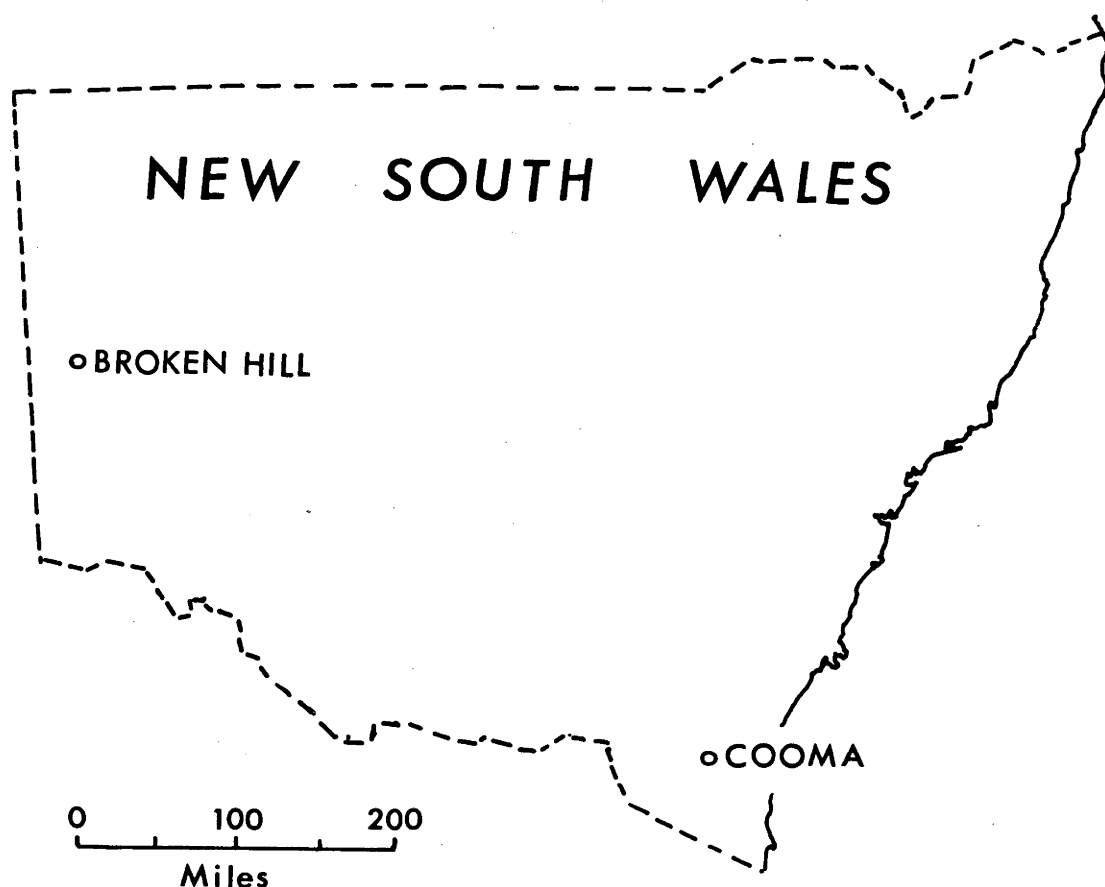


THE GEOCHRONOLOGY OF TWO REGIONALLY
METAMORPHOSED AREAS IN
NEW SOUTH WALES.

A thesis submitted for
the degree of
DOCTOR OF PHILOSOPHY
in the
Australian National University
by
R.T. Pidgeon
November, 1964.



STATEMENT.

The work contained in this thesis was performed by the author between July 1961 and July 1964. Approximately six weeks were spent in the field at Broken Hill and the field work at Cooma was accomplished by a number of one-day trips.

The thesis includes two supporting joint papers; one with Dr. W. Compston and the second with Dr. J.R. Richards. The author carried out most of the experimental work in the first and the Rb-Sr analyses in the second, and was jointly involved in the interpretation.

The chemistry on some of the Cooma granite samples was performed by Mr. M.J. Vernon and Dr. W. Compston made a number of the mass spectrometer measurements. Mr. H. Berry and Mr. R. Rudowski performed complete mineral separations on two selected Cooma granites and also provided total-rock and mineral samples on the majority of specimens bearing G.A. numbers.

All other work and interpretation except where acknowledged in the text was performed by the author.



(Signed) R. T. Pidgeon.

ACKNOWLEDGEMENTS.

This work was performed under the supervision and guidance of Dr. W. Compston. I had many helpful discussions with Dr. G.A. Joplin, Mr. M.J. Vernon, Dr. I. McDougall, Dr. K.S. Heir and especially Dr. J.R. Richards. I am indebted to Mr. H. Berry and Mr. R. Rudowski for a number of mineral separations, to Mr. E.H. Pederson and Mr. A.W. Powell for thin sections and to Dr. A.J. White for some x-ray determinations on feldspar. Other technical assistance from Mrs. A. Brown and Mr. E. Penikis is gratefully acknowledged.

I was fortunate in having brief discussions with Dr. R.A. Binns, Mr. J. Hodgson, Mr. T. Hopwood and Dr. T. Vallance on aspects of the work. I received every assistance from all Mine's Staffs at Broken Hill. The Zinc Corporation Ltd. assisted in organising both field trips.

I am grateful to the A.N.U. for a Commonwealth post-graduate award for the three years in which this work was performed.

I would like to thank Mrs. June Bastian for typing the thesis and Mr. V. Paral for photographing the figures.

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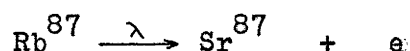
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CHAPTER I.

INTRODUCTION.

This thesis presents the results of an investigation of the geochronology of two regionally metamorphosed complexes in south eastern Australia. In this study use is made of the first order reaction



in conjunction with the results of K-Ar and U-Pb age determinations.

Early investigators of the geochronology of metamorphic areas relied largely on the results of mineral age determinations (e.g. Aldrich, 1958). These were adequate for igneous rocks, but because of a relative loss or gain of daughter isotopes, sometimes gave inconsistent results in metamorphic areas (Compston and Jeffery 1959, Wetherill 1960). Schreiner (1958), Compston and Jeffery (1959) and Compston, Jeffery and Riley (1960) introduced the total-rock Rb-Sr method of age determination which has been successful in areas where mineral ages have proved unreliable (e.g. Allsopp et. al. 1962, Hurley et. al. 1962). U-Pb geochronology on zircons by Tilton and others (Tilton et. al. 1957) has paralleled Rb-Sr progress and recently Silver (1962) has been able to decipher geological events by studying the ages of zircon populations from a single rock sample. Stanton and Russell (1959) investigating ore lead have established criteria for recognising single stage lead derived directly from

their parent U-Pb system, and Kanasewich (1962) has proposed a method of interpreting anomalous or multistage leads in terms of metamorphic events.

Over some years it has been found that the K-Ar method is of limited use in metamorphic areas as the minerals measured have generally lost argon. However the recent work of Hart (1964) has shown that, in an environment of contact metamorphism, hornblende is particularly retentive of its old age. This conclusion is supported by the few hornblende K-Ar results reported in this thesis.

The detailed investigation of the effect of temperature on mineral ages by Hart and Doe (1963) and Hart (1964) has added greatly to the empirical knowledge of the age retentivity, using different decay schemes, of various mineral phases such as biotite, potassium feldspar and hornblende. Previously age determinations using different decay schemes had been made on minerals from the same rock (e.g. Tilton et. al., 1962) but it is now realised that a single measurement or even a single method is often insufficient to adequately date a metamorphic event. Doe (1962) has compared lead ages of zircons, feldspar and the lead ore bodies to Rb-Sr and K-Ar ages on suitable minerals in a regionally metamorphosed area at Balmat, New York, in order to date the metamorphisms and to determine the origin of the lead.

Gast (1960), Hurley et. al. (1962) and Hedge and Walthall (1963) have developed a theory for establishing the origin of rocks

from their initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ and this has been applied to the origin of granitic rocks (e.g. Pidgeon and Compston, 1965).

These advances have gone hand in hand with improvements in technique and precision and it is now possible to successfully undertake a comprehensive investigation of the geochronology of complex regionally-metamorphosed areas.

The areas of regional metamorphism studied in this thesis present immediate geological problems such as the age and origin of the rocks. To answer such questions however involves a study of the behaviour of Sr and Rb isotopes under varying regional metamorphic conditions and in the following discussion both aspects will receive due attention. The distinct advantage of studying two regionally metamorphosed areas widely separated in space and time is that common features, if any, may be recognised.

This thesis is divided into two parts, I the regionally metamorphosed area at Cooma and II the regionally metamorphosed area of the Broken Hill district.

I. The Cooma area consists of a central granitic mass surrounded by zones of radially decreasing metamorphic grade. The metamorphism has been classified by Miyashiro (1961) as representative of the "sillimanite-andalusite type" and except for the absence of garnet-bearing rocks it is very similar to the Ryoke metamorphic belt in Japan.

The study of this complex has established the crustal

origin of the granite and that the granite is contemporaneous with the metamorphism of the surrounding metasediment, as well as with the migmatites and pegmatite. It was also found that these events were closely related in time to a later transgressive phase of the Murrumbidgee Batholith.

It was established that complete mixing of Sr isotopes which occurred during the recrystallising metamorphism extended out as far as the boundary of the "cordierite-orthoclase zone". Further out the greenschist sediments reflect a greater age. This could be interpreted as either the age of greenschist facies metamorphism or the age of sedimentation. To distinguish between the possibilities, measurements were made on shales from unmetamorphosed areas and on seawater samples collected from the east and west coasts of Australia. The results of these measurements suggest a new method for determining the age of shales (Compston and Pidgeon 1962, Part I, appendix 2).

A detailed investigation was made into the possibility of a later selective movement of radiogenic strontium as suggested by Hurley et. al. (1961), and evidence presented to show that in the Cooma rocks such a movement is unlikely. It appears that, since the recrystallisation of the sediments to form the granite and metamorphic zones, the rocks have remained closed systems to Rb and Sr isotopes.

II. The second part of this study is an investigation of

the geochronology of the regionally metamorphosed rocks of the Broken Hill district, New South Wales. The geology is extremely complex and no agreement has been reached about the order or the number of separate geological events. From granulite facies rocks at Broken Hill the metamorphic grade decreases to barely greenschist facies in the far north. The region is overprinted by retrogressive metamorphisms and intruded by granite, pegmatite and basic rocks. The presence of lead deposits introduces an added interest as previously no relationship has been demonstrated between ages in the country rock and model lead ages.

It has been possible to establish the age of the high grade metamorphism and a slightly younger period of pegmatite and granite intrusion was found. The lead age of the ore could be equated within possible error to either the high-grade metamorphism or the introduction of pegmatite and granite. Biotite ages reflect a Palaeozoic metamorphic event and correspond to Kanasewich's anomalous Thackaringa lead age and to biotite K-Ar ages (Richards and Pidgeon 1963, Part II appendix 2).

It is shown that during the Palaeozoic metamorphism the unsheared rocks remained closed systems, although within these rocks it appears that radiogenic strontium was selectively lost from the biotite and absorbed in the feldspars.

A description of the experimental method is included in both papers as appendices and may be found in more detail in

Compston et. al. 1965.

To calculate ages the following relationships were used:-

$$t = (\text{age}) = \frac{1}{\lambda} \ln (1 + \text{Sr}_*^{87}/\text{Rb}^{87}) \quad \text{--- (1)}$$

$$\text{and } \text{Sr}_*^{87} = \text{Sr}^{86} (\text{R}_p - \text{R}_i)$$

where λ denotes the Rb^{87} decay constant, taken for calculations in this thesis as $1.39 \times 10^{-11} \text{ y.}^{-1}$ (Alrich et. al. 1956). Sr_*^{87} is the concentration of radiogenic strontium and R_p and R_i the present day and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of the sample. These relationships are valid only if the sample has remained closed to rubidium and strontium.

Equation (1) may be written

$$t = \frac{1}{\lambda} \ln (1 + \theta) \quad \theta = \text{Sr}_*^{87}/\text{Rb}^{87}$$

which can be expanded as

$$= \frac{1}{\lambda} \left(\theta - \frac{\theta^2}{2} + \frac{\theta^3}{3} \text{ etc.} \right)$$

for Palaeozoic samples t closely approximates to $t \simeq \frac{1}{\lambda} \theta$; --- (2)

for older samples a correction is made for the squared term.

From the approximation

$$\lambda t \simeq \theta = (\text{Sr}^{86}/\text{Rb}^{87}) (\text{R}_p - \text{R}_i)$$

$$\text{R}_p = \text{R}_i + \theta (\text{Rb}^{87}/\text{Sr}^{86}) \text{ can be found which is}$$

independent of λ .

This is the equation of a straight line, if R_p and $\text{Rb}^{87}/\text{Sr}^{86}$ are regarded as variables, and the age is proportional to the gradient θ .

This method of presentation (Nicolaysen, 1960), labelled an isochron plot, is used throughout this thesis.

It has been shown in Chapter II that the uncertainty in an age calculated on samples with a low Rb/Sr ratio is strongly dependent on $(R_p - R_i)$. To measure R_p accurately on such samples unspiked strontium runs were made. To correct for mass-spectrometer effects on these runs the isotopic ratios were normalised to a $\text{Sr}^{88}/\text{Sr}^{86}$ of 8.34, which is the mean of these ratios observed in unspiked runs on the A.N.U. mass spectrometer MS2. S.G. during 1961, 1962. The normalised $\text{Sr}^{87}/\text{Sr}^{86}$ is included in the tables.

CHAPTER II.

THE PRECISION OF THE METHOD.

A. INTRODUCTION.

In this chapter two methods are presented from which the precision of an age measurement may be estimated. In these absolute accuracy is not considered and therefore no account is taken of systematic errors such as uncertainty in the decay constant or spike concentration, or of random geological errors. To account for random geological errors a third statistical method is introduced. This involves isotopic measurement of a statistically significant number of samples which, on geological evidence, should have the same age and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio.

B. THE PRECISION OF AN INDIVIDUAL AGE MEASUREMENT.

1. Introduction.

This section presents a method of estimating the precision of an individual age measurement assuming all error is random experimental error.

To calculate an age the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio must be known. An imprecise knowledge of this ratio could introduce other than experimental error into the result. The effect of error in R_1 can be found by differentiating $\theta = \text{Sr}^{86}/\text{Rb}^{87} (R_p - R_1)$ with respect to R_1 . This gives :-

$\frac{\Delta \theta}{\Delta R_i} = - \text{Sr}^{86}/\text{Rb}^{87}$ which in turn leads to an expression for the error magnification.

$$\frac{\Delta \theta}{\theta} = - \frac{R_i}{R_p - R_i} \frac{\Delta R_i}{R_i} \quad \left(\text{where } t \approx \frac{\theta}{\lambda} \right)$$

The magnitude of this error increases as $R_p \rightarrow R_i$.

For the purpose of the following argument I will assume no error in R_i .

The simplest estimation of the experimental error can be found by comparing ages calculated on replicate measurements of the same sample.

2. Analysis of variance of ages calculated from replicate measurements on a single sample.

From the replicate age determinations a "one way" analysis of variance table is prepared and the variance due to experimental error is estimated from the "within group" mean squares (Acton 1959, Brunk 1960). From this a "least significant difference" is calculated at the 95% level and expressed as a percentage of the measured age. Table 1 presents a sample calculation on Cooma granite data where the "least significant difference" or the experimental error at the 95% level is found to be $\pm 8.5\%$. This implies that the means of duplicate age determinations on Cooma granite samples are not significantly different if they are within ± 35 m.y. of each other. As the Cooma granite samples have a low $(R_p - R_i)$ an error due to uncertainty in R_i is probably included in the 8.5%. An estimate

of the experimental error of biotite ages from Broken Hill is $\pm 6.2\%$, corresponding to ± 34 m.y. in 550 m.y. In this example the error due to uncertainty in R_1 would be negligible but it is likely a sampling error was introduced. The biotite flakes were relatively coarse and were poured from the bottle instead of being properly split. Furthermore, the biotites have lost more than 2/3rds of their radiogenic Sr so an unusual variance in age resulting from variance in concentration of Sr^{87} might be expected.

This "analysis of variance" method assumes that the variance of $\frac{1}{\lambda} Sr^{86}/Rb^{87} (R_p - R_1)$ is the same for all values of R_p and Sr^{86} and Rb^{87} concentrations. This is not necessarily true. A second method assumes that the percentage standard deviations in the Sr^{86} and Rb^{87} concentrations and in R_p are constant and reflect the random experimental error. From experimental observations this is not entirely accurate but in this elementary treatment no more complex assumptions can be made.

3. Estimation of the error in an age from the individual errors in Sr^{86} , Rb^{87} and R_p .

It would not have been possible to derive the following method without a number of discussions of the problem with Mr. P.J. Brockwell and Mr. C.C. Heyde of the Statistics Department, I.A.S., A.N.U.

As a first step the percentage standard deviations in the concentrations of Sr^{86} , Rb^{87} and the value of R_p were estimated

(Tables 2, 3 and 4). The data used in these estimations were taken from total-rock and feldspar measurements at Broken Hill and Cooma and should be representative of data presented in this thesis.

The variance of each set of replicate analyses was estimated with

$$s^2 = \sum_{i=1}^n \left[\frac{(X_i - \bar{X})}{\bar{X}} 100 \right]^2$$

where n is the number of replicate measurements, generally two.

The variances were summed over all samples and an estimate of σ^2 , the population variance, was made using a χ^2 distribution.

$$\sum_{i=1}^Z \frac{(n-1) s^2}{2} = \chi^2_{\sum_{i=1}^Z (n-1)}$$

where Z is the number of sets of replicates.

As a second step it is necessary to derive the variance of the function

$$V \left[\text{Sr}^{86}/\text{Rb}^{87} (R_p - R_i) \right]$$

Let $\text{Sr}^{86} = X$, $R_p = Y$, $\text{Rb}^{87} = Z$ and $R_i = C$.

Also let X_0, Y_0, Z_0 be estimates of the true values of X, Y, Z and define $\Delta X, \Delta Y, \Delta Z$ as $X = X_0 + \Delta X$, $Y = Y_0 + \Delta Y$ and $Z = Z_0 + \Delta Z$.

From the expansion of Taylor's Theorem for functions of several variables

$$\begin{aligned} \Delta f = f(X, Y, Z) - f(X_0, Y_0, Z_0) &= \frac{\partial f(X_0, Y_0, Z_0)}{\partial X} \Delta X + \frac{\partial f(X_0, Y_0, Z_0)}{\partial Y} \Delta Y \\ &+ \frac{\partial f(X_0, Y_0, Z_0)}{\partial Z} \Delta Z + R \end{aligned}$$

$$\text{let } f(X, Y, Z) = \frac{X}{Z}(Y - C) = f$$

$$\text{Then } \left(\frac{\partial f}{\partial X}\right)_0 = \frac{Y_0 - C}{Z_0} ; \quad \left(\frac{\partial f}{\partial Z}\right)_0 = \frac{-X_0(Y_0 - C)}{Z_0^2} ;$$

$$\left(\frac{\partial f}{\partial Y}\right)_0 = \frac{X_0}{Z_0}$$

and

$$\begin{aligned} \Delta f^2 = & \left(\frac{Y_0 - C}{Z_0}\right)^2 \Delta X^2 + \left(\frac{X_0}{Z_0}\right)^2 \Delta Y^2 + \frac{X_0^2 (Y_0 - C)^2}{Z_0^2} \Delta Z^2 \\ & + \frac{X_0(Y_0 - C)}{Z_0^2} \Delta X \Delta Y - \frac{X_0^2 (Y_0 - C)}{Z_0^3} \Delta Z \Delta Y - \frac{X_0 (Y_0 - C)^2}{Z_0^3} \Delta X \Delta Z \end{aligned}$$

Take expected values and substitute $\rho_{XY} = E\left(\frac{\Delta X \Delta Y}{\sigma_X \sigma_Y}\right)$

and $E(\Delta X^2) = \sigma_X^2$ etc.

$$\begin{aligned} \sigma_f^2 = & \left(\frac{Y_0 - C}{Z_0}\right)^2 \sigma_X^2 + \left(\frac{X_0}{Z_0}\right)^2 \sigma_Y^2 + \frac{X_0^2 (Y_0 - C)^2}{Z_0^2} \sigma_Z^2 + \frac{X_0 (Y_0 - C)}{Z_0^2} \rho_{XY} \sigma_X \sigma_Y \\ & - \frac{X_0^2 (Y_0 - C)}{Z_0^3} \rho_{YZ} \sigma_Y \sigma_Z - \frac{X_0 (Y_0 - C)^2}{Z_0^3} \rho_{YZ} \sigma_X \sigma_Z \end{aligned}$$

If errors in X, Y and Z are assumed to be uncorrelated in

$[X/Z (Y-C)]$, $\rho = 0$ and the expression becomes (where Sr^{86} is low

the error in R_p and Sr^{86} are correlated however) :-

$$\hat{\sigma}_{f_1}^2 = \left(\frac{Y_0 - C}{Z_0}\right)^2 \hat{\sigma}_{X_1}^2 + \left(\frac{X_0}{Z_0}\right)^2 \hat{\sigma}_{Y_1}^2 + \frac{X_0^2 (Y_0 - C)^2}{Z_0^2} \hat{\sigma}_{Z_1}^2$$

where $\hat{\sigma}_{(X, Y \text{ or } Z)_1}$ is the estimate of the actual standard deviation

of the sample quantity found by multiplying the concentration, X_0

Y_0 or Z_0 , by the estimated percentage standard deviation $\sigma(X, Y \text{ or } Z)$.

If normality is assumed a 95% confidence interval can be estimated from the approximation

$$\mu = \bar{X} \pm 1.96 \sqrt{\frac{\sigma_f^2}{n}}$$

This can be expressed as a percentage of the sample's age.

Under the assumption that $\rho_{XY} = 0$ the experimental error calculated for the total-rock Cooma granite sample C2 is $\pm 8.15\%$. This is close to that found by an analysis of variance of replicate age measurements on Cooma granite samples (Table 1). Total-rock sample BH5 had a calculated error of $\pm 2.06\%$ (Table 5) whereas the experimental error in BH70 total-rock was $\pm 1.87\%$ of the measured age. The experimental error in BH5 biotite was calculated at $\pm 4.47\%$. The experimental error calculated for BH5 and C2 is changed very little if the correlation coefficient ρ is made equal to one.

The precision of BH5 and BH70 total rocks is near that expected intuitively. The improved precision (at the 95% level) of BH5 biotite calculated by this method as against the estimate from the analysis of variance suggests that an error has been introduced into the "age" from the initial sampling of the bottle. It is noted that the error in the biotite is due almost entirely to the term containing the error in the Rb^{87} concentration.

C. The precision of age measurements based on a number of samples.

Because R_i is generally not precisely known, it has been

found necessary to estimate this as well as the age by measuring Rb and Sr isotopes on a number of samples which on geological evidence are expected to have the same age and R_i . The method used is based on the method of least squares. The data do not fit the classical least squares model however as both X and Y have experimental and geological error. The experimental error can be estimated from replicate analyses but no estimate of the geological error can be made.

