have suffered modification since their first formation. All samples were normally magnetized and no case of reversal was observed.

The intensity of magnetization in a rock sample depends on the grain size and the composition of the ferromagnetic minerals present. The high degree of fluctuation in the values of intensity of magnetization and susceptibility in individual samples only a few metres apart is probably due to non-uniformity of distribution of ferromagnetic minerals. There is a fair correlation between values of J and k. large values of J generally being associated with large values of k, and *vice versa.*

Stability—If the initial direction of magnetization in igneous rocks has remained unchanged the ratio of intensity of magnetization to susceptibility (J/k) has in general a value equal to or greater than unity. A rock which has lost its initial direction of magnetization or has suffered modification of this direction usually yields a value of J/k less than about 0·5. In the present case J/k varies between 0·2 and 1·1, with an overall mean value of 0·66.

TABLE I
Magnetic Properties of Dolerite Drill Core

Depth ft	Dip			Intensity of Magnetisation 10^4J emu	Susceptibility 10^4k	Ratio J/k
	I_1	I_2	$I=\frac{1}{2}(I_1+I_2)$			
*5	—81°	—83°	—82°	9·1	17·8	0·51
10	—81	—79	—80	12·0	20·6	0·58
15	—77	—75	—76	13·6	34·1	0·40
*20	—78	—72	—75	10·5	16·6	0·63
†25	—84	—80	—82	83·6	81·0	1·03
*30	—79	—79	—79	48·5	44·5	1·09
35	—72	—75	—74	12·2	23·8	0·51
40	—74	—76	—75	9·4	13·2	0·71
45	—69	—69	—69	17·2	17·1	1·00
50	—72	—72	—72	22·7	19·8	1·10
55	—80	—77	—78	10·4	18·1	0·57
*60	—81	—80	—80	12·6	17·6	0·72
65	—70	—70	—70	9·0	17·1	0·52
70	—77	—79	—78	11·5	12·8	0·90
75	—74	—71	—72	9·9	19·8	0·50
80	—68	—66	—67	9·4	13·4	0·70
*85	—68	—70	—69	5·3	16·3	0·32
90	—82	—83	—82	5·3	13·8	0·38
95	—63	—66	—64	6·6	18·1	0·36
*100	—52	—55	—54	4·3	10·5	0·41
105	—58	—59	—58	4·7	15·4	0·30
110	—63	—63	—63	8·6	14·3	0·60
115	—60	—56	—58	3·6	14·9	0·24
*120	—63	—61	—62	8·8	13·0	0·68
125	—56	—54	—55	5·6	12·2	0·46
*130	—66	—69	—68	6·3	13·5	0·47
*135	—73	—75	—74	6·6	10·7	0·62
140	—70	—70	—70	3·4	10·7	0·32
145	—73	—73	—73	4·6	12·3	0·37
150	—81	—79	—80	5·7	14·2	0·40
*155	—75	—77	—76	9·8	18·5	0·53
*160	—66	—69	—68	12·7	14·2	0·89
165	—74	—75	—74	12·4	13·8	0·90
*170	—78	—78	—78	9·6	11·7	0·82
175	—79	—79	—79	12·1	16·3	0·74
180	—80	—80	—80	11·7	14·4	0·81
185	—66	—68	—67	6·8	13·5	0·50
190	—51	—49	—50	5·2	12·1	0·43
Mean Values ..	..	..	—71	12·1	18·2	0·66

* Mean of two samples only.
† Only one sample.

One of the main difficulties in the analysis and interpretation of rock magnetic data is to decide to what extent rocks have undergone modification physically, chemically and magnetically since they were first formed. It is suggested that the present material has partially changed both in direction and intensity of magnetization in the long period since its consolidation. In confirmation of this conclusion it was found that some specimens underwent a change of magnetization when stored for a period of about one month in the vicinity of a permanent magnet.