A treatment of this problem is given in Acton (1959) but in this thesis I have calculated ages and uncertainties by a simplified method.

Before presenting this I wish to acknowledge helpful discussions of the problem with Professor E.S. Hannan of the Statistics Department, S.G.S., A.N.U.

The first step is to determine the slope of the line (proportional to age) which best fits the data, plotted on a Rb^{87}/Sr^{86} against Sr^{87}/Sr^{86} diagram, and also to find the intercept on the Sr^{87}/Sr^{86} axis (R_i).

This is done by choosing Rb^{87}/Sr^{86} as X and Sr^{87}/Sr^{86} as Y, calculating the slope and intercept for Y on X and then for X on Y. The results are generally very close and the average of the two is taken.

The confidence intervals have been calculated for $X = Rb^{87}/Sr^{86}$.

Corrections can be made for the experimental error in X where necessary. Generally geological error far exceeds that due to experiment and since no correction is possible for geological error in X this method is unsatisfactory. At the time of writing no suitable, simple alternative method has been found.

Method.

Let $X_{jt} = \bar{v}_j + \varepsilon_{jt}$ where X is $\text{Rb}^{87}/\text{Sr}^{86}$ and ε_{jt} is the experimental error in $\text{Sr}^{87}/\text{Sr}^{86}$.

$Y_{jt} = \mu_j + \eta_{jt}$ where Y is the $\text{Sr}^{87}/\text{Sr}^{86}$ and η_{jt} is the experimental error in $\text{Sr}^{87}/\text{Sr}^{86}$.

j refers to a particular sample or group and t to a measurement on the sample.

$j = 1, \dots, J$; $t = 1, \dots, n_j$ where n_j is the number of measurements on sample j.

Let $\mu_j = \alpha + \beta \bar{v}_j + e_j$

$$\text{and } \text{var}(e_j) = \sigma^2$$

where e_j is the geological error assumed to be in the Y direction.

If the estimated variance of $\bar{X}$, $\frac{\hat{\sigma}_\varepsilon^2}{n_j}$, is negligibly small compared to σ^2 , then

$$b = \frac{\sum_j (\bar{Y}_j - \bar{Y})(\bar{X}_j - \bar{X})}{\sum_j (\bar{X}_j - \bar{X})^2}$$

$$\text{where } \bar{Y}_j = \frac{1}{n_j} \sum_{t=1}^{n_j} Y_{jt}$$

$$\text{and } \bar{Y} = \frac{1}{J} \sum_{j=1}^J Y_j$$

$$\text{and } a = \bar{Y} - b \bar{X}$$

where "b" is the least squares slope and "a" is the intercept on the Y axis.

The confidence interval for b is found from

$$S_b = \sqrt{\frac{\sum_j (\bar{Y}_j - \bar{Y})^2 - \frac{\sum_j (\bar{Y}_j - \bar{Y})(\bar{X}_j - \bar{X})}{\sum_j (\bar{X}_j - \bar{X})^2}}{J - 2}}$$

$$= \sqrt{\frac{\hat{\sigma}^2}{\sum_j (\bar{X}_j - \bar{X})^2}}$$

$$S_a = \sqrt{\frac{\hat{\sigma}^2}{J} + \frac{\hat{\sigma}^2 \bar{X}^2}{\sum_j (\bar{X}_j - \bar{X})^2}}$$

From these estimates 95% confidence intervals can be calculated for age and R_1 with $J - 2$ degrees of freedom.

TABLE 1. Analysis of Variance of some Cooma granite ages.

 In these calculations Cooma granite ages were deter-
mined using an R_1 of 0.7179 whereas ages from the high grade
metasediments were calculated using $R_1 = 0.7193$.

Sample	Age		T_i
55 Or.	400	401	801
55 T.R.	375	371	746
2 Musc.	419	429	848
5 T.R.	401	377	778
2 T.R.	417	416	833
2 Or.	452	487	939
4B T.R.	364	402	766
GA293 T.R.	413	392	<u>805</u>

$G = 6516$ $N = 16$

Total Sum of Squares $= \sum_i \sum_j X_{ij}^2 - \frac{G^2}{N} = 14709$

Between group Sum of Squares $= \sum_i \frac{t_i^2}{n_i} - \frac{G^2}{N} = 12806$

Within group Sum of Squares $= 1903$

(Acton, 1959)

The least significant difference between means is calculated using
a t test with N-K degrees of freedom (K = number of samples or groups).

For a significant difference

$$|\bar{X}_1 - \bar{X}_2| > t_{8, 5\%} \sqrt{\frac{S^2}{2} \times 2}$$

where S^2 is the within group mean square $\frac{1903}{8}$

$> 2.306 \times 15.4$

$> 35.5 \text{ m.y.}$

The means of duplicate measurements in different samples
of Cooma granite are not significantly different if they are within
 $\pm 8.5\%$ of each other.

TABLE 2. Estimation of the percentage standard deviation of the concentration of Sr^{86} .

Sample	Sr^{86} μ moles/gm	$\bar{X}$	$\sum_1^n \left[\frac{(x_i - \bar{X})}{\bar{X}} 100 \right]^2$	
BH25 T.R.	0.1021	0.1069	0.1045	10.552
BH25 S	0.2114	0.2092	0.2103	0.547
BH23 S	0.1442	0.1410	0.1426	2.518
BH135 S	0.0734	0.0731	0.0733	0.149
GA55 Or.	0.4710	0.4660	0.4865	0.570
GA55 T.R.	0.1337	0.1320	0.1328	0.725
C5 T.R.	0.1455	0.1467	0.1461	0.337
C2 T.R.	0.1314	0.1310	0.1316	0.046
C2 Or.	0.4960	0.5009	0.4985	0.502
C4B T.R.	0.1728	0.1740	0.1734	0.239
GA293 T.R.	0.5854	0.5890	0.5872	0.187
BH5 T.R.	0.0308	0.0300	0.0304	3.464
BH5 Or.	0.0679	0.0673	0.0676	0.394
BH21 T.R.	0.0295	0.0293	0.0294	0.221
BH21 Or.	0.0894	0.0926	0.0910	0.062

$$\frac{\sum_1^{15} (n-1) s^2}{\sigma^2}$$

$$= \chi^2_{\sum_1^{15} (n-1)} \quad \text{for } n = 2$$

$$\frac{(20.514)}{25}$$

$$= \hat{\sigma}^2$$

$$= 0.813$$

$$\hat{\sigma}$$

$$= 0.905\%$$

$$20.514 = \sum_1^{15} (n-1) s^2$$

TABLE 3. Estimation of the percentage standard deviation of the concentration of Rb^{87} .

Sample	Rb^{87}	$\mu\text{ moles/gm}$	$\bar{X}$	$\sum_1^n \left[\frac{(x_i - \bar{X})100}{\bar{X}} \right]^2$
BH25 T.R.	0.5150	0.5104	0.5127	0.403
BH25 S	0.7740	0.7850	0.7795	0.994
BH23 S	1.5443	1.5141	1.5292	1.948
BH135 S	0.9650	0.9792	0.9721	1.065
GA55 Or.	0.8070	0.8031	0.8050	0.115
GA55 T.R.	0.8650	0.8739	0.8695	0.512
C5 T.R.	0.5763	0.5770	0.5767	0.001
C2 T.R.	0.5915	0.6003	0.5959	1.089
C2 Or.	0.7823	0.7922	0.7872	0.774
C4B T.R.	0.8106	0.8092	0.8099	0.015
GA293 T.R.	0.1018	0.0994	0.1006	2.846
BH5 T.R.	1.5018	1.4677	1.4847	2.622
BH5 Or.	2.5183	2.5112	2.5147	0.039
BH21 T.R.	1.1183	1.1432	1.1313	2.213
BH21 Or.	1.7448	1.7544	1.7496	0.150

$$14.786 = \sum_1^{15} (n-1)s^2$$

$$\frac{\sum_1^{15} (n-1) s^2}{G^2} = \chi^2_{15} \sum_1^{15} (n-1) \quad \text{for } n = 2$$

$$\frac{14.786}{25} = \hat{G}^2 = 0.591$$

$$\hat{G} = 0.769\%$$

TABLE 4. Estimation of the percentage standard deviation of the value of R_p .

Sample	R_p	$(\text{Sr}^{87}/\text{Sr}^{86})$	$\bar{X}$	$\sum_{i=1}^n \left[\frac{(x_i - \bar{X})100}{\bar{X}} \right]^2$
BH25 T.R.	0.8711	0.8717	0.8714	0.00238
BH25 S	0.8668	0.8686	0.8677	0.02150
BH23 S	1.0784	1.0804	1.0794	0.01714
BH135 S	0.9527	0.9480	0.9503	0.11712
GA55 Or	0.7288	0.7289	0.7289	---
GA55 T.R.	0.7574	0.7565	0.7570	0.00870
C5 T.R.	0.7411	0.7389	0.7400	0.04416
C2 T.R.	0.7438	0.7444	0.7441	0.00324
C2 Or.	0.7286	0.7278	0.7282	0.00604
C4B T.R.	0.7439	0.7462	0.7451	0.04356
GA293 T.R.	0.7509	0.7502	0.7506	0.00568
BH5 Or.	1.8845	1.9050	1.8947	0.59100
BH21 T.R.	1.6362	1.6318	1.6340	0.03622

$$0.89674 = \sum_{i=1}^{13} (n-1)s^2$$

$$\frac{\sum_{i=1}^{13} (n-1) s^2}{\sigma^2} = \chi^2_{13} \quad \text{for } n = 2$$

$$\frac{0.89674}{22.4} = \hat{\sigma}^2 = 0.0400$$

$$\hat{\sigma} = 0.2\%$$

TABLE 5. An estimation of the experimental error in BH5 total-rock based on the estimates of the percentage standard deviation of Sr^{86} , Rb^{87} and R_p .

$$Z_o = \text{Rb}^{87} = 1.4848 \text{ } \mu\text{moles/gm}; \hat{G}_{Z_1} = 1.142 \times 10^{-2}; \hat{G}_{Z_1}^2 = 1.304 \times 10^{-4}$$

$$X_o = \text{Sr}^{86} = 0.0304 \text{ } \mu\text{moles/gm}; \hat{G}_{X_1} = 0.027 \times 10^{-2}; \hat{G}_{X_1}^2 = 7.51 \times 10^{-8}$$

$$Y_o = R_p = 1.8565; \hat{G}_{Y_1} = 0.371 \times 10^{-2}; \hat{G}_{Y_1}^2 = 0.138 \times 10^{-4}$$

$$C = R_i = 0.7595$$

$$\begin{aligned} \hat{G}_{f_1}^2 &= \left(\frac{Y_o - C}{Z_o} \right)^2 \hat{G}_{X_1}^2 + \left(\frac{X_o}{Z_o} \right)^2 \hat{G}_{Y_1}^2 + \frac{X_o^2 (Y_o - C)^2}{Z_o^2} \hat{G}_{Z_1}^2 \\ &= 0.546 \hat{G}_{X_1}^2 + 0.00042 \hat{G}_{Y_1}^2 + 0.000504 \hat{G}_{Z_1}^2 \\ &= 11.25 \times 10^{-8} \end{aligned}$$

Assuming normality the 95% confidence interval of the mean of two results can be estimated from

$$\begin{aligned} &= \bar{X} \pm 1.96 \sqrt{5.62 \times 10^{-8}} \\ &= \bar{X} \pm 4.64 \times 10^{-4} \end{aligned}$$

The value of $\frac{X}{Z}(Y-c)$ for BH5 total-rock is 0.02250. The percentage error is therefore $\left(\frac{4.64}{2.25} \right) = \pm 2.06\%$

PART I.THE AREA OF REGIONAL METAMORPHISMAT COOMA, N.S.W.

The material contained in Part I of this thesis has been accepted for publication in the Journal of Petrology Vol 6, Part 2, 1965, as a paper entitled -

"The age and origin of the Cooma granite and its associated metamorphic zones, New South Wales." by R.T. Pidgeon and Dr. W. Compston.

Part I follows closely the form of this paper.

CHAPTER III. THE GEOLOGY AND EXPERIMENTAL RESULTS.

A. INTRODUCTION.

Part I presents the results of a detailed rubidium-strontium isotopic study of the Cooma granite and its associated zones of regional metamorphism.

The Cooma granite is a small body surrounded by wide zones of progressively decreasing metamorphism. It exemplifies the "Ordovician-type" granite in Browne's classification of the granites in southeast Australia. Browne in David (1950) recognised three granite types which he related to Ordovician, Silurian and post-Silurian orogenies. These had definite characteristics and were later designated the "gneissic type", "foliated type" and "massive type" (Evernden and Richards, 1962; Joplin, 1962). In contrast to this chronology, Evernden and Richards (1962) have concluded that all three types of granite were emplaced during the time interval Middle Silurian to Middle Devonian, using radiometric age determinations by the K-Ar method.

This study is concerned with evaluating Evernden and Richards' interpretation of the K-Ar results. Attention is also given to the possibility of identifying the source of the strontium present in the Cooma granite at the time of its formation, and to the effect of metamorphism on the strontium isotope ratios in the

rocks of the metamorphic aureole.

To measure the age and initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ it is necessary to recognise any post-emplacement changes in the distribution of strontium isotopes between minerals. To accomplish this, isotopic ages have been compared with factual time relationships between rocks in the field. For example one may ask whether the indicated age of metasedimentary rocks intruded by granite is greater than that of the granite itself and whether the indicated ages of transgressive pegmatite and foliated-type granite in the Cooma area are younger than their host rocks. The consistency of the ages registered by each mineral species in the Cooma granite has been checked, and compared for agreement with the indicated age of total-rock samples. Lack of such consistency or the contradiction of definite field relationships would positively demonstrate a post-emplacement redistribution of radiogenic strontium.

It is not possible to decide, on the basis of strontium isotope data alone, whether the indicated age and initial content of Sr^{87} of the Cooma granite refer to the formation of the rock or to a complete internal redistribution of isotopes at some later time. This is a fundamental ambiguity in the Rb-Sr method. To overcome this problem the isotopic movement required for such a complete response to metamorphism is determined and the necessary spatial restrictions for the (hypothetical) metamorphism are defined.

GEOLOGY of the COOMA DISTRICT

-  Basalt
-  Syenite
-  Chlorite Zone
-  Biotite Zone
-  Andalusite Zone
-  Cordierite-Orthoclase Zone
-  Migmatite Zone
-  Cooma Granite
-  Murrumbucka tonalite

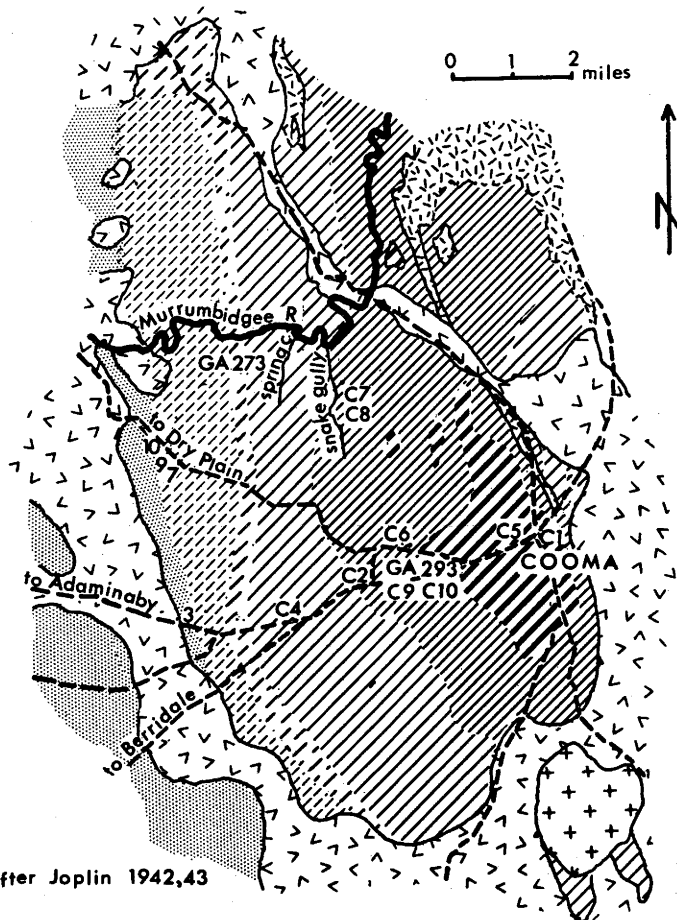
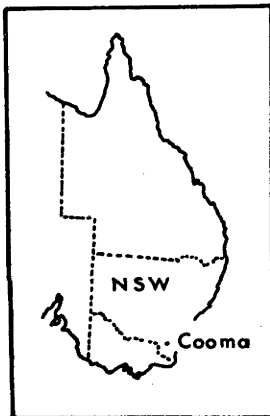


Figure 1

into unmetamorphosed sediments. The high grade zones contain isolated patches of Cooma granite. A similar metamorphic sequence occurs to the east (Joplin, 1943) but here the zones are much narrower and are mainly covered by a veneer of Tertiary basalt.

The granite itself consists of biotite, feldspar, quartz and muscovite and other less abundant minerals such as sillimanite, cordierite and andalusite. It contains numerous micaceous xenoliths, often showing a preferred orientation, and includes large basic bodies of amphibolite (Joplin, 1939). Gneissic foliation, although strongly developed in a few outcrops, is generally weak to absent. Pegmatites and granite dykes transgress the main body of granite and the high grade metamorphic zones. A phase of the Murrumbidgee Batholith, the Murrumbucka Tonalite (Snelling, 1960), also transgresses the granite (Joplin, 1943).

Joplin (1942) separated the metasedimentary rocks into zones on the basis of diagnostic minerals and assemblages. The zone farthest from the granite has been termed the chlorite zone. The rocks are psammites, pelites and possibly tuffaceous rocks and the sequence is known as the Binjura Beds. Joplin (1942) considered that the metamorphism of the Binjura Beds to greenschist facies in the chlorite zone slightly predates the main metamorphism associated with the Cooma granite. The western boundary of the chlorite zone appears to correspond to the contact of the Binjura Beds with a

chemically different series of unmetamorphosed sediments, the Coolringdon Beds (Joplin, 1942). The Coolringdon Beds contain Ordovician graptolites, but the age relationships of these to the Binjura Beds has not been definitely established. Browne (1943) considered the Binjura Beds to be younger than the Coolringdon Beds whereas Joplin (1943) suggests that they are older.

Towards the granite, the chlorite zone gives way to the biotite zone and at approximately three miles west of the granite to the andalusite zone. Half a mile closer this merges into the cordierite orthoclase zone (permeation zone of Joplin) which is the zone closest to the granite in which the Binjura Beds sediments can still be recognised. A strong contrast in fabric exists between the low grade schists and the high grade zones. Towards the inner boundary of the cordierite orthoclase zone occur ptigmatic veins of granitic material described as lit-par-lit injections (Browne, 1914 p.176; Joplin, 1942). The increased development of this "lit-par-lit" material marks the beginning of the migmatite zone (injection zone of Joplin). This zone merges into the Cooma granite in such a way that definite contacts can rarely be observed.

Chemical analyses of rocks from the metamorphic zones (Joplin, 1942) indicate that the major chemical constituents have not been appreciably redistributed during the metamorphism from the chloritised sediment to the cordierite orthoclase zone.

Browne (1914, 1929) considered the Cooma Gneiss (the Cooma granite) and the "mottled gneiss" (a unit of the high grade metamorphic zones) to be two separate intrusive phases contaminated by the incorporation of sedimentary fragments. Briefly, the "mottled gneiss" is an andalusite-cordierite-mica assemblage reverting to an andalusite-orthoclase-biotite assemblage and the mottled effect is due to the presence of residual micaceous patches which are dark in hand specimen.

Joplin (1942, p.180) showed that the so called "mottled gneiss" was originally a sedimentary rock and proposed (1947) on chemical evidence that the Cooma granite could have originated from the mixing of the psammo-pelitic sediments, the most abundant in the area, and an aplitic magma phase similar to analysed specimen C6. Vallance (1960) working on remarkably similar granitic bodies at Wantabadgery showed that biotites of both the granite and surrounding high grade meta-sediments have a similar composition. This strengthened the possibility of a largely sedimentary origin for the granite. Stacey, Joplin and Lindsay (1960) considered that the lit-par-lit type veins of the migmatite zone could be the result of segregation of the low melting point fraction into bands giving the impression of a multiple intrusion.

Joplin (1962) considers that although much differential melting of sedimentary rocks has occurred, some granitic material

has been added to a partially melted and mobilised psammo-pelitic sequence. This granitic material, however, may be differentially melted sediments from lower in the sequence.

C. EXPERIMENTAL RESULTS.

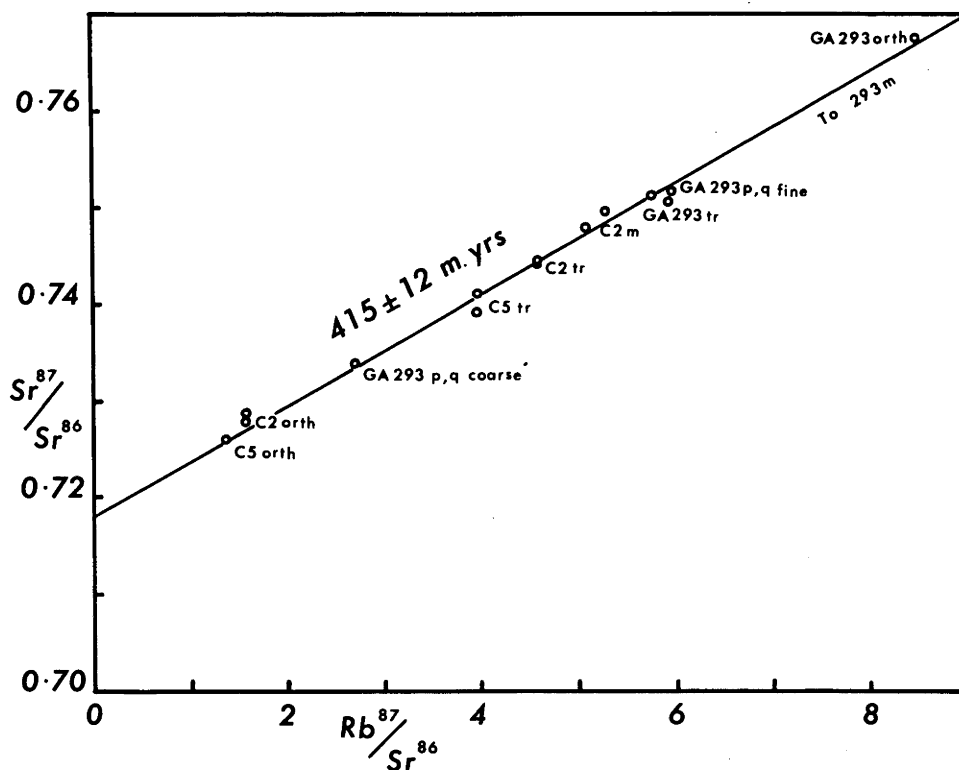
1. The Cooma granite.