It will be of interest to remeasure the material after they have been treated with an A.C. field of 50–100 Oe. I.R.M., being unstable, should be washed out and a much greater uniformity of dip should then be observed.

Acknowledgments

I am grateful to Blue Metal and Gravel Pty. Ltd. for permission to use the core, and to Drs. A. A. Day and H. G. Wilshire for advice and encouragement in the project.

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An Appraisal of Absolute Gravity Values for Gravity Base Stations in Sydney, Melbourne and Adelaide

I. A. Mumme

(*Received February* 2, 1960)

Sydney: University Base Station

An absolute gravity value here of 979·6884 gals was obtained by Muckenfuss by gravimeter tie with the gravity base station in the Commerce Building in Washington, D.C., U.S.A., where, a value of 980·1190 gals is accepted by Pendulum measurements.

The Commonwealth Bureau of Mineral Resources established a Pendulum station in the C.S.I.R.O. Buildings, Sydney, and obtained a value of 979·6841 gals based on a Cambridge value of gravity of 981·2688 gals.

Gravity measurements with a Worden gravimeter carried out by the University of Sydney show a difference of 2·8 milligals between the C.S.I.R.O. Pendulum station and the Sydney University base station, giving a value of gravity equal to 979·6813 gals. for the latter station.

This suggests that a probable value of gravity at the Sydney University base station is 979·6829 gals.

Melbourne: Footscray National Gravity Base Station

The writer obtained a gravity interval by gravimetric survey of 255·8 milligals between the Adelaide and the Melbourne absolute gravity base stations. This gives a value of 979·9790 gals for the Melbourne base station, based on a value of 979·7237 gals for the Adelaide base station. (See Mumme, 1960.)

An absolute gravity value was determined at Footscray of 979·9776 gals by E. McCarthy with Cambridge Pendulum equipment.

Dr. A. H. Cook of the National Physical Laboratory has carried out a comparison between results obtained with gravimeters in various countries. His conclusions indicate that the interval between Cambridge and Melbourne adopted by the Bureau of Mineral Resources may be 1·7 milligals too large, and suggests a value for Footscray of 979·9792 gals.

A probable value of 979·9791 gals is accepted for this station.

Table 1
Summary of Results

City	Station	Probable gravity value gal.
Cambridge	Pendulum House	981·2688
Washington	Commerce Building	980·1190
Sydney	University	979·6829
Melbourne	Footscray Laboratories	979·9791
Adelaide	New Observatory	979·7237

Adelaide: New Observatory Gravity Base Station

From a comparison of absolute gravity pendulum values obtained by E. McCarthy (on behalf of the B.M.R.), and gravimeter observations by Muckenfuss (on behalf of Wood's Hole Oceanographic Institute), Narain (University of Sydney), and Mumme (University of Adelaide), a probable absolute gravity value of 979·7237 gals was obtained.

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MUMME, I. A., 1960. Absolute gravity Determinations in Adelaide and recommendations for a new permanent absolute gravity base station. *Aust. J. Sci.*, **22**, 350.

MUMME, I. A. (in press). Absolute gravity Determinations on the Summits of a number of prominent Hills in the Mount Lofty Ranges. *Trans. Roy. Soc. S. Aust.*

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Comment

The value adopted for the acceleration due to gravity at the *External* Base Station, Dept. of Geology and Geophysics, University of Sydney, for all surveys conducted by the University is $g=979 \cdot 6821$ gal. This is based on the latest available value for the Bureau of Mineral Resources pendulum station, in the National Standards Laboratory, of $g=979 \cdot 6849$ gal.

Since this paper was submitted a note on the value of gravity at the Adelaide reference station has been published:

Dooley, J. C., and Williams, L. W., 1960. Absolute gravity value at Adelaide. *Aust. J. Sci.*, **23**, 17.

A. A. Day

Journal and Proceedings, Royal Society of N.S.W., Vol. 94, pp. 239–242, 1961

Electrode Shape and Finish in Applied Spectroscopy

S. C. Baker

(*Received April* 8, 1960)

Abstract—In the spectrochemical analysis of low alloy steels a satisfactory compromise between sensitivity, reproducibility and ease of sample preparation is achieved by sparking, in the case of rods, 150° cone-ended self-electrodes and in the case of blocks, a flat face finished on a 100 grit wet aluminium oxide wheel with 150° cone-ended graphite counter electrode. High sensitivity is associated with large deviation and vice versa. An efficient 7·5 kVA spark generator is described.

Introduction

When installing spectrographic equipment on a steelworks chill cast samples in various forms are readily available from established chemical procedures but the shape to which the ends of rods should be machined and the requisite quality of the finish on a flat surface of blocks for spark excitation has to be determined. This was done as follows.

Spark Generators

Two "uncontrolled" spark source units were employed, one of 0·25 kVA rating and the other 7·5 kVA. The former has been described in B.I.S.R.A. Special Report No. 47 (1952) and Ilford thin film half-tone plates were used as recommended in that report. However, a Hilger E185 quartz spectrograph and a Leeds and Northrup recording microphotometer were used here.

The 7·5 kVA generator is illustrated by Figure 1, in which *Tr* is an oil-cooled transformer designed to deliver 60 kV continuously. The leakage inductance together with the variac *A*, inductance *L* and condenser bank *C* (of total capacity 0·013 μF) comprise a charging circuit of self-frequency 150 c/s, whilst the resistances