Two specimens of the granite proper were analysed in detail. The first, specimen C2, was from an isolated outcrop of granite in the cordierite-orthoclase zone, and the second, C5, from the main body in Cooma. The Rb/Sr ratio in other specimens from the main body were measured by X-ray fluorescence but the values found did not significantly extend the range covered by C2 and C5. A third specimen, GA293, is from an andalusite-bearing granite dyke transgressing the migmatite zone. GA293 can be genetically related to the Cooma granite on chemical and petrological evidence. It was also analysed in detail, and Appendix 3 gives its modal analysis and the distribution of rubidium and strontium between the mineral phases.

The combined data are given in Table 6 and the ratios $\text{Rb}^{87}/\text{Sr}^{86}$ against $\text{Sr}^{87}/\text{Sr}^{86}$ are plotted in Fig. 2. (The biotite data have been omitted from this figure for reasons which will be given later.) Because the mineral concentrates and total-rock samples shown are genetically related, each may be expected to share a common initial value for the ratio $\text{Sr}^{87}/\text{Sr}^{86}$ as well as a common

TABLE 6. Rb-Sr isotopic analyses of the Cooma granite samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>Cooma granite C2</u>						
Total-rock	0.6006	0.1311	4.581	8.337		0.7438
	0.6004	0.1309	4.587		0.7444	
Orthoclase	0.7922	0.5009	1.582	8.341		0.7286
	0.7823	0.4960	1.577	8.345		0.7278
	0.7847	0.5422		8.373		0.7290
Muscovite	0.3918	0.0773	5.069		0.7479	
	0.3814	0.0726	5.253		0.7492	
Biotite	2.009	0.0121	166.4		1.6760	
	1.938	0.0114	170.3		1.7135	
<u>Cooma granite C5</u>						
Total-rock	0.5763	0.1454	3.964	8.315	0.7363	0.7411
	0.5779	0.1466	3.942	8.330		0.7389
Orthoclase	0.6860	0.4983	1.377	8.340		0.7260
Biotite	2.125	0.00755	281.4		2.279	
	2.134	0.00741	288.0		2.304	
<u>Granite dyke GA293.</u>						
Total-rock	0.5853	0.1018	5.750	8.321		0.7509
	0.5890	0.0994	5.926	8.317		0.7502
Orthoclase	1.455	0.1722	8.447		0.7674	
Biotite	3.078	0.00618	498.0		3.624	
	3.084	0.00621	496.6		3.582	
Muscovite	1.075	0.4032	26.66		0.8725	
<u>Plagioclase + quartz</u>						
coarse fraction						
	0.2315	0.0865	2.677		0.7338	
fine fraction						
	0.6560	0.1043	6.165		0.7516	



(Fig. 2) Isochron plot of the Cooma granite total-rock and mineral samples excluding biotite.
t.r. - total-rock, orth. - orthoclase,
m. - muscovite, p,q. - plagioclase and quartz mixture.

age. Thus, the linear array of data-points in Fig. 2 can be interpreted as an isochron*. The indicated age at the 95 percent confidence level is between 428 m.y. and 402 m.y., with initial $\text{Sr}^{87}/\text{Sr}^{86}$ between 0.7184 and 0.7174. Other interpretations of the linear correlation in Fig. 2 will be discussed later.

2. The migmatite zone.

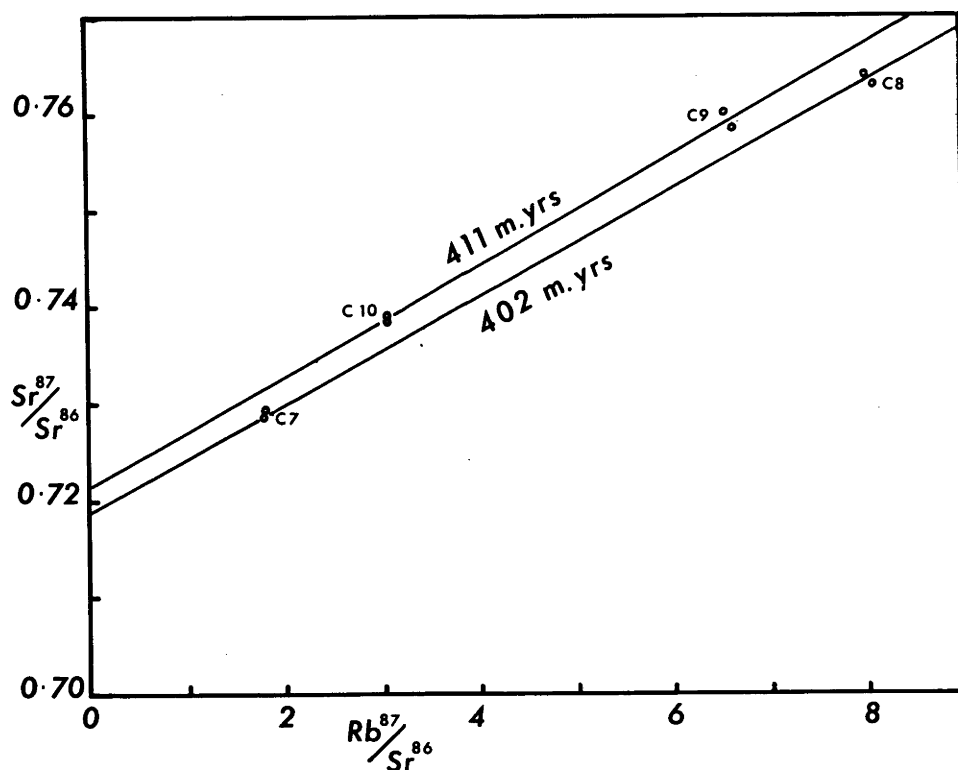
Four total-rock samples from this zone were analysed. These were specimens of adjacent biotite-rich and feldspathic bands or "lits" in the migmatite from two separate areas (Table 7).

The lines in Fig. 3 joining the data-points for these samples may be interpreted as isochrons which date the generation of the bands provided that the migmatite formed by metamorphic segregation or differential melting and the strontium of the original sediments became isotopically homogeneous on a local scale during this process. Such an origin for the migmatite at Cooma has been proposed by Stacey, Joplin and Lindsay (1960).

* An isochron is a straight line, drawn on a $\text{Rb}^{87}/\text{Sr}^{86}$ versus $\text{Sr}^{87}/\text{Sr}^{86}$ plot, on which lie all rock and mineral data points having the same age and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio. The age is given by the slope of the line, and the initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$, by the intercept of the line on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis.

TABLE 7. Rb-Sr isotopic analyses of the migmatite zone samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
Feldspar-rich						
band, C7	0.4271	0.2405	1.776	8.352	0.7291	0.7285
	0.4295	0.2374	1.809		0.7293	
Biotite-rich						
band, C8	0.8318	0.1042	7.980	8.327	0.7638	0.7639
	0.8316	0.1025	8.095		0.7629	
Feldspar-rich						
band, C10	0.6832	0.2248	3.039	8.340	0.7394	0.7390
	0.6748	0.2191	3.080	8.329	0.7361	0.7385
Biotite-rich						
band, C9	0.7695	0.1159	6.639		0.7582	
	0.7749	0.1183	6.552	8.344	0.7599	0.7600



(Fig. 3) Isochron plot of the migmatite total-rock samples. C7 and C8 and C9 and C10 are two pairs of adjacent acid and basic bands or lits. C7 and C10 are the acid bands.

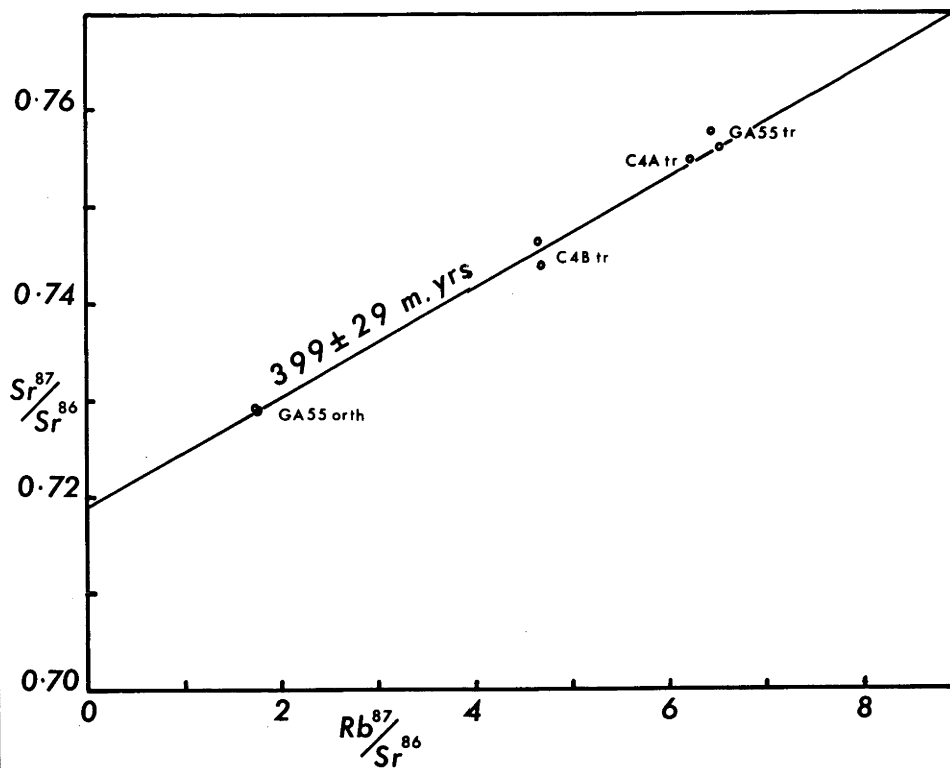
The two isochrons in Fig. 3 have identical ages, equal to that of the Cooma granite to within experimental error. The values for initial $\text{Sr}^{87}/\text{Sr}^{86}$ are both high, with a small but significant difference presumably due to differences in $\text{Sr}^{87}/\text{Sr}^{86}$ in the original sediments. The mean value is close to that in the Cooma granite itself, which together with the equality in indicated age, suggests the existence of some genetic relationship between the granite and the migmatite.

3. The cordierite-orthoclase zone (permeation zone, Joplin).

Three specimens were analysed (Table 8) from this zone. These were GA55, a sample of the "mottled gneiss" (Browne 1914, Joplin 1942) prepared from a 120lb. crushing; C4A, representative of the relict psammitic bands in the metasediments and C4B, representative of relict pelitic material. The analytical data are plotted in Fig. 4, excepting that of the biotite, and the linear relationship of points can be interpreted as an isochron if homogenisation of the Sr isotopes occurred during the isochemical recrystallization of the sedimentary rocks which formed the cordierite-orthoclase zone. As in the case of the migmatite components, the indicated age which this interpretation allows is identical within experimental error with that of the Cooma granite, and the initial $\text{Sr}^{87}/\text{Sr}^{86}$ is likewise very similar. The 95 percent confidence interval for the age is 428 m.y. to 370 m.y., and for the

TABLE 8. Rb-Sr isotopic analyses of the cordierite-orthoclase zone samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>Mottled Gneiss GA55.</u>						
Total-rock	0.8620	0.1321	6.525		0.7560	
	0.8930	0.1231	7.254		0.7565	
	0.8622	0.1336	6.470	8.320	0.7574	0.7539
Orthoclase	0.8070	0.470	1.717	8.318		0.7288
	0.8031	0.4660	1.723	8.343		0.7289
Biotite	2.299	0.00631	364.3		2.779	
	2.184	0.00958	228.1		2.028	
	1.850	0.01039	178.1		1.902	
<u>Mottled Gneiss C4.</u>						
"shaly band"						
Total-rock, C4B.						
	0.8106	0.1728	4.691	8.320	0.7472	0.7439
	0.8092	0.1738	4.658	8.331	0.7445	0.7462
"sandy band"						
Total-rock, C4A						
	0.6875	0.1106	6.218	8.310	0.7495	0.7547
	0.6860					



(Fig. 4) Isochron plot of the cordierite-orthoclase zone total-rock and mineral samples excluding biotite.
t.r. - total-rock, orth. - orthoclase.

initial $\text{Sr}^{87}/\text{Sr}^{86}$ 0.7213 to 0.7172.

4. The chlorite and biotite zones.

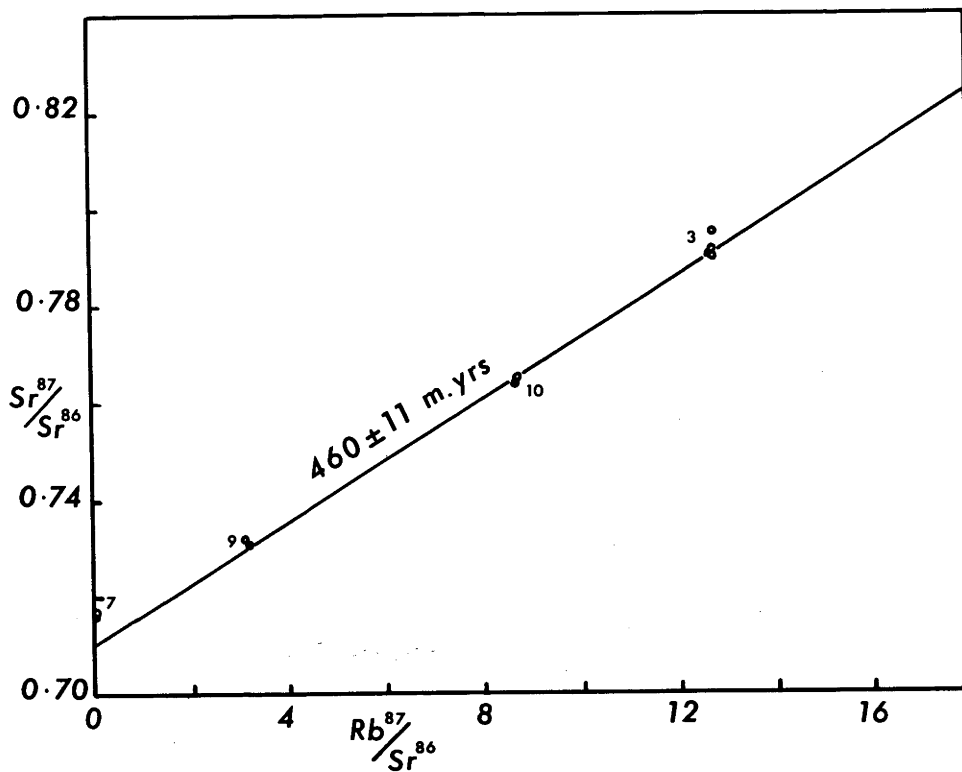
The analyses of total-rock samples of three biotite-muscovite schists and a quartz-epidote rock from the Binjura Beds have been reported earlier (Compston and Pidgeon, 1962). These data are reproduced in Table 9 and Fig. 5, together with a further analysis of specimen 3 and with the present-day $\text{Sr}^{87}/\text{Sr}^{86}$ values for all samples normalised to a constant value for $\text{Sr}^{88}/\text{Sr}^{86}$ (8.340) to correct for mass spectrometer effects. The (apparent) isochron for the schists now corresponds to an age of 460 m.y. with 95 percent confidence interval of ± 11 m.y. It is thus significantly older than the indicated age of the Cooma granite. The indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ of the schists, 0.710 ± 0.002 , is significantly lower than that of the granite, whereas that of the quartz epidote rock is similar.

5. Amphibolite and associated pegmatite.

Analyses were made of a pyroxene-amphibolite, specimen C1, which is included in the Cooma granite as a large xenolithic mass some hundreds of feet wide, and also orthoclase from a pegmatite-vein which transgresses this mass and the adjacent "basified" granite (Table 10). An analysis of Tertiary basalt from the Cooma region is given for comparison.

TABLE 9. Rb-Sr isotopic analyses of the Binjura Bed schist samples.

Specimen	$\mu\text{moles/gm}$	$\mu\text{moles/gm}$	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated Normalised	
	Rb^{87}	Sr^{86}			$\text{Sr}^{87}/\text{Sr}^{86}$	$\text{Sr}^{87}/\text{Sr}^{86}$
Quartz-chlorite-						
muscovite	0.6080	0.0481	12.64	8.305	0.7900	0.7908
schist, 3.	0.6093	0.0482	12.64	8.317	0.7845	0.7897
	0.6070	0.0477	12.72	8.331	0.7936	0.7900
	0.6081	0.0481	12.63	8.324	0.7990	0.7955
	0.6095	0.0486			0.7900	
Quartz-biotite-						
schist, 9.	0.4937	0.1555	3.175	8.301	0.731	0.7307
	0.5061	0.1617	3.130	8.355		0.7314
Quartz-muscovite-cordierite-						
biotite schist,						
10.	0.5673	0.0658	8.622	8.315	0.7648	0.7638
	0.5768	0.0663	8.700		0.7643	
Quartz-epidote						
rock, 7.	0.0061	0.2377	0.025	8.330	0.7127	0.7160
				8.303		0.7176
				8.300		0.7172



(Fig. 5) Isochron plot of the Binjura Bed schists total-rock samples.

TABLE 10. Rb-Sr isotopic analyses of the amphibolite and associated pegmatite.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>Amphibolite.</u>						
Total-rock,	0.0109	0.2623	0.0416	8.322	0.7043	0.7038
C1.	0.0106	0.2616	0.0405		0.7068	
<u>Tertiary basalt.</u>						
Total-rock,	0.1156	0.9210	0.1255	8.323	0.7020	0.7028
C11.						
<u>Soho St. pegmatite.</u>						
Orthoclase,	1.194	0.3005			0.7274	
GA272	1.150	0.2990			0.7282	

The initial $\text{Sr}^{87}/\text{Sr}^{86}$ for the amphibolite is not distinguishable from that of recent basic igneous rocks, which is consistent with the conclusion of Joplin (1939) that the amphibolite was originally a gabbro or norite. The value for this ratio is approximately 2 percent lower than that of the Cooma granite, thus showing that no significant mixing of strontium isotopes occurred between xenolith and host rock in this instance.

Owing to its low enrichment of Sr^{87} , no age can be obtained for the orthoclase in the later pegmatite without assuming a value for its initial $\text{Sr}^{87}/\text{Sr}^{86}$. If the strontium in the pegmatite was genetically associated with that in the Cooma granite, then the orthoclase data-point should lie on the granite isochron in Fig. 2, indicating that it shared the common value of 0.718 as its initial $\text{Sr}^{87}/\text{Sr}^{86}$. This is not the case. If we assume an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.704, corresponding to the strontium in the amphibolite, the age becomes 440 m.y. with an uncertainty of at least ± 40 m.y. owing to the small enrichment in Sr^{87} .

6. Related intrusive rocks.

Table 11 presents the analytical data for (i) a pegmatite dyke, which transgresses the cordierite-orthoclase zone, (iii) a leucogranite, of unknown structural relationship in the migmatite zone (Joplin, 1942), and (ii) a sample of the Shannon's Flat

Granodiorite, a phase of the Murrumbidgee Batholith. (A separate phase of the batholith, the Murrumbucka Tonalite, transgresses the Cooma granite and its associated metasediments.)

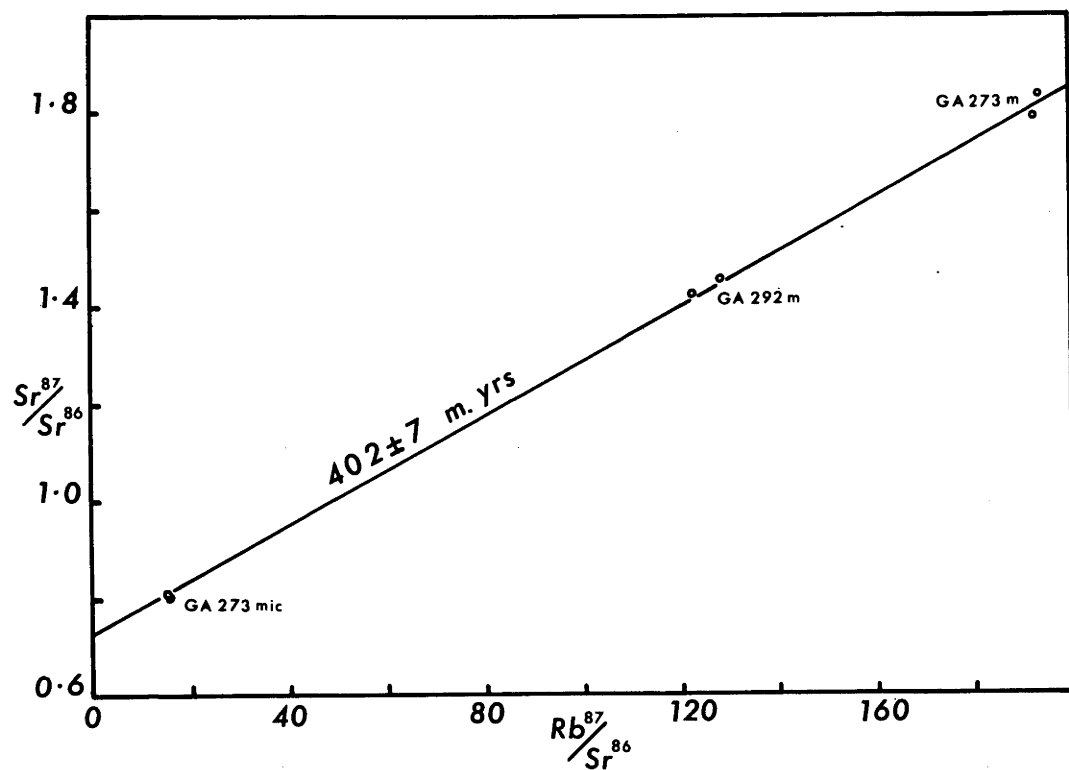
(i) Fig. 6 shows the mineral data for the pegmatite on a plot of $\text{Rb}^{87}/\text{Sr}^{86}$ against $\text{Sr}^{87}/\text{Sr}^{86}$. The indicated age 402 ± 7 m.y., is very close to that of the Cooma granite, and the initial $\text{Sr}^{87}/\text{Sr}^{86}$, 0.724 ± 0.004 , is only slightly greater. As in the case of the components of the migmatite zone, this is consistent with an origin for the pegmatite by metamorphic segregation from pre-existing sedimentary rocks.

(ii) Fig. 7 shows the isochron plot for the Granodiorite, with the data point for the biotite included in this case in the assessment of the least squares line. The indicated age is 417 m.y. The initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio indicated from Fig. 7 is 0.707 some 1.4 percent lower than that of the Cooma granite, which if representative of the whole Granodiorite suggests that the strontium in the two masses has different source material.