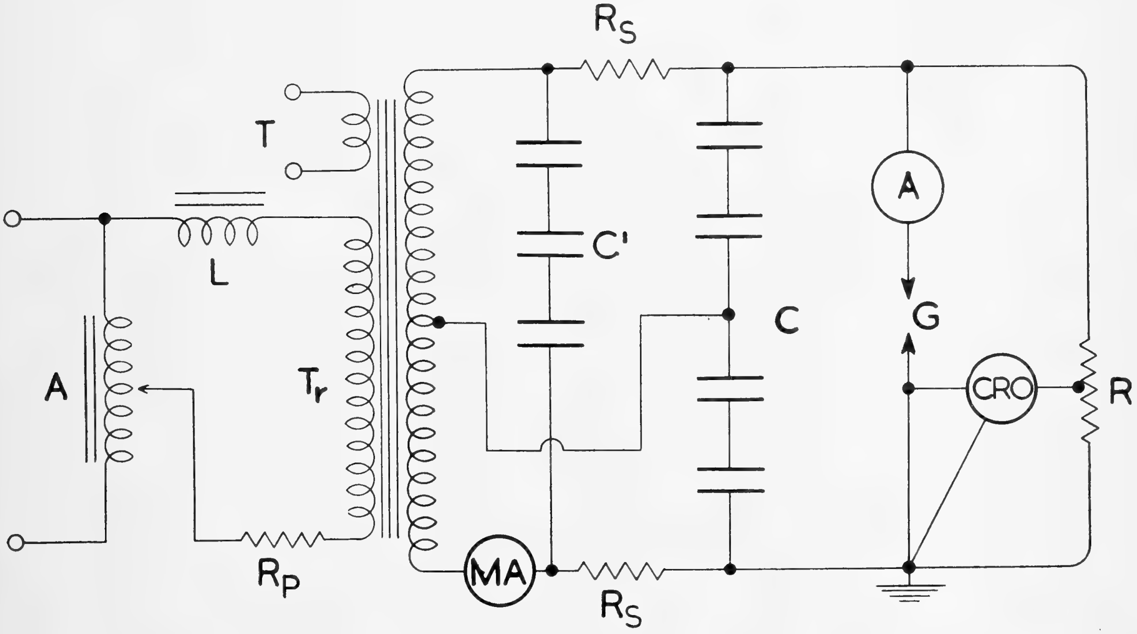


Fig. 1

R_p and R_s control the damping. For critical damping of the charging circuit R_p=4 ohms and R_s=25,000 ohms each. *T* is a tertiary winding connected to a meter indicating open circuit emf (r.m.s.) at the secondary terminals but when connected to a cathode ray oscilloscope showed that the bye-pass condenser *C′* is necessary to eliminate high frequency from the transformer even though the resistances R_s are wound inductively. The double beam cathode ray oscilloscope *CRO* indicates the form of the emf on *C* by means of the bleeder resistance *R* and the rate of change of current form in the analytical gap *G*. The thermocouple milliammeter *MA* and ammeter *A* serve to indicate the normal functioning of the unit. Satisfactory results are obtained with 3 sparks per half cycle of the 50 c/s supply with *A* reading 10, *MA* 150 and the meter connected to *T* 32 kV. All connections are made with $\frac{1}{4}$ inch diameter copper tubing and the junctions are brazed. Subsequently it has been found that the long term variability of analyses is almost eliminated by connecting in series with *G* an auxiliary gap across which a stream of dried air is blown; the resistances R_s are reduced to 1000 ohms each and the generator adjusted to give 5 sparks per half cycle of the supply.

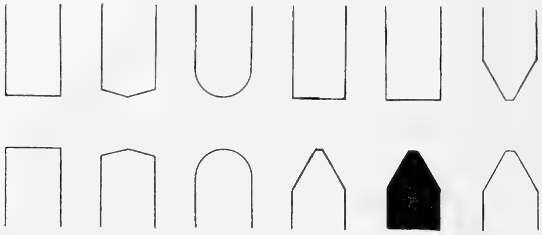
Rod Samples

The influence of the shape of the electrode ends on the sensitivity and reproducibility of silicon and manganese determinations in low alloy steels was investigated with both spark generators. In the first instance an $\frac{11}{16}$ inch diameter drawn rod was cut into 11 pieces each 3 inches long and pairs formed from random positions along the rod, the odd piece being paired with a graphite rod. The ends of the rods were then turned in a lathe to the shapes represented by the figure at the top of Table 1, opposite ends of each rod being given different shapes to increase randomness. Furthermore the spectra from the different electrode pairs were spread over all the plates to minimize the effect of plate variability and any variation in composition along the original rod. Small flats 1 mm in diameter were turned on the tips of the 60° cones because preliminary work had shown that sharp points caused instability; this applies to the graphite too, which is shaded in the figure. The analysis of the steel was 0·016% C, 0·019% P, 0·49% Mn, 0·191% Si and 0·018% S.

A 2 mm spark gap and intermediate slit illumination were used together with a 5 seconds pre-exposure sparking but exposures were varied according to electrode shape to secure approximately equal line densities on the plates. Thus

Table 1

Electrode shapes



	0·25 kVA generator					
Si 2881 / Fe 2874	1·25	0·97	1·23	0·96	0·88	0·89
δ(S)	0·016	0·006	0·009	0·006	0·006	0·005
Mn 2933 / Fe 2936·9	2·23	1·52	1·72	1·52	1·18	1·46
δ(Mn)	0·027	0·009	0·015	0·008	0·010	0·006
	7·5 kVA generator (underdamped)					
Si. 2881 / Fe 2874	1·25	1·06	1·09	0·99	1·13	1·13
δ(Si)	0·015	0·012	0·036	0·010	0·006	0·013
Mn 2933 / Fe 2936·9	2·43	1·34	1·39	1·25	1·27	1·15
δ(Mn)	0·022	0·013	0·018	0·018	0·020	0·022

with the smaller generator the flat-ended electrodes required 100 seconds, the 60° cones 80 seconds and the 60° cone-ended graphite to flat-ended steel rod two superposed exposures of 90 seconds each.