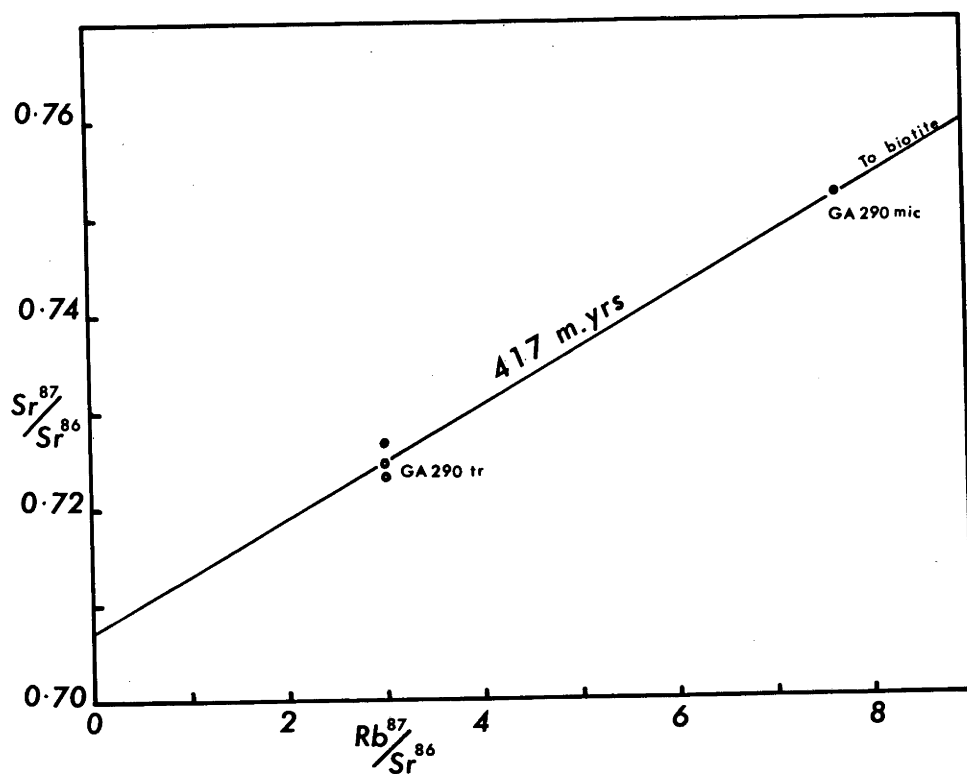
(iii) The total-rock and orthoclase from the leucogranite yield an apparent isochron which has an age of 590 m.y. (Fig. 8). This is significantly greater than the indicated age of the granite and the migmatite, and thereby contradicts the geological evidence if the latter is taken as representing the age of rock emplacement.

TABLE 11. Rb-Sr isotopic analyses of the related intrusive rocks.

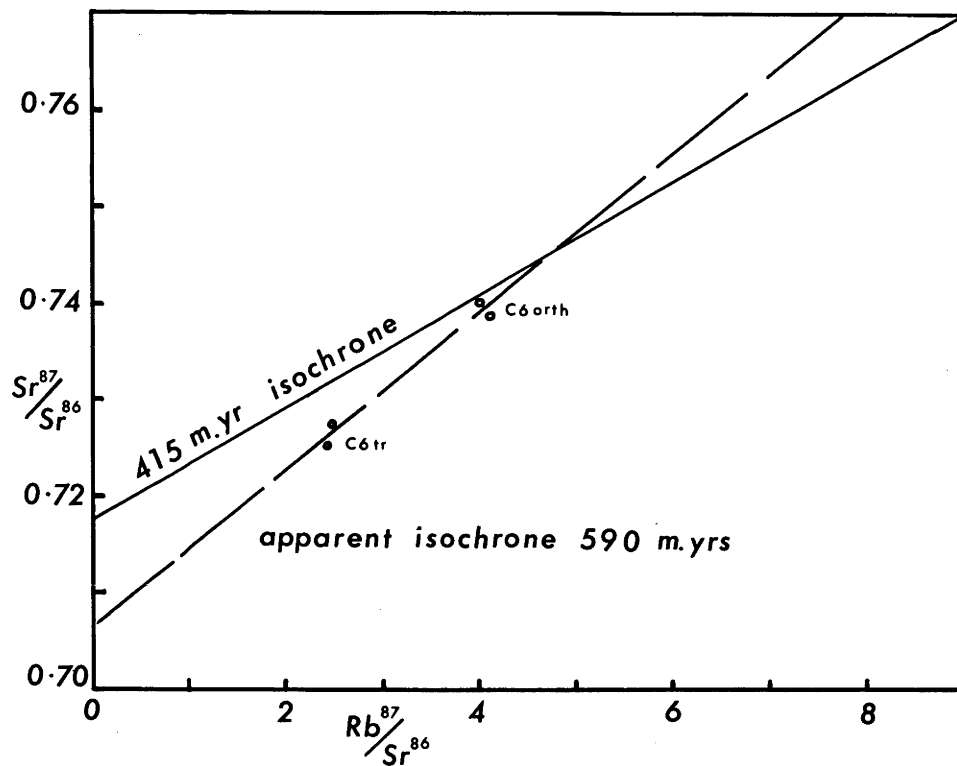
Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>Spring Creek pegmatite, GA273.</u>						
Muscovite	1.7537	0.00905	193.8		1.826	
	1.7633	0.00915	192.6		1.778	
Microcline	1.551	0.1152			0.8010	
	1.536	0.1032	14.88		0.8061	
	1.534	0.1010	15.19		0.8037	
Biotite	4.749	0.0297	160.1		1.297	
	4.706	0.0294	159.8		1.301	
<u>Spring Creek pegmatite, GA292.</u>						
Muscovite	1.658	0.0136	122.0		1.421	
	1.647	0.0129	127.7		1.452	
<u>Leucogranite, C6.</u>						
Total-rock	0.4248	0.1727	2.460	8.311	0.7242	0.7272
	0.4204	0.1735	2.420	8.341	0.7262	0.7250
	0.4201	0.1727	2.432		0.7267	
Orthoclase	1.159			8.330		0.7404
	1.174	0.2936	4.00	8.330		0.7400
	1.160	0.2828	4.10		0.7385	
<u>Murrumbidgee Batholith, GA290.</u>						
Total-rock	0.5555	0.1836	3.025		0.7267	
	0.5555	0.1846	3.009			
	0.5464	0.1816	3.009	8.364	0.7247	0.7221
Microcline	1.207	0.1574	7.669		0.7519	
Biotite	2.623	0.0275	95.38		1.256	



(Fig. 6) Isochron plot of the pegmatite mineral samples excluding biotite.
m. - muscovite, mic. - microcline.



(Fig. 7) Isochron plot of the Shannon's Flat Granodiorite (Murrumbidgee Batholith) total-rock and minerals.
 t.r. - total-rock, mic. - microcline.



(Fig. 8) Isochron plot of the leucogranite total-rock and orthoclase samples.

However the orthoclase alone lies on the Cooma granite isochron. This may be chance, or it may indicate that the orthoclase has preserved its original age but that the total-rock has lost radiogenic Sr. Sericite, with strong preferred orientation, and albite are present and it is possible that this assemblage is the result of a local retrogressive metamorphism, with the recrystallization of original minerals (except the orthoclase) and the loss of radiogenic Sr from the whole rock.

D. THE MICA AGES.

1. Sensitivity to initial $\text{Sr}^{87}/\text{Sr}^{86}$.

Table 12 presents the indicated ages of the biotite and muscovite specimens. The first two columns contain values of the Rb-Sr age for each sample corresponding to the lowest (0.704 as in basic igneous rocks) and the highest (0.720 from the face value interpretation of the isochron diagrams) limiting values for the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio. Except for the last two specimens, the average difference between the ages is only 1.3 percent, comparable with the technical reproducibility of analysis. Thus, the indicated ages of these particular minerals, - the biotites and the pegmatitic muscovites - can be regarded as independent of the choice for initial $\text{Sr}^{87}/\text{Sr}^{86}$. Offset against this advantage is the knowledge that biotite is particularly susceptible to the diffusive loss of radiogenic strontium. No independent means of predicting the

TABLE 12. Biotite and muscovite ages.

	Rb-Sr age (m.y.)		K-Ar age (m.y.)
	$R_i = 0.704$	$R_i = 0.720$	
GA290 Biotite	415	404	404
GA273 Biotite	266 268	259 261	266
GA273 Muscovite	415 399	409 395	361 364
GA292 Muscovite	421 419	412 410	371
GA293 Biotite	420 416	418 413	370
C2 Biotite	426 419	419 412	-
C5 Biotite	396 399	392 394	-
GA239 Biotite	-	-	382
GA55 Biotite	417 409	512 405	-
293 Muscovite	453	410	-
C2 Muscovite	620	401	-

0.704 and 0.720 are taken as limiting values for the initial Sr^{87}/Sr^{86} (R_i).

absence of such loss is known, so that it becomes essential to corroborate any biotite age by measurements on other minerals.

Accurate knowledge of initial $\text{Sr}^{87}/\text{Sr}^{86}$ is evidently needed to obtain a precise age for the muscovites from the Cooma granite specimens, C2 and GA293.

2. Comparison with the K-Ar ages.

Direct comparison with the K-Ar is possible for 3 biotite and 2 muscovite samples, using unpublished data kindly made available by Dr. J.R. Richards. Indirect comparison may be made also between the mean Rb-Sr age for the Cooma granite biotites and the K-Ar age for specimen GA239 measured by Evernden and Richards (1962).

From the data in Table 12, argon has been lost relative to radiogenic Sr in four out of the six cases, in amounts averaging 11 percent. The exact amount of Ar leakage is obscured by possible systematic error in the choice of decay constants. If the Rb-Sr ages are reduced by 6 percent to allow for this possibility, then Ar leakage averages 5 percent for 3 of the 6 comparisons. In specimen GA273, both radiogenic Sr and argon have been lost from the biotite in equal proportions relative to the Rb-Sr age of the cogenetic muscovite. In contrast to the others this particular biotite had been strongly weathered, suggesting that recent weather-

ing is responsible for the 35 percent reduction in its indicated age. (It is noteworthy that the base-exchange effect during weathering proposed by Engel and Kulp (1963) appears to be absent.)

It thus appears that mutual corroboration of the Rb-Sr and K-Ar ages is available only for specimen GA290 and possibly for GA239.

3. Comparison with the field relationships.

The field evidence at Cooma demands that the indicated ages for C2, C5, and GA239 (the granite) should be identical if the biotites are preserving their true ages. In addition, the age for GA293 (transgressive dyke) should be equal to or younger than for GA55 (the host rock), and the latter in turn should be equal to or older than the biotites from the granite. These requirements are only partially met: C5 at 393 m.y. is significantly younger than C2 at 416 m.y., and GA239 (K-Ar) at 382 m.y. is considerably younger. The fact that the Rb-Sr ages of C2, GA293 and GA55 fall within the range 409 to 416 m.y. suggests that the (minimum) age for the granite is 416 m.y., and that the biotite from C5 has experienced some loss in radiogenic Sr. The latter is clearly a local effect.

Field evidence also requires that the micas from GA292 and GA273 (discordant pegmatite) must not be significantly greater

in age than GA55, and the age of GA290 (Murrumbidgee Batholith) should not be greater than GA55, C2, C5 and GA239. Except for C5, this requirement is met by the Rb-Sr ages, but GA290 shows the highest K-Ar age, which testifies again to the argon leakage in GA292, GA273 and GA239.

We conclude that except for C5, the Rb-Sr mica ages do not contradict the field relationships.

Comparison of biotite with feldspar and total-rock ages.

If biotites were included in the previous isochron diagrams (Figs 2 to 4) they would almost completely control the isochron-gradients. This is due to the very great values of $\text{Rb}^{87}/\text{Sr}^{86}$ in the biotites in comparison with those of the total-rock and feldspar samples. Consequently the two groups of samples have been assessed separately in order to obtain an independent measure of age based on the properties of feldspar and total-rock.

Excellent agreement is obtained on comparing a biotite age of the Cooma granite of 418 ± 4 m.y. (from Table 12) with the interpretation of the linear plot on Fig. 2 as an isochron. Similarly, the biotite age for the cordierite-orthoclase zone agrees with the interpretation of the linear plot on Fig. 4 as an isochron. These findings strongly suggest that the total-rock, feldspar and mica samples of all measured rocks are each registering the same isotopic event. This event may be the original formation

of the granite and metamorphic zones or it may be some later metamorphism.

CHAPTER IV.

THE INTERPRETATION OF THEEXPERIMENTAL RESULTS.

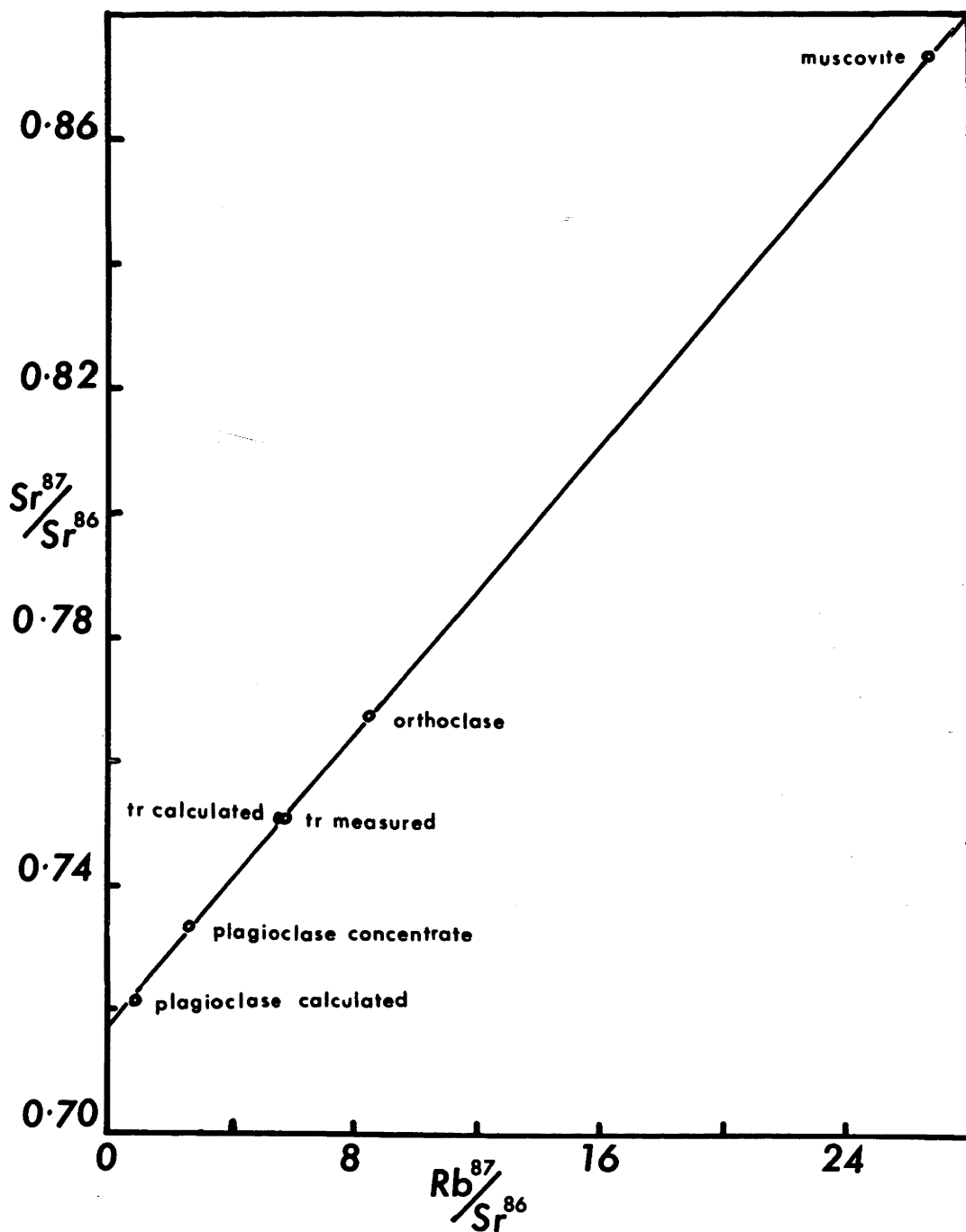
A. ALTERNATIVE INTERPRETATION OF THE ISOCHRON DIAGRAM.

Figures 2 to 4 have been tacitly interpreted as isochrons dating the generation of the granite and its associated zones of high grade metamorphism. In this chapter it is intended to examine the possibility that these isochrons refer to the rearrangement of isotopes at some time significantly later than the granite's generation. In so doing the movement of strontium isotopes necessary to explain the experimental observations is detailed and finally a discussion of the age of the granite is presented.

To test the data for explanations alternative to that of an isochron consider first GA293. Dr. W. Compston carried out a material balance on GA293 assisted, in the mineral separation, by R. Rudowski and H. Berry and, in the assessment of the percentage composition of the light fractions, by myself.

1. Material balance of GA293.

In this section is examined the extent to which the alignment of data-points in Fig. 9 might be a necessary consequence of the particular distribution of Rb and Sr in this sample.



(Fig. 9) Isochron plot of the micro-granite dyke total-rock and mineral samples.

Pidgeon and Compston (1965) Appendix 2 shows that 93 percent of the rubidium and $99\frac{1}{2}$ percent of the common strontium in specimen GA293 is situated in the orthoclase and plagioclase. Thus in Fig. 9 the data-point for the total-rock must lie on or very close to the plagioclase-orthoclase line because the total-rock is effectively a diluted mixture of the two feldspars as regards Rb and Sr. A shift above or below this line would be produced by a large excess or depletion of radiogenic Sr in the quartz fraction or in a minor mineral phase. However this possibility is denied by the direct analysis of an independent sample TR2 of the total-rock GA293 (Fig. 9), which was adjacent in the dyke to the sample totally split into mineral concentrates. Its data-point lies on the line and also very close to the point for the calculated total-rock sample, showing that effectively all the rubidium, common strontium and radiogenic strontium have been accounted for by the amounts measured in the two feldspars and the two micas. It follows that the "isochron" defined by the plagioclase, total-rock and orthoclase points alone could be a trivial consequence of material balance. Thus, if no other Rb-bearing phase had been measured, there could be no case whatever for a unique interpretation of Fig. 9 as an isochron.

On the other hand, the coincidence of the muscovite and biotite data points on the extrapolated plagioclase-orthoclase line

cannot be interpreted as the result of material balance. Both of these mica samples were pure minerals, both are very minor in their contribution of Rb and Sr to the total-rock, and the biotite has the highest value for Rb/Sr of all the minerals analysed.

2. Ambiguity of the isochron interpretation.

The previous section shows that the occurrence of the muscovite and biotite data-points on the extended plagioclase-orthoclase line is the essential property in Fig. 9 by which it obtains geological significance. The particularly strong linear correlation immediately suggests interpretation as an isochron, with the implication that each mineral shared a uniform value for $\text{Sr}^{87}/\text{Sr}^{86}$ at the time corresponding to the isochron age.

The value for this uniform $\text{Sr}^{87}/\text{Sr}^{86}$ given by Fig. 9, 0.718, is unusually high. If the isochron age is taken to refer to the original cooling of the rock, the high value for initial $\text{Sr}^{87}/\text{Sr}^{86}$ shows that an appreciable amount of radiogenic Sr was inherited during its generation. Alternatively, the high "initial" $\text{Sr}^{87}/\text{Sr}^{86}$ may indicate that internal rearrangement of radiogenic Sr between minerals has occurred at some time later, presumably during a second younger metamorphism, so that the values for age and uniform $\text{Sr}^{87}/\text{Sr}^{86}$ deduced from Fig. 9 would refer to this younger metamorphic period. If this is the case, then the observed uniform $\text{Sr}^{87}/\text{Sr}^{86}$ immediately indicates one possible mechanism for

the proposed internal rearrangement. This is the complete mixing of radiogenic with common Sr throughout the rock, so that the same fractional excess in Sr^{87} occurs in each mineral by the end of metamorphism regardless of its concentration of common Sr. Movement of common Sr is implied by this mechanism, and movement of Rb would also be expected.

The degree of metamorphism required for such mixing of trace elements has not yet been established. It would probably occur if the rock is totally recrystallized, but if it has occurred in specimen GA293 it must take place without mineralogical change, according to the petrographic evidence (Appendix 1).

3. Selective movement of radiogenic Sr relative to common Sr.

Many observations, for example those of Hart (1964) and Allsopp et. al. (1962), suggest that radiogenic Sr in some minerals may be less strongly held than common Sr. It is thus possible that radiogenic Sr may be redistributed between minerals during an extremely weak metamorphism which is not easily detected by petrographic evidence. In this section, we examine the possibility that the linear correlation in Fig. 9 might be produced by redistribution of radiogenic Sr only, with no movement of the original common Sr.

Many instances are now known in which total-rock samples of granitic bodies have remained chemically closed with respect to

Rb and Sr during low-grade metamorphism. Making this assumption for sample GA293, it would be necessary to redistribute the radiogenic Sr produced in the total-rock during the time interval between its (unknown) age of emplacement and the (unknown) age of later metamorphism amongst its various constituent minerals.

To consider any two phases, for example muscovite and plagioclase, the equilibrium distribution of Sr at a temperature T will have the general form in an ideal system:

$$\frac{(\text{Sr})_{\text{plagioclase}}}{(\text{Sr})_{\text{muscovite}}} = e^{\Delta G^{\circ}/RT}$$

where ΔG° is the difference between the standard free energy of Sr in the muscovite and in the plagioclase and the bracketed terms represent concentrations. This expression applies both to the common Sr during the original crystallization and to the radiogenic Sr during the subsequent low temperature redistribution being considered. However, owing to the reduction in T (evident by the lack of mineralogical change), the ratio (common Sr^{87}) plagioclase/(common Sr^{87}) muscovite will be much less than the ratio (radiogenic Sr^{87}) plagioclase/(radiogenic Sr^{87}) muscovite. This indicates that the value for total $\text{Sr}^{87}/\text{Sr}^{86}$ in the plagioclase at the close of metamorphism will differ from that of the muscovite, and by a similar argument, from that of other co-existing minerals. This prediction is thus quite contrary to the implication of a uniform value for $\text{Sr}^{87}/\text{Sr}^{86}$ for all the minerals, which follows from the isochron interpretation of Fig. 9.

The question now arises whether the line in Fig. 9 does in fact represent an isochron. Dr. W. Compston has shown (pers. comm. 1964) that it is possible to get a straight line relationship of data-points where the slope does not correspond to the time of metamorphism which produces the isotope rearrangement. It may be shown that if R_e , θ_e represent the intercept and gradient of this line (which is now stripped of any direct geological meaning), and θ_m the gradient of an isochron equivalent in age to the hypothetical metamorphism, then the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio R_j for any mineral (j) at the close of metamorphism must have the value

$$R = R_e + (\theta_e - \theta_m) \left(\frac{\text{Rb}^{87}}{\text{Sr}^{86}} \right)_j$$

Thus, the various minerals need not have a uniform value for $\text{Sr}^{87}/\text{Sr}^{86}$ after the metamorphism to explain the linear correlation, but instead they would have values which are related very specifically to their particular contents of rubidium and common Sr.

No mechanism for linking the proposed redistribution of radiogenic Sr between minerals with their ratios of $\text{Rb}^{87}/\text{Sr}^{86}$ can be seen, nor is there any obvious reason why R_e and θ_e should in general be the same for different rock samples. For example, the data for sample C2, which has a completely different modal analysis to GA293 and different value for $\text{Rb}^{87}/\text{Sr}^{86}$, show exactly the same values for the isochron intercept and gradient. Thus, it appears that selective

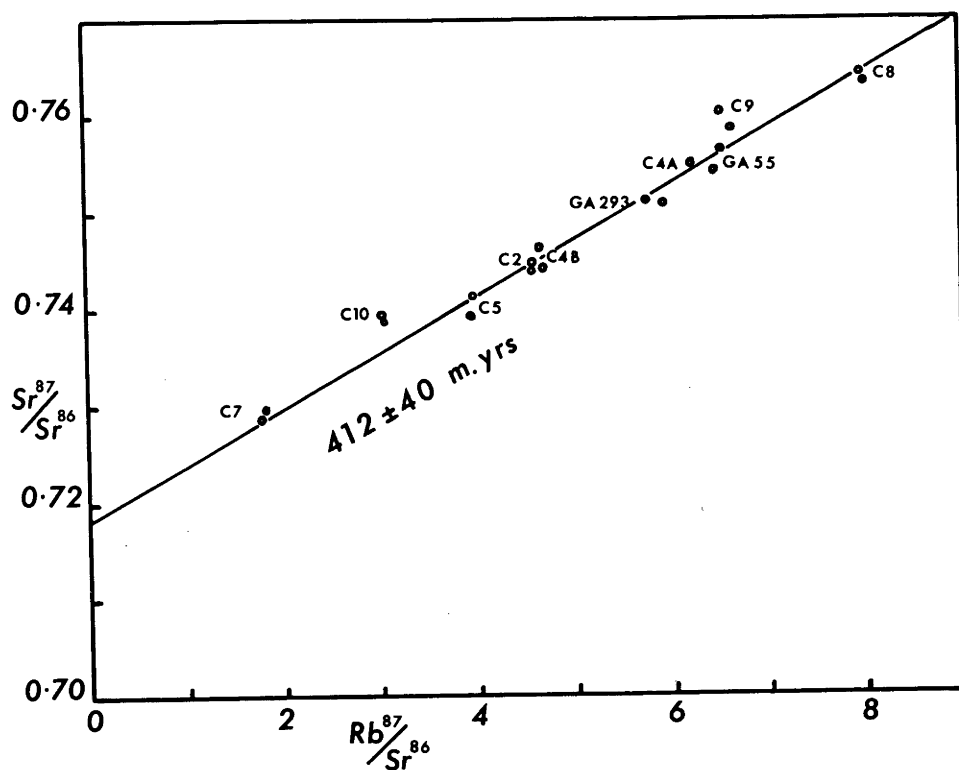
redistribution of radiogenic Sr alone cannot account for the experimental observations thereby discounting the possibility that an extremely weak metamorphism might have produced the various isochrons by moving lightly-held radiogenic Sr.

4. Total-rock isochron produced by later metamorphism.

The equality in age indicated by the separate isochrons of the Cooma granite, the migmatite zone, the cordierite-orthoclase zone and the later pegmatite has already been discussed. In addition, the values for initial $\text{Sr}^{87}/\text{Sr}^{86}$ for these groups are similar, although small differences evidently exist from place to place. Thus it is predictable that the data-points of the total-rock samples will show a good linear correlation when plotted together on an isochron diagram. This is shown in Fig. 10.*

The high and approximately uniform value for initial $\text{Sr}^{87}/\text{Sr}^{86}$ may be the result of original inheritance of radiogenic Sr or else its later internal rearrangement between total-rock samples. Following the previous discussion, it appears that the

* The parameters in Fig. 10, age 412 ± 40 m.y., and intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.718 ± 0.001 are not strictly valid as they have been calculated by least squares without taking into account the known variation in the initial $\text{Sr}^{87}/\text{Sr}^{86}$, as for example between the migmatite pairs.



(Fig. 10) Isochron plot of the combined total-rock samples from the Cooma granite and high-grade metamorphic zones.

necessary movement of radiogenic Sr for the later-metamorphism hypothesis is one of extensive mixing with common Sr on a regional scale, to produce the near-uniform $\text{Sr}^{87}/\text{Sr}^{86}$ throughout the granite and its high-grade metamorphic surroundings.

There are only minor occurrences of retrograde mineral assemblages in the high-grade metamorphic assemblages. These may be late stage products of the original event, or the result of later localised deformation. Thus, if the isochron in Fig. 10 is the result of a metamorphism later than the high-grade event, this hypothetical metamorphism has had no overall effect on the mineralogy. This lack of mineralogical evidence is incompatible with the large scale mixing of Sr isotopes required to produce the isochron.

The chlorite and biotite zone metasediments register an older isotopic event and a lower initial $\text{Sr}^{87}/\text{Sr}^{86}$ than the Cooma granite (Fig. 5). They have been therefore unaffected by the extensive mixing of isotopes inferred from the isochron for the higher grade rocks. This older event may be the original age of deposition (c.f. Compston and Pidgeon, 1962) or the age of a regional metamorphism described by Joplin (1942) as preceding the high-grade mineral assemblage. It would be reasonable in either case to associate the extensive isotopic mixing with the occurrence of the high-grade metamorphism itself.

In contrast to this picture, if we choose to associate

the production of the high uniform $\text{Sr}^{87}/\text{Sr}^{86}$ in the granite and high-grade metasediments with the (hypothetical) later metamorphism, then the boundaries of the latter appear to coincide with the boundaries of the high-grade event. This seems highly unlikely. Moreover, it would mean that all isotopic record of the high-grade metamorphism had been lost, unless we interpret the isotopic event in the low-grade zones as due to this rather than the regional event preceding the high-grade metamorphism.

B. TOTAL-ROCK ISOCHRON ASSOCIATED WITH GRANITE FORMATION.

In the previous section, it has been shown how the interpretation of the linear correlation in Fig. 10 as the product of a metamorphism later than the high-grade event leads to inconsistencies with the geological evidence. In this section are considered the consequences of the simplest interpretation of the data, namely, that the line in Fig. 10 is an isochron which dates the formation of the high-grade metasediments and the Cooma granite.

1. Inheritance of radiogenic Sr.

Interpretation of the separate isochrons for the Cooma granite, migmatite zone and cordierite-orthoclase zone samples on the products of their first formation leads to the following observations

(a) The inheritance of appreciable amounts of radiogenic Sr in the

granite proper and in the related microgranite dyke must be invoked to explain the high initial $\text{Sr}^{87}/\text{Sr}^{86}$.

- (b) Within experimental error, the primary $\text{Sr}^{87}/\text{Sr}^{86}$ values for these bodies are identical.
- (c) The primary $\text{Sr}^{87}/\text{Sr}^{86}$ ratio in the granite is close to that in the high-grade metasediments at the time of granite emplacement.

From the above it is inferred that almost complete mixing and exchange of the Sr isotopes occurred between the (igneous) Cooma granite and the surrounding metasediments during the period of its formation. As regards the mechanism of this process, the simplest possibility would be the generation of the granite itself by melting of the local metasediments more or less in situ. Such an origin would minimise the need for diffusive transport of Sr and also allow for the clear instances of non-mixing of isotopes in the case of the large amphibolite xenoliths.

Alternatively, if the granite was generated elsewhere, it has evidently lost any detectable record of the strontium from its original source, unless this (hypothetical) source chanced to have a similar value for $\text{Sr}^{87}/\text{Sr}^{86}$ as the Cooma metasediments at the time of generation. Such a loss of record must be produced by dilution of the original strontium in the granite by that of the surrounding metasediments, perhaps through the assimilation of sedimentary xenoliths having a high content of radiogenic Sr.

2. Suitability of the Binjura Beds as a source of the granite.

If local anatexis was responsible for the generation of the Cooma granite, the values for age and Rb/Sr ratio in the pre-existing sediments at the time of their proposed fusion must be mutually compatible with the production of the observed primary value of $\text{Sr}^{87}/\text{Sr}^{86}$ in the granite. Strictly speaking it is now impossible to sample these pre-existing sediments since, by hypothesis, they have been transformed. However the granite itself or else the surrounding metasediments may be taken as approximations to the sediments.

The Rb/Sr ratio of the granite is probably about 1.7, ranging up to 2.0 in GA293, and down to 1.3 in C5. If this were the ratio in the pre-existing sediments, then the extrapolation back in time from $\text{Sr}^{87}/\text{Sr}^{86}$ equal to 0.718 at 420 m.y. ago to the lowest reasonable value for $\text{Sr}^{87}/\text{Sr}^{86}$, 0.704, gives an age of the sediments of about 620 m.y. This would be a maximum age since the sediments may well have been deposited with a higher value for initial $\text{Sr}^{87}/\text{Sr}^{86}$. The result, an early Cambrian age, is too old for the local sediments, although it would be consistent with the age expected for the basal sediments in the Tasman Geosyncline. An objection to this estimate is the probability that Rb has been chemically fractionated from Sr during the melting process, together with the possibility that radiogenic Sr may be concentrated in the

melt. Furthermore the implied Rb/Sr ratio of the basal beds of the geosyncline is unexpectedly high.

The cordierite-orthoclase zone samples have a higher mean value for Rb/Sr, about 2.2, if the specimen GA55 is taken as representative. This leads to a lower estimate for the maximum age, 550 m.y., which would be reasonably consistent with the geological evidence.

The low-grade metasediments show a wide range of Rb/Sr. Taking their uniform $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.710 at 450 m.y. (Fig. 5), the time necessary to increase the value to the primary value of 0.718 in the granite ranges from 50 to 150 m.y. Thus those members of the Binjura Beds having the higher Rb/Sr values are suitable source material for the strontium in the Cooma granite.

In summary it appears that suitable source material for the Cooma granite is present in its local sedimentary environment. It is thus unnecessary, using the theory of anatectic melting for the origin of the granite, to propose any more distant source than this as far as the Sr isotope evidence is concerned.

C. SUMMARY AND CONCLUSIONS.

The Cooma granite is situated at the centre of concentric zones of progressively decreasing metamorphism similar to Miyashiro's (1961) sillimanite-andalusite type.

Rb-Sr measurements on total-rock and mineral samples are

highly correlated when plotted on an isochron diagram. The gradient of this (apparent) isochron gives an age identical with the maximum age of co-existing biotites, but the (apparent) initial value for $\text{Sr}^{87}/\text{Sr}^{86}$ is unusually high. The latter signifies either the inheritance of radiogenic Sr at the time of formation, or else the occurrence of a rearrangement of radiogenic Sr within the granite after its formation.

Measurements on similar samples from the high-grade metasediments which surround the granite are likewise well correlated. Their apparent ages are identical with that of the granite but a small but real variation exists in the apparent initial $\text{Sr}^{87}/\text{Sr}^{86}$. The average value for initial $\text{Sr}^{87}/\text{Sr}^{86}$ is very close to that of the granite, signifying either inheritance or later rearrangement of radiogenic Sr. In contrast to this, the more distant biotite and greenschist facies metasediments have a significantly greater value for the apparent age and a lower initial $\text{Sr}^{87}/\text{Sr}^{86}$.

Two models for the movement of radiogenic Sr during a possible later rearrangement are considered in detail. The high degree of linear correlation in the isochron-diagrams indicates that an extensive mixing process is required on a regional scale. This must produce a nearly-uniform value for $\text{Sr}^{87}/\text{Sr}^{86}$ in the granite and in the high-grade zones regardless of local variations in the concentration of common Sr.

There are certain difficulties in this interpretation.

Despite the extensive mixing of isotopes proposed, no mineralogical evidence for extensive metamorphism later than the high-grade event is present, and there is none of the inconsistency between the maximum biotite ages and observed field relationships which we expect a later metamorphism to produce. Furthermore, the preservation of an older isotopic age by the greenschist facies rocks shows that the hypothetical later metamorphism must be restricted by chance to within the areal boundaries of the Cooma granite and its associated high-grade metamorphism.

For these reasons, an extensive metamorphism at Cooma later than the high-grade event seems unlikely, and therefore the high value for initial $\text{Sr}^{87}/\text{Sr}^{86}$ in the granite must be an original feature. The granite then is an example of an igneous rock bearing radiogenic Sr inherited from its source material during generation or from the assimilation of crustal xenoliths during emplacement.

The age and Sr/Rb ratios of the adjacent metasedimentary rocks yield a range in $\text{Sr}^{87}/\text{Sr}^{86}$ values at the time of the granite's formation whose mean value would approximate to the primary value observed in the granite. Production of the granite by anatexis of the Binjura Bed sediments is therefore quite compatible with its high Sr^{87} abundance.

PART I - APPENDIX 1.

THE PETROGRAPHY OF THE ANALYSED ROCKS.

C2. Andalusite-bearing granite.

This occurs as a pod of granite in the migmatite zone about two miles south of Cooma.

The rock consists of porphyritic orthoclase in a medium-grained allotriomorphic matrix of quartz, orthoclase, biotite, andalusite, andesine and accessories. Quartz (approx. 55%) forms interlocking grains about 1 mm. x 0.5 mm. Orthoclase (approx. 25%) varies from 1 mm. x 0.5 mm. to 5 mm. x 5 mm. and is associated with myrmekite. Biotite (approx. 5%) is pleochroic brown and about 0.5 mm. x 0.4 mm. Andalusite (approx. 5%) forms small highly dissected crystals and andesine (approx. 4%) forms anhedral crystals up to 0.5 mm. x 0.5 mm. which are zoned, poorly twinned and strained. Random muscovite crystals are about 0.5 mm. x 0.2 mm. and sillimanite forms small fibrous crystals associated with andalusite. Zircon is accessory.

C5. Andalusite-bearing granite.

This specimen was from the main granite body in Cooma.

In section this is medium grained allotriomorphic with porphyritic orthoclase. It consists of quartz (approx. 50%),

interlocking crystals with wavy extinction; biotite (approx. 15%), pleochroic brown crystals about 1 mm. x 0.4 mm. slightly altered to a green phyllosilicate and iron ore; andesine (approx. 15%), about 0.5 mm. x 0.5 mm. with severe zoning; orthoclase (approx. 10%), untwinned crystals from 1 mm. x 0.6 mm. to 5 mm. x 5 mm. associated with myrmekite; muscovite (approx. 5%) crystals about 0.5 mm. x 0.2 mm; dissected andalusite (approx. 4%) crystals about 0.5 mm. x 0.5 mm; sillimanite (approx. 1%) needle-like aggregates which appear to be developing from biotite. Zircon and iron ore are accessories.

GA293

Granite.

This forms a dyke about two feet wide transgressing the injection zone. It was found in a creek off the Adaminaby road $\frac{1}{2}$ mile on the Cooma side of the Dry-plains road turnoff.

It is a medium grained allotriomorphic granite consisting of quartz (approx. 35%), about 0.6 mm. x 0.5 mm; orthoclase (approx. 45%), anhedral crystals up to 5 mm. x 2.5 mm. with myrmekitic alteration; oligoclase (approx. 15%) forms weakly zoned twinned crystals and biotite (approx. 1%) forms anhedral crystals about 0.3 mm. x 0.2 mm. Sillimanite, andalusite and muscovite are accessories.

The migmatite zone samples.

The leucocratic bands are mainly medium-grained crystals of orthoclase showing extensive myrmekite alteration. These occur

in a fine matrix of serrated quartz, muscovite and biotite and a little plagioclase. The melanocratic bands are composed of elongated quartz and biotite with muscovite, orthoclase, andalusite and plagioclase. Areas of pinite represent relict cordierites.

C7 and C8.

These are specimens of adjoining leucocratic and melanocratic bands from the migmatite zone in Snake Gully, near the Murrumbidgee River.

C10 and C9.

These are specimens of adjoining leucocratic and melanocratic bands from the migmatite zone from a creek half a mile towards Cooma from the Dry-plains road turnoff along the Adaminaby road (in the vicinity of GA293).

The cordierite-orthoclase zone.

4A. Biotite-andalusite-orthoclase gneiss ("mottled gneiss").

This was considered to be representative of Dr. Joplin's "sandy band". It was collected in the vicinity of the Adaminaby-Berridale road junction.

This type occurs in bands approximately 6" in width which alternate with bands of "mottled gneiss" type 4B. It is medium-grained granoblastic with blastoglomeritic aggregates reflecting original composition. The rock is composed of interlocking quartz

(45%), pleochroic red-brown biotite (approx. 25%) about 0.2 mm. x 0.1 mm. with a strong preferred orientation; highly dissected crystals of andalusite (approx. 20%); myrmekite-altered orthoclase (approx. 10%) about 1 mm. x 0.5 mm., transgressed by quartz veinlets. Zircon is accessory.

4 B. Biotite-orthoclase-andalusite gneiss (mottled gneiss).

This is an example of the mottled gneiss derived from aluminous pelite (Joplin, 1942 p.175).

It was collected near C4A.

It is granoblastic becoming porphyroblastic, with aggregates of biotite and andalusite forming brown patches which give this rock its mottled appearance. Constituent minerals are biotite (approx. 35%) about 0.5 mm. x 0.3 mm; orthoclase (approx. 40%) about 1 mm. x 1 mm; andalusite (approx. 15%) forms highly dissected crystals in a mat with biotite and muscovite; quartz (approx. 9%) about 0.5 mm. x 0.5 mm; muscovite (approx. 1%) about 0.4 mm. x 0.1 mm. and a few small plagioclase grains with albite twinning. Zircon is accessory.

GA55. This is a 120 lb. crushing from approximately the same area and includes both types.

C1. Clino-pyroxene amphibolite.

This specimen was collected from the Soho St quarry, Cooma.

It is dark green and medium grained and in section consists of poikiloblastic plagioclase and some porphyroblastic amphibole in a medium grained groundmass of plagioclase, amphibole and clino-pyroxene. The rock contains light green amphibole (approx. 65%) about 0.2 mm. x 0.2 mm. up to 1 mm. x 1 mm. occasionally with brown centres having iron ore schiller inclusions; plagioclase (approx. 15%) porphyroblasts about 5 mm. x 5 mm; clino-pyroxene (approx. 5%) and about 0.1 mm. x 0.1 mm., mostly in clusters and quartz (approx. 10%) replaces plagioclase. Apatite is accessory.

GA273.

Muscovite pegmatite.

This formed an intrusive pegmatite in the cordierite-orthoclase zone in the bed of Spring Creek. Dr. Joplin (pers. comm.) described the rock as consisting of quartz, microcline, muscovite and albite, and a trace of andalusite. The feldspars are intergrown in microperthitic fashion, the albite units being very coarse. Microcline occurs in large irregular crystals and these together with large crystals of quartz may be surrounded by a fine granular matrix of feldspar, mica and quartz. Muscovite occurs in flakes about 1 mm. in length and shows a tendency to a plumose arrangement. A few grains of andalusite are present and tiny needles of sillimanite are noted in some quartz grains.

GA290.

Shannon's Flat granodiorite.

This specimen was collected just south of the Tidbinbilla road, Gibraltar Creek crossing, A.C.T.

This is medium to coarse-grained hypidiomorphic with evidence of considerable mechanical crushing accompanied by some minor chemical changes such as indentation of grain boundaries. The rock consists of anhedral to subhedral plagioclase, (approx. 80%) zoned from about An_{42} at the edge to An_{50} at the centre where it is saussuritised; quartz (approx. 10%) about 0.3 mm. x 0.3 mm. with mottled extinction; pleochroic brown biotites (approx. 10%) about 1 mm. x 0.6 mm. altering to chlorite, and has inclusions of apatite, pleochroic halos and iron ore in the form of equidimensional crystals and schiller inclusions.

RP6.

Leucogranite.

This was collected from a quarry beside the old entrance to the Dry-plains road, near the junction of the Cooma granite and the migmatite zone.

The relationship of this rock to the injection zone has not been conclusively determined.

The rock is medium-grained allotriomorphic with myrmekite strongly developed. The constituent minerals in the section studied were orthoclase (approx. 55%) about 2 mm. x 1 mm.; albite (approx. 15%) about 1 mm. x 0.8 mm. appears to develop from

orthoclase through myrmekite. Quartz (approx. 25%) about 0.8 mm. x 0.5 mm; muscovite (approx. 4%) crystals have a preferred orientation. The rock contains minor biotite.

The low grade metasediments of the chorite and biotite zones.

Descriptions of Binjura Bed samples RP3, RP9, RP10 and RP7 are contained in Compston and Pidgeon 1962.

PART I - APPENDIX 2.

The Rubidium-Strontium Dating of Shales by the Total-rock Method
by W. Compston and R.T. Pidgeon.

Dr. W. Compston carried out the Cardup Shale analyses in the Physics Department of the University of Western Australia. M.J. Vernon and V.M. Bofinger assisted with several of the other analyses and I did the rest under the supervision of Dr. W. Compston.

The field work in the Cooma area was carried out in 1961 and early 1962. The water samples were collected by Mr. Ian Martin (Elwood Beach sample) and myself in January, 1962.

Rubidium-Strontium Dating of Shales by the Total-Rock Method

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Abstract. Measurements of Rb^{87} , Sr^{86} , and $\text{Sr}^{87}/\text{Sr}^{86}$ are reported for total-rock samples of three shale formations. These data allow calculation of the time of deposition for one formation known to be of Lower Silurian age and of either the deposition or metamorphism for another. The calculation is based on the model that each formation was once uniform in its ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ and that the observed distribution of Rb/Sr through each formation was established at that time. By considering the sources of error in our measurements, we believe that a small but definite range in $\text{Sr}^{87}/\text{Sr}^{86}$ actually occurred, rather than complete uniformity. Nevertheless, excellent agreement is found between our calculated value and the current estimates for the absolute age of Lower Silurian. The data for the third formation indicate that its ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ was always highly nonuniform. Measurements of $\text{Sr}^{87}/\text{Sr}^{86}$ for sea water from various localities are also reported. The variation in this ratio is very small, and the absolute values are significantly lower than those calculated for $\text{Sr}^{87}/\text{Sr}^{86}$ in the shale formations at the times of their deposition. These observations show that the strontium fixed in the shales during deposition was not entirely precipitated from sea water: some must already have been enriched in radiogenic strontium relative to sea water. We therefore believe that a small amount of detrital mica or feldspar distributed irregularly through the shales must be responsible for the nonuniformity of their initial ratios of $\text{Sr}^{87}/\text{Sr}^{86}$.

1. *Introduction.* In studying the geochronology of two areas over the past two years, we had occasion to analyze samples of sedimentary rocks. Most of these were alkali-rich shales and metashales. Many possessed a high ratio of Rb/Sr , so that the radioactive decay of Rb^{87} produced large increases in the ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ during their lifetimes. We were led, therefore, to try calculations of the absolute age of the samples to make some assessment of the potential of such shales as dating material.

Results for two formations, the Cardup shale and the Cooma metamorphosed sediments are discussed in sections 3 and 4 and are shown to provide valuable information. They suggested that an attempt should be made to determine the absolute accuracy possible in shale dating, and a shale whose stratigraphic position is precisely known was chosen for this purpose. Results on this shale, the State Circle shale, were excellent and are described in section 5.

These results suggest that $\text{Rb}-\text{Sr}$ dating of shales by the total-rock method can be a useful and accurate method of dating sediments. Detailed work on a wide range of sedimentary rocks is planned for the future.