In Table 1 δ(Si) denotes the standard deviation of the mean intensity ratio of the spectral lines Si 2881A/Fe2874A calculated from the expression $[\Sigma(\bar{x}-x_i)^2/(n-1)]^{\frac{1}{2}}$ for 30 individual readings. Similarly δ(Mn) is the standard deviation of the mean intensity ratio of Mn 2933A/Fe 2936·9A.

When the charging circuit of the 7·5 kVA generator is critically damped and the auxiliary spark gap omitted results are practically identical with those of the smaller unit given in Table 1 and therefore they are not repeated here. This result agrees with that of Shirley, Oldfield and Kitchen (1950). However, in the underdamped condition the intensities of some lines are enhanced and equal those produced by an A.C. arc. The electrodes glow and boron, for example, can be estimated very satisfactorily. Results in Table 1 show that manganese and silicon can be estimated with sufficient accuracy at the same time.

Since electrode shape and exposure were the only variables for a given generator, it is evident that the large changes in the line intensity ratios are due to the different electrode shapes so the deviations have not been broken down into their components as was done by the B.I.S.R.A. Spectrographic Analysis Sub-Committee (1952). The results indicate that high sensitivity is associated with large deviation and *vice versa.* Some thought was given to Kaiser and Sohm's (1942) electrode "natural shape" but this was abandoned on account of difficult preparation and the 150° cone-ended self-electrodes have been adopted as a compromise between sensitivity and reproducibility and also because they can be machined easily with high accuracy and excellent finish.

Block Samples

Chill-cast blocks approximately 1″×1″×2″ known as "pit" samples are suitable for sparking against graphite rods on a Petrey stand when one face is ground flat. To determine the requisite quality of the finish on the flat surface the series of papers and wheels listed in Table 2 were used in turn. The 7·5 kVA generator with auxiliary gap was used in this case. 150° cone-ended graphite counter-electrodes and a 3 mm analytical gap were employed to determine the same line intensity ratios as above.

Considerable labour was involved in grinding by hand in running water and therefore the standard deviations in Table 2 are derived from only four separate readings—this being the maximum number of separate sparkings that could be made on one block face without overlapping the spark burns. Block No. 1 contained 0·198% Mn and 0·213% Si. The last 4 readings were made independently on Block No. 2, which contained 0·27% Mn and 0·220% Si.

These results are not as conclusive as desired but they suggest that the finer the surface finish the better the reproducibility and the lower the sensitivity but that there is no marked advantage in extremely fine finish. Wet finishing is slightly better than dry provided the specimen is not unduly heated by the grinding process. The method adopted by the steelworks is to cut a thin slice off one end of the block with a

TABLE 2

Material	Grit No.	$\frac{\text{Si 2881}}{\text{Fe 2874}}$	δ(Si)	$\frac{\text{Mn 2933}}{\text{Fe 2936·9}}$	δ(Mn)
		Block No. 1			
Wet paper ..	600	1·12	0·014	0·45	0·016
Wet paper ..	400	1·11	0·014	0·47	0·009
Wet paper ..	280	1·12	0·015	0·42	0·011
Wet paper ..	150	1·12	0·020	0·47	0·022
Wet paper ..	100	1·13	0·020	0·47	0·039
Wet wheel ..	60	1·18	0·012	0·46	0·021
Wet wheel ..	30	1·14	0·033	0·47	0·025
		Block No. 2			
Wet paper ..	600	1·13	0·009	0·72	0·009
Dry paper ..	600	1·15	0·012	0·76	0·010
Wet wheel ..	30	1·11	0·019	0·76	0·016
Dry wheel ..	30	1·18	0·018	0·75	0·023

water-cooled high speed cutting wheel and then finish the exposed end of the block on a wet 100-grit aluminium oxide grinding wheel.

Though the rods are easier to prepare for sparking and give better overall results the "pit" samples cause less confusion on the plant and have been used almost exclusively during the first year of spectrographic operation. Excellent working curves have been established for Mn, Si, Cr, Ni, Mo, Cu, Al and Zr in the normal concentration ranges in low alloy steels.

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