2. *Measurement of isotopic ratios.* The mass

spectrometer used in this work is a Metropolitan-Vickers type MS2-SG. It was modified to use a Cary vibrating-reed electrometer and to measure isotopic ratios by rapid switching of the magnetic field. Rubidium and strontium were analyzed as chlorides by the triple-filament technique. Full details of the chemical and mass-spectrometric procedures will be published later.

To compare correctly measurements of $\text{Sr}^{87}/\text{Sr}^{86}$ made on this machine with those made elsewhere, we give our results to date on the standard strontium used by Aldrich, Herzog, Doak, and Davis [1953]:

$$\text{Sr}^{88}/\text{Sr}^{86} = 8.293 \pm 0.006$$

$$\text{Sr}^{87}/\text{Sr}^{86} = 0.7053 \pm 0.0003$$

The uncertainties quoted are the standard errors of the mean. Measurements of this standard approximately 1 per cent higher for each ratio were recently reported by Faure and Hurley [1962], and the measurements by these authors on the strontium from basic igneous rocks is also 1 per cent higher than unpublished observations here. On the other hand, our measurements on the Moore County achondrite agree exactly with those of P. W. Gast (personal

TABLE 1. Rb-Sr Isotopic Analyses of the Cardup Shale Samples

Specimen	Rb ⁸⁷ , μm/g	Sr ⁸⁶ , μm/g	Rb ⁸⁷	Sr ⁸⁷
			Sr ⁸⁶	Sr ⁸⁶
Composite	0.799 ± 2	0.0209	38.2	1.207
white shale 1		0.0213	37.5	1.216
Dark band 2	0.599 ± 5	0.0193	31.0	1.109
		0.0197	30.4	1.130
White band 3	0.630 ± 3	0.0206	30.6	1.210
		0.0204	30.9	1.212
Black shale 4	0.918 ± 3	0.0160	57.3	1.304
		0.0166	55.3	1.286
Black shale 5	0.540 ± 2	0.01535	35.2	1.099

communication). These systematic differences appear to be characteristics of individual mass spectrometers: the true isotopic ratios cannot be determined until an absolute calibration of one machine has been made using known mixtures of the separated isotopes. Such a calibration of the A.N.U. machine is in progress. Determination of Sr⁸⁶ and Rb⁸⁷ are independent of systematic machine error if the 'spike' solutions have been calibrated against standard solutions of the natural elements.

The deviations of our Sr⁸⁶/Sr⁸⁸ and Sr⁸⁷/Sr⁸⁶ measurements from their mean values over a series of replicate observations appear to be quite independent of one another. Thus the Sr⁸⁷/Sr⁸⁶ measurements of unspiked strontium made on the A.N.U. machine should not be normalized to a fixed value of Sr⁸⁶/Sr⁸⁸, in contrast to the evident validity of this procedure on the machines used by Faure and Hurley. This situation also is probably due to the characteristics of the individual machines.

3. *The Cardup shale.* Rubidium-strontium isotopic analyses of biotite from the 2450-m.y.-old Mundaring granite in Western Australia have suggested that the western margin of this mass may have experienced a mild regional metamorphism some 600 to 700 m.y. ago (Compston, Riley and Jeffery, in preparation). This was one of several possible explanations for the biotite apparent ages, and it requires, if correct, that the deposition of the overlying Cardup shale must have taken place later than this time, since metamorphic effects in the shale are almost nonexistent. It was in order to test this hypothesis of regional metamorphism that

measurements on total rock samples of shale were first undertaken. Subsequently, convincing evidence for a metamorphic event at 630 m.y. was obtained from another source so that this figure could be set as an upper limit to the time of deposition.

The Cardup shale can be traced for some 30 miles along the Darling scarp near Perth, Western Australia. It comprises black carbonaceous shale, white banded shale, sandstone, and minor conglomerate. The beds unconformably overlie 2450-m.y.-old gneiss and are themselves overlain by Quarternary gravels and sands. They dip 70° to the west and have a weakly developed fracture cleavage. They have been intruded by a spilitic-type sill and later by quartz dolerite dikes. Biotite developed in the contact zone of the latter gives an age of about 550 m.y., which sets a lower limit to the time of deposition.

The white shale is composed of fine fibrous sericite, quartz, and biotite, the latter becoming locally more abundant to produce the banded appearance. It is high in Si, Al, and K, very low in Ca, and is thought to be derived from illite-rich clays [Prider, 1941]. The biotite is believed to be detrital (Prider, personal communication). The black shale is composed of sericite with minor quartz and graphitic material. It is apparently free of biotite. Idioblastic tourmaline is present in both shale types. This is believed to be due to recrystallization of original shale constituents rather than to the later introduction of external material [Prider, 1941]. According to Singh [1958], the shales were formed by 'slow or aperiodic introduction of fine clastic material into neritic, possibly lower neritic waters.' Their tectonic environment is 'stable shelf facies.'

Except in the immediate vicinity of the dikes, petrological evidence suggests that the shale has remained a closed chemical system since alkali fixation was completed in the sericite, presumably very soon after deposition. Thus, except for the problem of inherited radiogenic strontium in the detrital biotite, it was expected that total-rock age determinations would yield values very close to the age of shale deposition.

The samples analyzed are shown in Table 1. Single dissolutions were made, Rb⁸⁷ and Sr⁸⁶ were determined by isotope dilution on separate aliquots of the sample solution, and the Sr⁸⁷/Sr⁸⁶ ratio of the sample was calculated from the

TABLE 2. Cardup Shale Apparent Ages

Specimen	$10^3 \theta$	Age, m.y.
1	1.32	900
2	1.34	910
3	1.63	1110
4	1.04	710
5	1.10	750

measured isotope ratios of the mixtures of aliquots and Sr^{86} 'spike.'

To calculate the age, the following relationships were used:

$$t = (\text{age}) = 1/\lambda \ln (1 + \text{Sr}^{87}_*/\text{Rb}^{87})$$

and

$$\text{Sr}^{87}_* = \text{Sr}^{86}(R_p - R_i)$$

where λ denotes the Rb^{87} decay constant (here taken as 1.47×10^{-11} /year), Sr^{87}_* the radiogenic strontium, and R_p and R_i the present-day and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of the sample.

For Paleozoic minerals $\ln(1 + \text{Sr}^{87}_*/\text{Rb}^{87})$ very closely approximates to the ratio $\text{Sr}^{87}_*/\text{Rb}^{87}$, which will be here denoted as θ . Thus,

$$\lambda t = \theta = (\text{Sr}^{86}/\text{Rb}^{87})(R_p - R_i) \quad (1)$$

To determine θ , it is usually sufficient to assume R_i to be 0.71, an average value for common Sr in most rocks. If this is done with the data for the Cardup shale, we obtain the apparent ages in Table 2. These should all be equal and less than 660 m.y. if the ages measured are to be the ages of deposition. However, only the black shale specimens give ages reasonably close to 660 m.y., the rest being greater, as if they had experienced a recent loss in Rb^{87} or a gain in radiogenic strontium at any time in their history.

Loss in Rb^{87} and gain in Sr^{87}_* after diagenesis are unlikely on the grounds that the specimens show no independent evidence for being open systems. On the other hand, undecomposed detrital biotite is present, and some of the sericite also may be fine flakes of unaltered muscovite from the adjacent Archaean shield, or second-generation (or older) hydromicas formed during previous sedimentary cycles. Thus the most likely explanation of the high apparent ages is a variable excess of radiogenic strontium

which has been present in the specimens from the time of deposition.

This situation is best seen by using the graphical expression of data given by Nicolaysen [1961]. Equation 1 may be rearranged to give

$$R_p = R_i + \theta(\text{Rb}^{87}/\text{Sr}^{86}) \quad (2)$$

which becomes the equation of a straight line if R_p and $\text{Rb}^{87}/\text{Sr}^{86}$ are regarded as variables. The age is proportional to the gradient θ of such a line, and R_i is given by its intercept on the R_p axis.

Equation 2 was developed to handle a number of samples having the same (unknown) age and the same (unknown) R_i , for which the R_p - $\text{Rb}^{87}/\text{Sr}^{86}$ points corresponding to the different samples will define a single straight line. This line constitutes an isochrone for such a group of samples. For the Cardup shale, it is known that the age of deposition is approximately the same for all samples and probably not greater than 660 m.y. This corresponds to an isochrone whose gradient θ is 0.0097. Figure 1 shows the R_p - $\text{Rb}^{87}/\text{Sr}^{86}$ plot for these samples with isochrones drawn through sample points corresponding to this maximum value for the gradient. Had the samples (assumed 660 m.y. old) all possessed the same R_i , these isochrones would superimpose. Instead, the figure shows that each sample must have commenced with significantly different values for R_i , ranging from 0.735 to 0.90, or even higher if the gradient corresponding to the lower age limit of 550 m.y. is assumed. These Rb-Sr age determinations provide a measure of the variability of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio throughout the shale rather than an accurate measure of age.

As suggested above, undecomposed detrital micas are probably responsible for this variability. The age of the detrital biotite would be 660 m.y. It follows, therefore, that much of the detrital mica must be sericite, lying in the apparently older sericite-bearing bands. This is consistent with the observations that the dark band, specimen 2, containing most detrital biotite, has a lower R_i value than the composite shale, and this in turn has a lower value than the most sericite-rich member.

The carbonaceous shale specimens appear least contaminated with inherited radiogenic strontium. This raises the important question

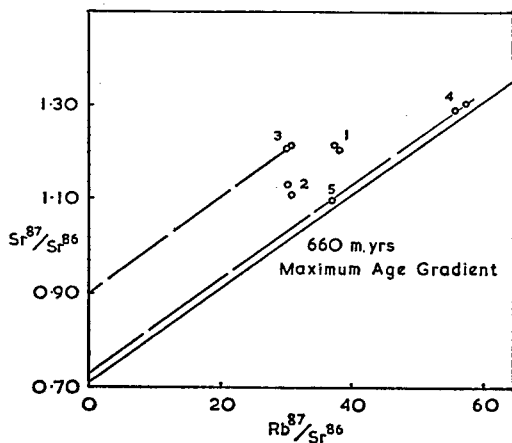


Fig. 1. $\text{Sr}^{87}/\text{Sr}^{86}$ versus $\text{Rb}^{87}/\text{Sr}^{86}$ for the Cardup shale total-rock samples.

whether carbonaceous shales in general possess an extremely low content of detrital mica.

4. *The Cooma metamorphosed sediments.* Analyses of the Cooma metasediments were made primarily to compare their ratios of $\text{Sr}^{87}/\text{Sr}^{86}$ and Rb/Sr with those of an associated igneous body, the Cooma gneiss. We wished to see whether the value of the initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ for the gneiss was consistent with the theory that it was formed wholly from the metasediments by some process of palingenesis. This study will be reported later. Only the dating application of this data will be considered here.

The specimens analyzed were collected approximately 3 miles west of Cooma, N.S.W., from the Binjura beds [Joplin, 1942-1943]. The main rocks here are aluminous pelites consisting largely of chlorite, biotite, muscovite, and quartz, and psammites, containing small amounts of chlorite and mica, which are usually interbedded with the pelites. Tuffaceous sandstones and rocks gradational between the pelites and psammites are also present. The beds are tightly folded and, according to Joplin, have probably experienced two separate metamorphisms, not widely separated in time. The older of these was regional, producing chlorite and biotite schists, whereas the second is evident as zones of progressively higher metamorphic grade surrounding the Cooma gneiss, apparently a thermal effect associated with the emplacement or generation of this mass.

No fossils have been discovered, and so the precise stratigraphic position of the Binjura beds is not known. Unmetamorphosed siliceous shales nearby contain Upper Ordovician graptolites, but the mutual relationship of the two formations is obscure. However, Browne [1943] proposed an Upper Ordovician age, and Joplin (personal communication) a Middle or Lower Ordovician age, on the basis of interpretations of structural and chemical evidence. A definite minimum age limit of 395 m.y. is set by unpublished mineral and whole-rock rubidium-strontium analyses from the intrusive Cooma gneiss and associated pegmatites (Pidgeon and Compston, in preparation). This figure is essentially in agreement with the potassium-argon age reported by Evernden and Richards [1962] for biotite from the same body.

The analytical data for four samples are shown in Table 3. A fist-sized piece of each was crushed to pass 40 mesh, then split to about 10 grams. This was crushed further to pass 100 mesh, and half-gram portions were taken for analysis. Replicate measurements of R_p using unspiked aliquots have been made for most dissolutions. Comparison with the calculated R_p values shows that no great increase in experimental error would arise if only the latter were available. For this reason, sample 10B has been given equal weight with the rest. The data are plotted in Figure 2 as R_p - $\text{Rb}^{87}/\text{Sr}^{86}$ points, and in Figure 3 as θ - R_p lines [Riley and Compston, 1962].

A maximum age of deposition for the Binjura beds can be set from Figure 2 on the following assumptions:

1. The samples analyzed have remained closed systems with respect to rubidium and strontium during metamorphisms.
2. Sample 3 was deposited with R_p equal to that of basic igneous rocks.

With regard to the first assumption, petrographic and chemical studies by Joplin [1942] suggest that the metasediments have retained their macrochemical compositions up to a higher metamorphic grade than these samples. This may also be true for their trace constituents, in particular rubidium and strontium. With regard to the second, basic igneous rock R_p has the lowest value known (excepting that of certain types of meteorite). It is 0.702 ± 0.001 , as

TABLE 3. Rb-Sr Isotopic Analyses of the Cooma Metasediments Samples

Specimen		Rb ⁸⁷ , $\mu\text{m/g}$	Sr ⁸⁶ , $\mu\text{m/g}$	Rb ⁸⁷ /Sr ⁸⁶	R_p (calc.)	R_p (meas.)
Quartz-chlorite-muscovite schist	3A	(0.619)	0.04769	(12.98)	0.794	0.7907 0.7889 0.7894
	3B	0.6081	0.04811	12.64	0.799	(0.795)
	3C	0.6080	0.04809	12.64	0.790	0.7903 0.7892
	3D	0.6093	0.04815	12.65	0.785	0.7886
	7A	0.00607	0.2377	0.0255	0.713	0.7155
Quartz-epidote rock	7B					0.7161
	7C					0.7156
Quartz-biotite schist	9A	0.4937	0.1555	3.175	0.731	0.7301
	9B	0.5061	0.1617	3.130		0.7331 0.7312
Quartz-muscovite-cordierite-biotite schist	10A	0.5673	0.06582	8.62	0.765	0.7629
	10B	0.5768	0.06628	8.70	0.764	0.7626
Averaged data						
	3C			12.64		0.7898
	3D			12.65		0.7886
	7A			0.0255		0.7157
	9A			3.175		0.7301
	9B			3.130		0.7321
	10A			8.62		0.7628
	10B			8.70		0.7640

measured on the A.N.U. machine. The line joining this value and the sample 3 point in Figure 2 therefore defines a maximum age isochrone, and lines of higher gradient drawn through the sample points have no physical meaning. (Sample 3 is considered because lines of different gradient drawn through this point will produce a greater range in the R_p intercept than corresponding lines drawn through the other points.) The value of this maximum age, 460 m.y., calculated from the slope of the isochrone, is consistent with the Middle or Lower Ordovician age proposed by Joplin. R_i for the different samples, found from Figure 2 by extending lines of the same maximum gradient through each point to the R_p -axis, ranges from 0.702 to 0.715.

Other lines drawn in Figure 2 are the minimum age isochrone for 395 m.y. and the least-squares fit to all the experimental points. If it may be assumed that R_i was the same for all samples, the physical meaning of the least-squares line is clear: it is an approximation to the isochrone on which all points will lie in the

absence of experimental error. As such, its gradient would correspond to an event at 403 m.y., with 95 per cent confidence interval of 410 to 394 m.y., and the event itself could refer either to the original deposition of the sediments, if the samples have remained closed systems during metamorphism, or to the metamorphism itself if they have not. On the other hand, if there were a measurable variance in R_i , the chronological meaning of the least-squares gradient would be much less obvious. In this case, the statistical derivation of the gradient would amount to deliberate choice of the smallest variance in R_i which will fit the measured data. However, there is no a priori knowledge of R_i variance. For this reason the 'age' corresponding to the least-squares gradient merits no preference at present over that based upon other assumptions.

An analysis of variance in Figure 2 will reveal whether experimental error or R_i variance is responsible for the observed scatter of points. A simpler (if less objective) indication is given by the θ - R_i plot in Figure 3, which emphasizes

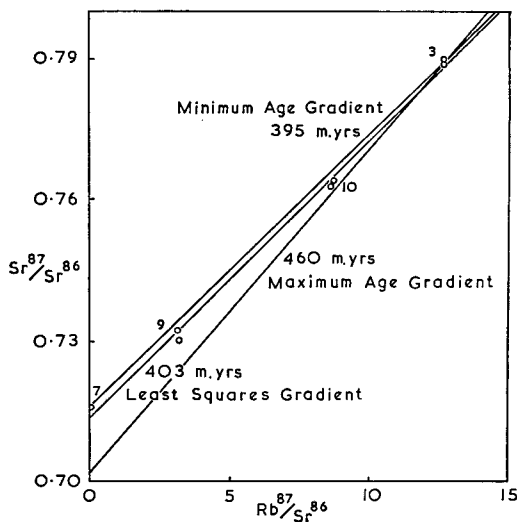


Fig. 2. $\text{Sr}^{87}/\text{Sr}^{86}$ versus $\text{Rb}^{87}/\text{Sr}^{86}$ for the Cooma total-rock samples.

how the value of 0.711 for R_i in sample 7 would produce an intersection of all lines apparently to within measurement reproducibility. The difference between 0.711 and the measured 0.716 seems quite beyond the limits of experimental error. It must be concluded that a significant R_i difference exists, at least between sample 7 and the rest, and therefore that the least-squares line shown in Figure 2 is not the best isochrone approximation. On the other hand, the least-squares fit to samples 9, 10, and 3 only, would be an excellent approximation, and this line yields an age of 416 m.y. with 95 per cent confidence interval of 425 to 407 m.y. This result, a Silurian age for the Binjura beds, does not conflict with known geological facts. Referring to the petrographic appendix, it is clear that there are valid geological grounds also for isolating sample 7: this sample was originally an impure sandstone, whereas the other three were shales.

5. *The State Circle shale.* This formation is a member of the Lower Silurian sequence in the Canberra District [Öpik, 1958]. It consists of noncalcareous sandy shale and black shale containing beds of fine-grained sandstone. It has a total thickness of about 200 feet. From its areal extent, Öpik suggests that this formation is a transgressive unit indicating a general deepening of the Silurian sea.

Specimens selected for analysis were from an

occurrence of the State Circle shale at Etheridge Creek on the eastern slopes of Black Mountain, about two miles northwest of Canberra.

The age of the shale is upper Lower Silurian, zone 22, determined by the occurrence of the graptolites *Monograptus turriculatus*, *M. spiralis*, *M. exiguus*. On the time scale compiled by Kulp [1961] the absolute age of the formation would be about 420 m.y. or using that of Evernden and Richards [1962], about 430 m.y. For convenience, we have assumed in the following discussion that no age uncertainty exists in the Palaeozoic time scale beyond these limits. It is acknowledged, however, that the Silurian absolute age is the least well known.

Samples 12 and 13 were collected within a few feet of each other, whereas sample 17 was some 70 feet higher in the section. It is possible that the age of sample 17 may be 1 or 2 per cent less than the others.

The detailed and averaged analytical data are given in Table 4, and the averaged data are plotted in Figure 4. As before, only the measured R_p values are used. The averaged Rb^{87} , Sr^{86} , and R_p values for two or more sample dissolutions were used in this case, rather than individual points corresponding to the different dissolutions, because complete data were available for only two out of the eight dissolutions. 12C and 12D were small weight dissolutions spiked for rubidium only. Thus the experimental variance is not obvious from Figure 4, but it may be estimated from Table 4.

The two lines drawn through the sample-13

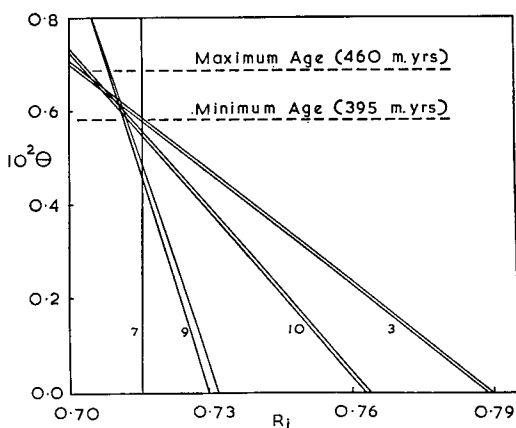


Fig. 3. $\theta(\text{Sr}^{87}/\text{Rb}^{87})$ versus R_i (initial $\text{Sr}^{87}/\text{Sr}^{86}$) for the Cooma total-rock samples.

TABLE 4. Rb-Sr Isotopic Analyses of the State Circle Shale Samples

Specimen	Rb ⁸⁷ , $\mu\text{m/g}$	Sr ⁸⁶ , $\mu\text{m/g}$	Rb ⁸⁷ /Sr ⁸⁶	R_p (calc.)	R_p (meas.)
Shale 12A	0.6238	0.05458		0.7822	0.7868
B	0.6231			0.7885	0.7857
C	0.6232				0.7860
D	0.6198				
E		0.05446		0.7817	
Shale 13A		0.02578		0.841	0.8450
B	0.5332				
C	0.5353	0.02579		0.853	0.8465
Shale 17A	0.5788	0.03677	15.74	0.817	0.8160
B	0.5765	0.03603	16.00	0.8183	0.8181
Averaged data					
12	0.6225	0.05452	11.42		0.7862
13	0.5342	0.02578	20.72		0.8457
17	0.5776	0.0364	15.87		0.8170

point are isochrones corresponding to the limits of 420 and 430 m.y. Assuming that the deposition of all three samples occurred within a 2-m.y. interval, so that the isochrones through each point will be parallel, then R_i values required for equal ages range from limits of about 0.714 to 0.719. None of these samples can have commenced with basic igneous rock R_i , since this would yield an age greatly in excess of the lower limit. Instead, two alternatives seem to be possible: a measurable but small R_i variance among the samples, perhaps as much as the above limits, or no significant R_i variance, the deviations of the points from the least-squares fit being caused by experimental error only. At present, there are insufficient data to objectively distinguish between these alternatives. However, it is our impression that a significant R_i variance exists. In either case, it is definite that the average R_i for the formation will be about 0.714, and the least-squares lines could be an isochrone equivalent to an age of 433 m.y. in essential agreement with the estimate from *Evernden and Richards* [1961].

6. *Sea-water strontium.* It has been suggested that the presence of older detrital micas was responsible for the larger R_i variance in the Cardup shale. This explanation could also be applied to the Binjura beds and to the State Circle shale, but, since the apparent range in R_i is much smaller in these instances, it also ap-

peared possible that variations in the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of sea water might have been responsible.

In theory, sea-water $\text{Sr}^{87}/\text{Sr}^{86}$ may range from the minimum value 0.702 of basic igneous rocks up to an undefined maximum value in regions of the sea contaminated with radiogenic strontium from the weathering of ancient rubidium-rich rocks. Through the growth of authigenic minerals and by exchange of strontium in detrital clays, it seems likely that the strontium fixed in at least some shales should have the same isotopic composition as the environmental sea water. Granted such equilibration mecha-

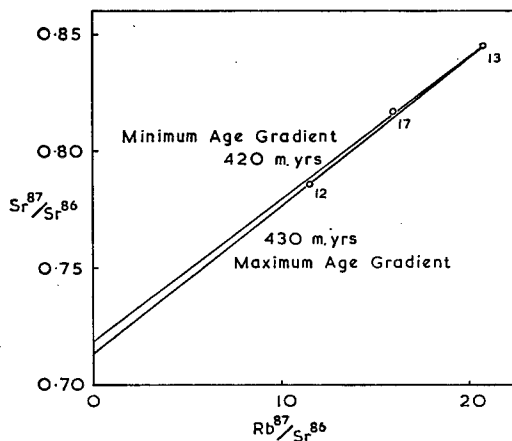


Fig. 4. $\text{Sr}^{87}/\text{Sr}^{86}$ versus $\text{Rb}^{87}/\text{Sr}^{86}$ for the State Circle shale total-rock samples.

TABLE 5. Rb-Sr Isotopic Analyses of Water Samples

Location	87/86	Rb, μg/g	Sr, μg/g
Rottneest Island, Perth, Western Australia	0.7065	0.117	7.76
Sorrento Beach, Perth, Western Australia	0.7068	0.118	7.78
Elwood Beach, Port Phillip Bay, Victoria	0.7088	0.112	7.51
Rosedale Beach, Bate- mans Bay, N.S.W.	0.708 ± 1	0.116	7.76
Mundaring Weir, Western Australia	0.723 ± 1	0.0073	0.088

nisms, any change in sea-water $\text{Sr}^{87}/\text{Sr}^{86}$ with time or from place to place in the deposition site of a sediment would produce a variance in the sediment R_i . For this reason, analyses of five water samples were undertaken to see whether significant changes in sea-water $\text{Sr}^{87}/\text{Sr}^{86}$ do in fact occur.

The results are shown in Table 5. The four sea-water samples show a striking uniformity in strontium concentration and isotopic composition, which furthermore are in agreement with results for Atlantic Ocean water found by P. J. Anderson, W. H. Pinson, L. F. Herzog, and R. F. Cormier (personal communication), after making allowance for the 1 per cent difference in ratio measurement mentioned earlier. No sea-water $\text{Sr}^{87}/\text{Sr}^{86}$ ratio equals the lowest R_i value (0.714) inferred for the State Circle shale, or the least-squares value (0.711) for the three Binjura beds samples. It appears either that these sea-water samples are not representative of the depositional environments or that detrital minerals of higher $\text{Sr}^{87}/\text{Sr}^{86}$ than typical seawater are responsible for the observed shale R_i .

One fresh-water sample from Mundaring weir was also analyzed. The watershed here is a 2450-m.y.-old granodiorite batholith abundantly intruded by quartz-dolerite dikes. The $\text{Sr}^{87}/\text{Sr}^{86}$ ratio measured has approximately the value expected, but in comparison with that of sea water the strontium concentration is extremely low. It is evident that no reasonable dilution of sea water by the water from Mundaring weir could measurably change the sea-water $\text{Sr}^{87}/\text{Sr}^{86}$ ratio. The over-all evidence from water analyses therefore suggests that the small R_i variance inferred

for the Binjura beds and the State Circle shale, as well as the gross variance present in the Cardup shale, must be due to older detrital mica or clays which have not exchanged their excess radiogenic strontium with sea water. Convincing evidence for the existence of such material elsewhere has been recently reported by Hurley, Brooking, Pinson, Hart, and Fairbairn [1961], in the form of 200-m.y. (and older) illites from the Mississippi River delta deposits.

7. *Comparison with potassium-argon dating.* Considerable work has been done on the evaluation of illite for K-Ar dating of sedimentary rocks, [Evernden, Curtis, Obradovich, and Kistler, 1961] and on the inverse problem of deducing the genesis and history of illites from their apparent K-Ar ages [Hurley et al., 1961]. To consider the dating application only, the difficulties in the K-Ar method are the inheritance of radiogenic argon retained by older micas and illites and the diffusive loss of argon from extremely small shale components. Loss of daughter product from the whole rock seems much less likely for the Rb-Sr method, but the inheritance of radiogenic strontium locked in older micas is at least as likely as the inheritance of argon.

In contrast to the argon situation, however, there is some hope that approximate correction for inherited radiogenic strontium can be made, depending on the nature of the shale constituents and on the processes which determine their final rubidium and strontium distributions. If the shale as a whole is composed of a uniform mixture of detrital and authigenic components, its $\text{Sr}^{87}/\text{Sr}^{86}$ will be anomalously high (relative to sea water) but *uniform*. If in addition the rubidium concentration of the shale independently varies from place to place, so that samples of different Rb/Sr ratios can be obtained for analysis, an isochrone could be defined by plotting the R_i - $\text{Rb}^{87}/\text{Sr}^{86}$ points of the different samples. This isochrone would designate the time at which the various Rb/Sr ratios and the uniform $\text{Sr}^{87}/\text{Sr}^{86}$ ratio were established. If this is also assumed to be the time of deposition or early diagenesis of the shale, then fixation of rubidium in clay mineral at this time is implied.

The small R_i variance and the excellent apparent age for the State Circle shale indicate that the above conditions have been closely approached in this formation. On the other hand,

the Cardup shale samples show definite non-uniform mixing of authigenic and detrital components, the latter being of at least two different ages. (The case of nonuniform two-component mixtures has a simple θ - R_i pattern which is discussed by *Riley and Compston* [1962]. The Cardup shale data do not show such a pattern.)

To check for inherited radiogenic argon in the State Circle shale, potassium and argon analyses were made on sample 13. The results were:

Potassium	3.23 per cent
$\text{Ar}^{40}/\text{K}^{40}$	18.2×10^{-8}
Apparent age	289×10^6 years
Air correction	88.5 per cent

The high air correction and probable diffusive loss of argon minimize the significance of this young age. No further K-Ar work was done.

APPENDIX

Petrography of the Analyzed Rocks

The Binjura Beds Specimens

Estimates of metamorphic grade are based on the metamorphic facies proposed by *Turner and Verhoogen* [1960].

Specimen 3. Quartz-chlorite-muscovite schist. Specimen 3 is foliated schist consisting of alternating bands, approximately 0.6 mm wide, of (1) quartz and minor green chlorite and (2) chlorite and muscovite with minor quartz, graphite, and possibly iron ore. A few limonite stringers are present, suggesting weathering solutions. The metamorphic facies is considered to be greenschist or albite-epidote hornfels.

Specimen 7. Quartz-epidote rock. Specimen 7 is a blue-gray, fine-grained homogeneous rock consisting of approximately 60 per cent quartz, 38 per cent clinozoisite, 2 per cent iron ore, and a few subhedral crystals of zircon. Some iron ore is altered to limonite. *Joplin* [1942, p. 167] suggests that this may have been a psammite with a tuffaceous matrix. However, the high $\text{Sr}^{87}/\text{Sr}^{86}$ ratio (Figure 3) indicates that this rock was possibly originally a graywacke or a contaminated sandstone.

Specimen 9. Quartz-muscovite-biotite schist. Specimen 9 is a light brown, strongly foliated schist with some biotite muscovite bands, ap-

proximately 0.3 mm wide, in an approximately homogeneous matrix of quartz (approx. 70 per cent) biotite and muscovite (approx. 30 per cent), and some andalusite and chlorite. The micas are oriented in at least two foliation planes, indicating a complex directed pressure during metamorphism. The metamorphic facies is considered to be albite-epidote hornfels or hornblende hornfels.

Specimen 10. Quartz-muscovite-cordierite-biotite schist. Specimen 10 is a green foliated schist consisting of alternating bands, approximately 0.1 mm wide, of (1) muscovite and minor biotite and (2) quartz and minor muscovite and biotite. Pinitized porphyroblasts of cordierite with associated iron ore constitute approximately 10 per cent of the rock. The metamorphic facies is thought to be hornblende hornfels.

The State Circle Shale Specimens

Specimen 12. Shale. Specimen 12 is a pink, fine-grained, foliated shale. It consists of bands, approximately 0.1 mm wide, of (1) fine-grained semiopaque green-brown clay with minor sericite and (2) quartz with interstitial sericite clay and limonite. An orientation of clay particles at approximately 30° to the bedding plane was probably produced by a minor movement.

Specimen 13. Shale. Specimen 13 is yellow and weakly foliated. It consists of semiopaque, fine, green-brown clay with sericite, some quartz fragments, and iron ore. A little limonite occurs as a stain on the clays. Specimen 17 is very similar to this rock.

Acknowledgments. We wish to thank M. J. Vernon and V. M. Bofinger for assisting with several analyses, Dr. I. McDougall for the argon analysis, Dr. G. A. Joplin for a stimulating tour of the Cooma region and for commenting on the text, and Professor D. A. Brown for suggesting the use of the State Circle shale and showing us favorable sampling sites.

The analyses of the Cardup shale were made by W. Compston while he was at the Department of Physics, University of Western Australia.

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(Manuscript received March 14, 1962; revised May 4, 1962.)

PART II.

THE AREA OF REGIONAL METAMORPHISM IN

THE BROKEN HILL DISTRICT, N.S.W.

CHAPTER V. THE GEOLOGY OF THE BROKEN HILL DISTRICT.

A. INTRODUCTION.

Part II presents the results of a detailed rubidium-strontium isotopic study of the regionally metamorphosed "Willyama Series" (Mawson, 1912) of the Broken Hill district.

The object of this study is firstly to measure the ages of separate geological events, secondly to determine the significance of the indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of the individual rock units and thirdly to investigate the movement of strontium isotopes under specific metamorphic conditions. The Rb-Sr ages have been compared with factual time relationships in the field in order to investigate later metamorphic effects and also with ages determined by U-Pb and K-Ar methods. The occurrence of one or more "later" metamorphisms has allowed detailed study of the possibility of preferential movement of radiogenic strontium between phases in a closed system.

The rest of this chapter describes the geology and geological histories, proposed by a number of authors, of the Willyama Series. It concludes with a summary of the geological histories and comments on the time relationships of certain geological events.

B. THE GEOLOGY.

The Precambrian succession in the vicinity of Broken Hill is (King and Thomson, 1953):-

<u>Age</u>	<u>Series</u>	<u>Rocks</u>
"Proterozoic"	Torrowangee	low grade claystones, sandstones, basalt, tillite, etc.
"Archaeanozoic"	Willyama	metamorphosed sedimentary and igneous rocks.

In this thesis I am concerned with the so-called "Archaeanozoic" Willyama complex.

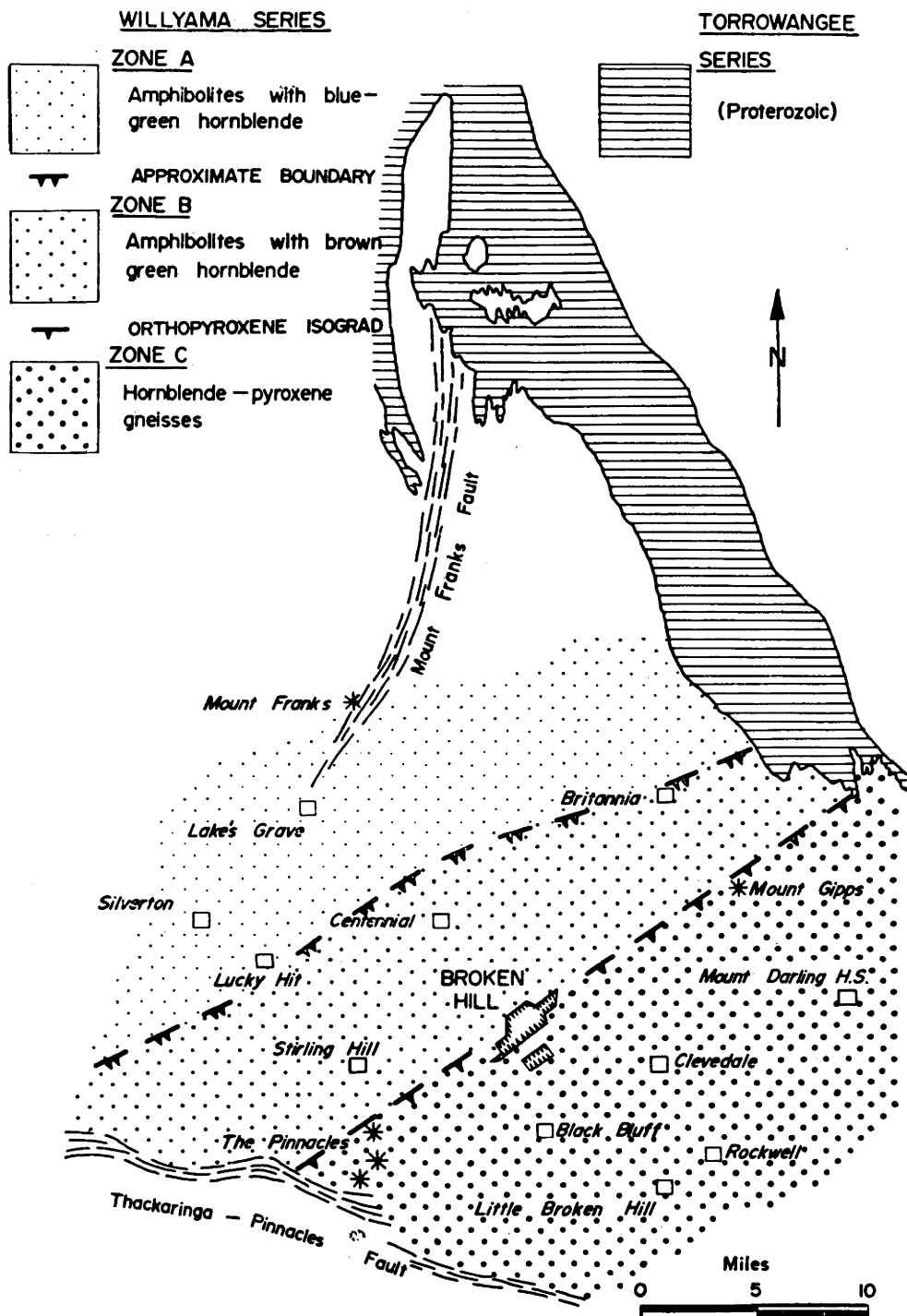
The polymetamorphosed Willyama rocks are separated from the weakly metamorphosed Torrowangee series in the north-east by the "Grand Unconformity" (Mawson, 1912). To the west a fault contact separates the Willyama rocks from recent sediments of the Mundi Mundi plain. To the south there is a complete cover of alluvium but to the south-west the Willyama rocks appear to continue into the Olary province of South Australia and to form the basement underlying the Adelaide System in the region (Mawson 1912, Campana 1958).

In general geological work has been concentrated in areas of economic importance. Comprehensive studies of the Broken Hill

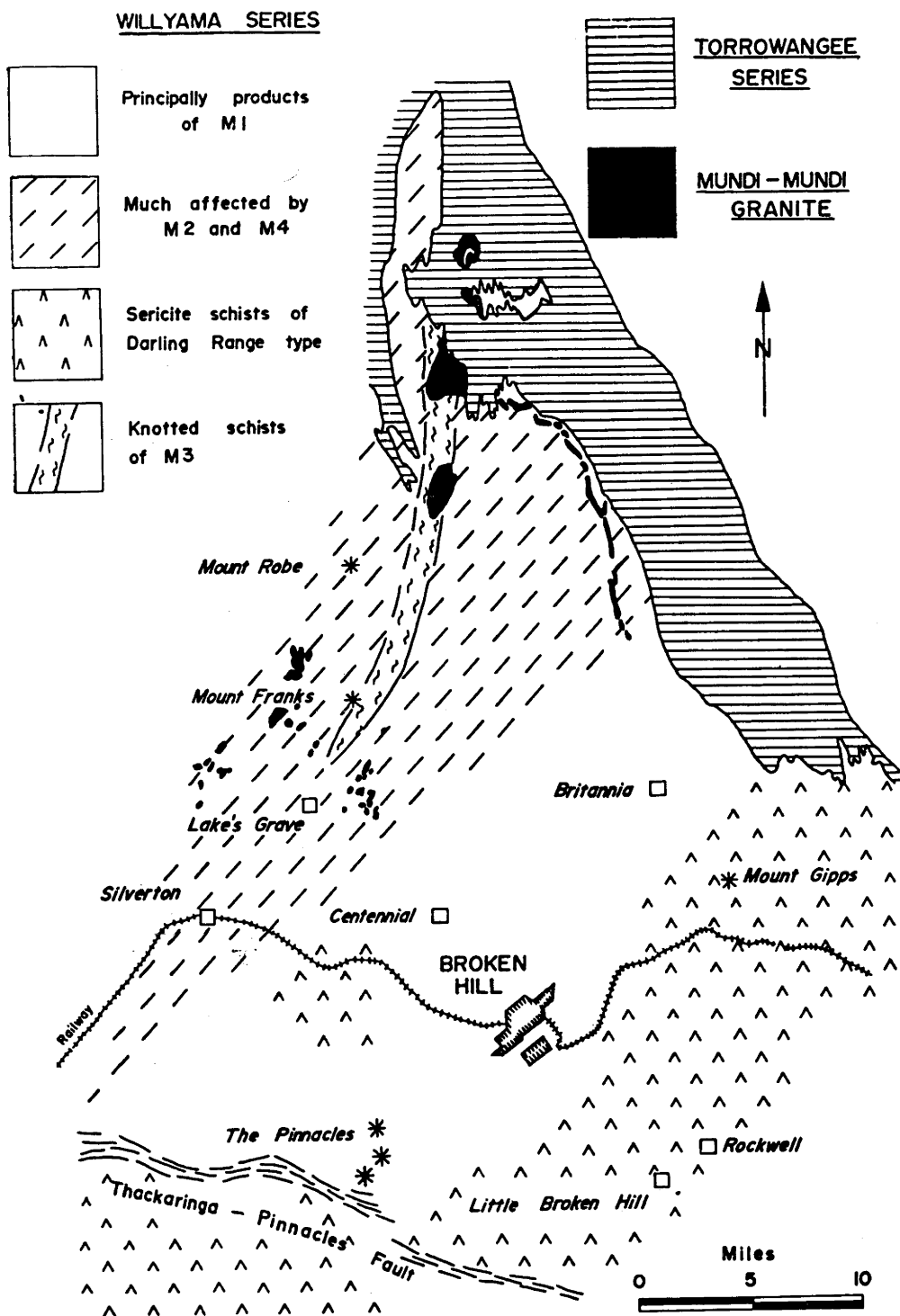
In general geological work has been concentrated in areas of economic importance. Comprehensive studies of the Broken Hill area have been published by Mawson (1912), Andrews (1922) with supplements by Browne and Stillwell, Gustafson, Burrell and Garretty (1950), and King and Thomson (1953).

The Willyama rocks are extensively folded and have suffered complex polymetamorphism and intrusion by basic and acidic phases. The grade of metamorphism reaches granulite facies in the south and decreases to the north (Fig. 11). Sillimanite, kyanite, staurolite, garnet, cordierite and brown hornblende occur near Broken Hill and give way further north to andalusite, muscovite and blue-green hornblende, suggesting at first sight a relationship with Miyashiro's (1961) Andalusite-sillimanite type or Kyanite-sillimanite type of regional metamorphism. The presence of extensive retrogressive metamorphism however indicates that these may not be equilibrium assemblages (Fig. 12).

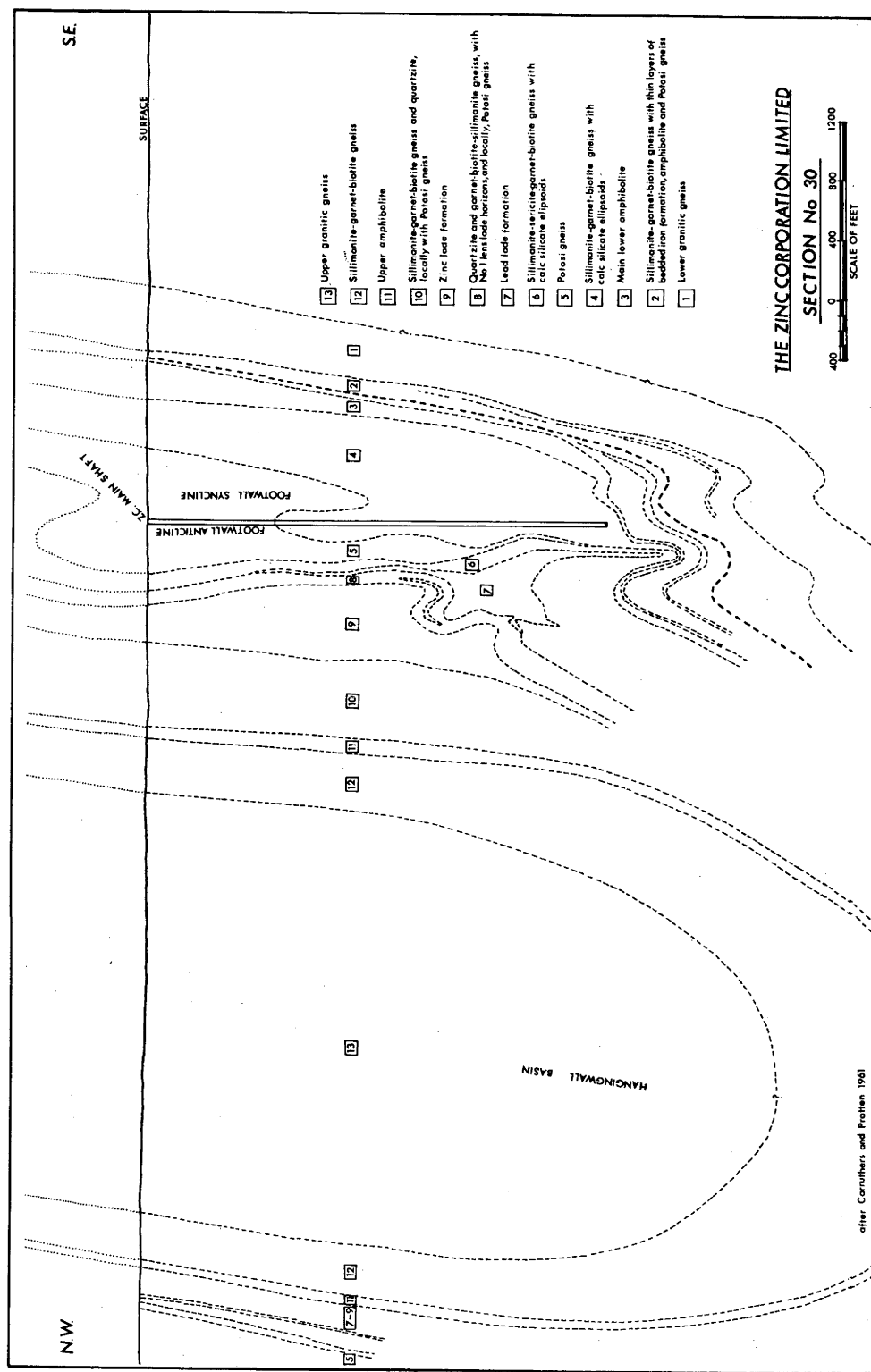
Numerous silver-lead-zinc deposits occur throughout the complex, the largest being the lead-zinc body at Broken Hill. King and Thomson (1953) have classified the silver-lead-zinc deposits



(Fig. 11) The intensity distribution of the original high-grade M_1 metamorphism; after Binns 1963.



(Fig. 12) The retrogressive metamorphism at Broken Hill; after Binns 1963.



(Fig. 13) The stratigraphy in the immediate Mines area, Broken Hill; after Carruthers and Pratten 1961.

into two types, the Broken Hill type and the Thackaringa type under the following criteria:

1. Characteristics of the Broken Hill type ores.

- (a) occur in high grade metamorphic rocks.
- (b) occur as replacement of beds and/or shears in a tightly folded environment.
- (c) are associated with rock alteration involving the introduction or development of much quartz and garnet, producing siliceous garnet rocks, garnet quartzite and garnet sandstones.
- (d) galena and marmatite occur, in association with calcite, fluorite, manganese silicates, pyroxenes, blue or opalescent quartz, green feldspar and gahnite.

The Broken Hill lode contains all these features whereas, in outlying deposits some characteristics may be missing.

2. Characteristics of the Thackaringa type ores.

- (a) occur with one notable exception in the outer fringe of the Broken Hill type deposits, and on the fringe of the high grade metamorphic area.
- (b) Occur along fractures, generally weak and mostly flat dipping. (Thackaringa alone appears to behave like a folded bed.)

- (c) occur as veins with variable development of banding and quartz crystals.
- (d) the ore is coarse-grained galena in a gangue of coarse to very coarse-grained siderite with quartz.
- (e) garnet is absent and blue quartz, gahnite and sphalerite are uncommon. The presence of some of these minerals in or near siderite lodes suggests that there is some gradation from one type to another.

The richest of the Thackaringa type ore-bodies, the Consul mine, is only 600 yards east of the outcrops of the Broken Hill lodes.

The following sections briefly describe the geology by dividing the region into a number of areas.

1. The Broken Hill area.

This section of the Willyama complex is by far the best known geologically. The rocks have undergone metamorphism to granulite facies (Appendix 1, Turner and Verhoogen, 1960) and are now folded granitic gneisses, sillimanite-garnet-biotite gneisses and amphibolites, some with two pyroxenes (Binns, 1962). Shearing and recrystallization to greenschist and amphibolite facies is widespread and shear zones, concordant and discordant with the main structural trend are common, as are concordant and discordant

pegmatite. Gustafson et. al. (1950) proposed a detailed stratigraphic column. Additions to this were made by King and Thompson (1953) and Carruthers and Pratten (1958) reinterpreted the succession across the Zinc Corporation Ltd. lease. (Fig. 13).

2. The North West.

The region from Mt. Robe to Silverton is composed of andalusite-mica schist with minor sillimanite and garnet, amphibolites, minor granite intrusions and immense areas of pegmatite. It appears that the grade of metamorphism has decreased to the north. (King and Thompson 1953, p.556; Andrews 1922; Binns 1963, Figure 3, p.243.) Binns concludes on petrological evidence that a later metamorphism with metasomatic introduction of potassium has been responsible for many of the petrological features of this area. Along the line of the Mt. Franks Fault Binns describes knotted schists which have crystallized from pelitic sediments without the introduction of potassium. He considers that these two distinct metamorphic types may be related.

The area contains numerous lead deposits of the Thackaringa type.

3. The North East.

Between the Mt. Franks Fault, Brewery Well and Yanco Glen the rocks consist mainly of metamorphosed sandy or shaly

sediments. Original bedding is preserved and the schists may be mistaken for Torrowangee sediments. North of Yanco Glen great masses of pegmatite occur which in general parallel the structural trend. This area also contains the main intrusions of Mundi Mundi granite; a massive coarse-grained muscovite-albite-microcline granite with a few sedimentary (schistose) xenoliths.

The area has lead deposits which are mainly Thackaringa type, though King and Thompson (1953) have marked the Allendale Mine as Broken Hill type.

4. Thackaringa area.

This area is to the west of Broken Hill and to the south of an immense east-west crush zone, the Thackaringa-Pinnacles Fault. The rocks are micaceous and feldspathic schists with negligible sillimanite and garnet. There are numerous large sills of amphibolite, augen gneiss, aplite, and pegmatite generally concordant with the schistosity.

This area contains the "type" Thackaringa lead deposits.

5. The Little Broken Hill area.

The rocks are granitic gneisses, amphibolites and "Potosi" gneisses which have been strongly folded and sheared. These are associated with innumerable concordant and discordant pegmatites and some serpentinite intrusions.

The lead-zinc lode is of the Broken Hill type and resembles these lodes in everything but size.

Binns (1963) refers to the retrogressive metamorphism in this area as the Darling Range type metamorphism (Fig. 12).

C. THE GEOLOGICAL HISTORY.

In order that isotopic age determinations may be compared with field relationships it is essential that the geological history of the region be accurately known.

A number of authors have proposed geological histories for the Broken Hill region. The major contributions are ^{recorded} here.

Andrews (1922)

- (a) Deposition of the sediments.
- (b) Deep burial leading to metamorphism and
 - (i) intrusion of granitic rocks
 - (ii) intrusion of gabbro
 - (iii) emplacement of pegmatite
 - (iv) intense folding
- (c) Shear zones developed
- (d) The lodes were emplaced in the shears.
- (e) Granite, serpentinite and dolerite were emplaced in areas of tension
- (f) Deposition of the Torrowangee sediments
- (g) Folding of the Torrowangee sediments.

Browne (1922) in the same volume proposed a slightly different history which is not included here. Browne and Andrews recognised a decrease in intensity of metamorphism to the north.

Gustafson, Burrell and Garretty (1950)

- (a) Deposition of the sediments
- (b) Intrusion of granite, gabbro and pegmatite sills.
- (c) Regional folding and metamorphism producing gneisses.
- (d) Intrusion of serpentinite, granite, aplite and large quantities of pegmatite
- (e) Uplift and erosion
- (f) Development of crush zones and zones of shear
- (g) Intrusion of dolerite
- (h) Emplacement of "Lode pegmatites", shearing on old planes and emplacement of the lodes
- (i) Uplift and erosion
- (j) Deposition of the Torrowangee sediments

Previous authors (Mawson 1912, Stillwell 1922, 1958) postulated that the ore was emplaced in shear zones whereas Gustafson et. al. considered the ore was introduced by replacement of favourable beds.

King and Thompson (1953)

- (a) Deposition of sediments, including ferruginous horizons.

- (i) introduction of lead and zinc sulphides by some syngenetic process
- (ii) introduction of basic sills
- (b) Severe deformation and high grade metamorphism. The iron-bearing and the lead-zinc deposits were recrystallized and structurally concentrated along particular fold axes
 - (i) ultrabasic serpentinites were introduced.
- (c) Intrusion of dolerite dykes
- (d) Uplift and erosion
- (e) Deposition of Torrowangee sediments
- (f) Folding and faulting and the emplacement of granite and pegmatite in the Willyama.
- (g) Erosion and late movements produce present topography.

Leslie and White (1955) found Mundi Mundi granite boulders in the basal tillite of the Torrowangee thereby proving that the granite was older than the Torrowangee sediments. The absence of pegmatite from the Torrowangee indicates the pegmatite is pre-Torrowangee. Step (f) should therefore be in an "older" position.

The theory of a sedimentary origin for the lead-zinc lode has produced an unsettled controversy. Stillwell (1959) prefers the theory of the hydrothermal introduction of the ore into shears

at some time later than the dolerite dykes and probably contemporaneous with a period of dynamic metamorphism. Stanton (1960) and Stanton and Russell (1959) have greatly developed the theory of syngenetic ore deposits (Chapter VI).

Binns (1963) proposed the following history

- (a) M1 Detrital sediments were metamorphosed and reconstituted into garnetiferous, feldspathic, siliceous and pyroxene gneisses.
- (b) M2 A period of potassium metasomatism was experienced in the north-west Barrier Ranges.
- (c) M3 Recrystallization of pelitic and basic rocks to andalusite schists and amphibolites along a line parallel to the Mt. Franks Fault.
- (d) Deposition of the Torrowangee sediments
- (e) M4 Dynamic metamorphism altering M2 and M3 products in the north and north west
- (f) Darling Range Type Metamorphism. To the west and east of Broken Hill sericitisation and recrystallization is widespread and often accompanied by shearing.

Binns considers that M2 and M3 may be related in time and that possibly the Mundi Mundi granite intrusions are of the same epoch.

D. CONCLUSIONS.

Previous authors are in agreement that a major metamorphism occurred which was most intense in the Broken Hill area but weakened to the north and west. Generally the possibility of a metamorphism before this major event is not considered although Andrews (1922), Gustafson et. al. (1950) and King and Thompson (1953) proposed igneous intrusions of granite, amphibolite and pegmatite at or before the major metamorphism.

It is possible therefore that considerable time has elapsed between the deposition of the initial sediments and the major metamorphism, an important point in the discussion of the lead ages.

The relative ages of the pegmatites are very difficult to determine. Large bodies as well as lesser veins and lenses occur everywhere. Andrews considers the pegmatites to be early phases of the major metamorphism. Gustafson et. al. proposed three periods of pegmatite injection, one before the major metamorphism, one immediately afterwards and a third "Lode pegmatite emplacement" with the lodes at a later period. King and Thompson had them intruded after the deposition of the Torrowangee sediments.

It appears that a number of pegmatites have been deformed, by the major metamorphism. Others post-date at least the most intense phase of the major metamorphism, as they appear

uncertainty in the lead model ages arising from the uncertainty in the age of the earth. The purpose of this section is to determine this uncertainty, and also to determine the uncertainty in the age due to errors in the measurement of the lead isotopes. First it is necessary to consider the physical models on which the lead age calculations are based.

At present methods of model-lead age calculations are mainly of two types.

The first model, called the Holmes-Houtermans method by Russell and Farquar (1960) assumes that all lead at time t_0 had the same "Primordial" isotopic composition and that, throughout time, the source region has remained closed to uranium, lead and thorium. The U/Pb, Th/Pb ratios are not uniform throughout the source region but can vary from one U-Pb system to another. The lead age t represents the time since lead was separated from its parent U-Pb system and concentrated in the crust as lead minerals.

The theoretically derived equation used by Holmes (e.g. 1956) and Houtermans (e.g. 1953) to calculate lead ages (t_1) is

$$\frac{y - y_0}{x - x_0} = \frac{U^{235}}{U^{238}} \frac{e^{\lambda_2 t_0} - e^{\lambda_2 t_1}}{e^{\lambda_1 t_0} - e^{\lambda_1 t_1}} \quad \text{----(1)}$$

where x , y are the ratios $\text{Pb}^{206}/\text{Pb}^{204}$ and $\text{Pb}^{207}/\text{Pb}^{204}$ for the sample, x_0 and y_0 the corresponding values for "primordial" lead λ_1 and λ_2 are the decay constants of U^{238} and U^{235} and $\text{U}^{238}/\text{U}^{235} = 137.8$.

A second model for the calculation of lead ages is that proposed by Alpher and Herman (1951) and adopted and modified by Russell and associates in later years. This model requires that U/Pb and Th/Pb ratios have remained uniform throughout the source region since t_0 . This contrasts with the Holmes-Houtermans model which requires constant values for U/Pb and Th/Pb ratios since t_0 in any part of the source region but allows a variation in these values between parts. Although the assumption of uniform ratios throughout the source region since t_0 seems to be a severe restriction, recent work indicates that this model is closer to the truth than that proposed by Holmes and Houtermans.

Russell defines anomalous leads as those which have been derived from more than one Th-U-Pb system, and clearly feels that many leads assigned ages on the Holmes-Houtermans model should be classed as anomalous. In the Russell-Farquar model data-points from "single stage" or "ordinary" leads should lie on a single growth curve beginning at a point representing primordial lead. The selection of single stage leads has been facilitated by the theories of Stanton (1960), (Stanton and Russell, 1959). Stanton interprets lead from conformable lead deposits (e.g. Broken Hill type, Chapter 5) as being derived directly from the parent Th-U-Pb source region during a magmatic episode under conditions similar to island-arc volcanism.

Russell and Farquar (1960) calculate lead ages by means

of the following relationship of x and y in terms of t , the time of formation of the single stage lead deposit.

$$\frac{x}{y} = \frac{U^{235}}{U^{238}} \left(\frac{\frac{a}{137.8V_0} - e^{\lambda_1 t} + 1}{\frac{b}{V_0} - e^{\lambda_2 t} + 1} \right) \quad \text{----(2)}$$

Kanasewich (1962).

where a , b and V_0 are the present day ratios of Pb^{206}/Pb^{204} , Pb^{207}/Pb^{204} and U^{235}/Pb^{204} respectively. a , b and V_0 are determined experimentally from a combination of meteoritic data and single stage terrestrial leads.

The values of " a " and " b " do not appear to be independent of assumptions for a_0 , b_0 and t_0 as:-

$$a = x_0 + 137.8 V_0 (e^{\lambda_1 t_0} - 1)$$

$$b = y_0 + V_0 (e^{\lambda_2 t_0} - 1)$$

which if substituted in Russell's equation reduces it to a form identical with the Holmes-Houtermans expression.

Assuming that a particular sample lies on Russell's growth curve the main advantage in Russell's equation appears to be that errors in the relative value of Pb^{204} are not so readily introduced.

C. THE RELIABILITY OF THE CONFORMABLE LEAD AGES.

It has been noted that mathematically both lead methods can be expressed in the Holmes-Houtermans form. An error in value

of t , assuming a single stage lead, is the result of errors in x_0 , y_0 , t_0 and x and y . In the following pages I shall consider the effect on t of errors in t_0 and x and y .

1. The uncertainty in t due to errors in x and y .

A simple differentiation of the Holmes-Houtermans expression with respect to a variable " z " gives

$$\frac{\Delta t}{t} = \frac{x}{t} \left[\frac{\frac{1}{c} (e^{\lambda_2 t_0} - e^{\lambda_2 t})}{\left\{ \frac{1}{c} (x - x_0) \lambda_2 e^{\lambda_2 t} \right\} - \left\{ (y - y_0) \lambda_1 e^{\lambda_1 t} \right\}} \right] \frac{\Delta x}{x} - \frac{y}{t} \left[\frac{(e^{\lambda_1 t_0} - e^{\lambda_1 t})}{\left\{ \frac{1}{c} (x - x_0) \lambda_2 e^{\lambda_2 t} \right\} - \left\{ (y - y_0) \lambda_1 e^{\lambda_1 t} \right\}} \right] \frac{\Delta y}{y}$$

where $\lambda_1 = 0.154 \times 10^{-9} \text{ y.}^{-1}$, $\lambda_2 = 0.98 \times 10^{-9} \text{ y.}^{-1}$, $x_0 = 9.56$, $y_0 = 10.42$ (Murthy and Patterson, 1962).

For Broken Hill leads x varies from 16.109 to 16.131 and y from 15.526 to 15.548 (Ostic, 1962).

Assuming $t_0 = 4.5 \times 10^9 \text{ y.}$ and $t = 1.5 \times 10^9 \text{ y.}$, then

$$\frac{\Delta t}{t} = 0.631 \frac{\Delta x}{x} - 0.788 \frac{\Delta y}{y} \quad \text{---(3)}$$

The precision of measurements of x and y in the literature is in the order of 0.5% standard deviation or better. The uncertainty in t (for $t = 1500$) due to errors in measurement is small.

Richards (1962 a and b) and Russell (1963) suggest the major discrepancy between lead ages calculated from different models

is due to uncertainty in t_0 .

2. The uncertainty in t due to uncertainty in t_0 .

The Holmes-Houtermans equation can be differentiated with respect to t_0 to give -

$$\frac{\Delta t}{t} = \frac{t_0}{t} \left\{ \frac{a \lambda_1 e^{\lambda_1 t_0} - b \lambda_2 e^{\lambda_2 t_0}}{a \lambda_1 e^{\lambda_1 t} - b \lambda_2 e^{\lambda_2 t}} \right\} \frac{\Delta t_0}{t}$$

where $a = e^{\lambda_2 t_0} - e^{\lambda_2 t}$; $b = e^{\lambda_1 t_0} - e^{\lambda_1 t}$

Assuming $t = 1.5 \times 10^9$ y. and $t_0 = 4.5 \times 10^9$ y. the error magnification expression becomes

$$\frac{\Delta t}{t} = - 9.1 \frac{\Delta t_0}{t_0} \quad \text{-----(4)}$$

3. The precision of t_0 .

The recent determinations of t_0 range from 4.50 to 4.56×10^9 y. Patterson (1956) placed t_0 in the range $4.56 \pm 0.07 \times 10^9$ y.

(the meaning of the limits is not clear to me). An independent calculation of the slope of the isochron through Patterson's five points gives 0.608 (calculated by double regression) with a standard deviation of approximately 1.06% . This corresponds to a standard deviation of approximately 0.32% and 95% confidence limits of $\pm 1.02\%$ in t_0 .

Murthy and Patterson suggest 0.59 ± 0.01 as the slope of

the zero isochron, corresponding to a t_0 of $4.55 \pm 0.025 \times 10^9$ y. The limits refer to a standard deviation. This slope corresponds to a t_0 of 4.55 ± 0.025 (S.D.) $\times 10^9$ y. with 95% limits (assuming normality) of $\pm 1.1\%$.

On present knowledge $\pm 1.1\%$ appears to be a reasonable 95% limit for t_0 .

4. Broken Hill Lead Ages.

Ostic (1962, p.60) records the following lead ages for the Broken Hill conformable lead deposit.

$$\begin{aligned} t_0 &= 4.55 \times 10^9 \text{ y.} & , & & t_{B.H.} &= 1616 \times 10^6 \text{ y.} \\ t_0 &= 4.53 \times 10^9 \text{ y.} & , & & t_{B.H.} &= 1661 \times 10^6 \text{ y.} \end{aligned}$$

Richards (1962) presents two analyses of Broken Hill conformable leads with ages calculated using the Russell-Farquar model and the Holmes-Houtermans model

Sample	Russell-Farquar		Holmes-Houtermans	
	6-7	8-4	$t_0 = 4.55$	$t_0 = 4.51 \times 10^9 \text{ y.}$
13	1590	1620	1571	1683
66	1577	1560	1560	1673

It is obvious that no close limits can be set on this age. If Murthy and Patterson's range in t_0 is accepted the uncertainty in the Broken Hill lead age is (at the 95% level) $\pm 10\%$.

Tentatively this age is 1600 ± 160 m.y. Stanton and

Russell (1959) have classified lead from the Broken Hill deposit as single stage or ordinary lead. The model age of the lead therefore represents the time when the lead was separated from its parent Th-U-Pb system. It is likely that this is also the time of emplacement as a lead deposit, as long periods in the crust as a minor constituent would increase the probability of this single stage lead being contaminated by radiogenic lead. The lead age is not necessarily the age of the enclosing sediments. To state this implies :-

- (i) a syngenetic origin of the lead
- (ii) emplacement of the lead very soon after deposition of the sediment

In summary the age of the Broken Hill conformable lead deposit represents the age the lead was differentiated from its parent Th-U-Pb system calculated assuming a t_0 and a primordial lead composition. This age is approximately 1600 m.y. with an uncertainty of as much as $\pm 10\%$ depending on the limits of uncertainty in t_0 .

D. THACKARINGA LEADS.

The distinct geological difference between the Broken Hill conformable leads and the Thackaringa vein leads is discussed in Chapter V. Russell and others (e.g. Russell et. al. 1957, Kanasewich 1963) have measured lead isotopes from these deposits and

have found that unlike the consistent isotopic ratios of leads from the Broken Hill lodes, the Thackaringa leads have ratios with wide variations. These ratios do not lie on the growth curve for primary lead. These authors therefore consider the Thackaringa leads to be anomalous leads resulting from the mixture of lead from two or more Th-U-Pb systems. Under the assumption that the Thackaringa leads were two stage leads Kanasewich (1963) calculated the time of mixing of lead from system 1 with that of system 2 as 510 ± 80 m.y. (S.D.).

The expression used to calculate this was -

$$R = \frac{y - y_0}{x - x_0} = \frac{1}{137.8} \frac{(e^{\lambda_2 t_1} - e^{\lambda_2 t_2})}{(e^{\lambda_1 t_1} - e^{\lambda_1 t_2})} \quad \text{----(5)}$$

where x_0 and y_0 are the $\text{Pb}^{206}/\text{Pb}^{204}$ and $\text{Pb}^{807}/\text{Pb}^{204}$ ratios of ordinary lead at t_1 . x and y are the measured ratios established by mixing ordinary lead, separated from its parent Th-U-Pb system at t_1 , with radiogenic lead formed between t_1 and t_2 , at time t_2 and concentrating this mixed lead in an ore deposit. As well as assuming that the contaminating radiogenic lead formed between t_1 and t_2 the model assumes that the only "common" lead in the system 2 "radiogenic" lead is ordinary lead separated from the parent Th-U-Pb system at t_1 .

I shall briefly discuss the uncertainty in this age due to an uncertainty in t_0 . It can be seen that the form of Kanasewich's equation is identical with that of Holmes and Houtermans. Therefore following equation

$$\frac{\Delta t_2}{t_2} = \frac{t_1}{t_2} \left\{ \frac{c \lambda_1 e^{\lambda_1 t_1} - d \lambda_2 e^{\lambda_2 t_1}}{c \lambda_1 e^{\lambda_1 t_2} - d \lambda_2 e^{\lambda_2 t_2}} \right\} \frac{\Delta t_1}{t_1}$$

where $d = e^{\lambda_1 t_1} - e^{\lambda_1 t_2}$, $c = e^{\lambda_2 t_1} - e^{\lambda_2 t_2}$ and $t_1 = 1.5 \times 10^9$ y., $t_2 = 0.50 \times 10^9$ y., $t_0 = 4.5 \times 10^9$ y.

$$\begin{aligned} \text{Then } \frac{\Delta t_2}{t_2} &= 3 \left\{ -1.26 \right\} \frac{\Delta t_1}{t_1} \\ &= -3.78 \frac{\Delta t_1}{t_1} \end{aligned}$$

$$\frac{\Delta t_2}{t_2} = 34.4 \frac{\Delta t_0}{t_0} \quad \text{----(6)}$$

The uncertainty in t_2 is proportional to the uncertainty in t_1 and as t_1 depends on t_0 , a one percent uncertainty in t_0 is magnified to a possible 34.4% uncertainty in t_2 (where t_2 is 0.50×10^9 y.).

E. URANIUM-LEAD AGES.

1. Olary Province.

U-Pb ages have been reported for Pre-Adelaide System rocks from the Olary Province, South Australia. These rocks have been correlated with the Willyama Series (i.e. Campana, 1958).

Crocker's Well : Greenhalgh and Jeffery (1959) report U-Pb and

Th-Pb age determinations on brannerite and davidite from this area.

Brannerite occurs as fracture filling and replacement in a brecciated

shear zone in an adamellite, believed to be a late stage local intrusive into the "Archaean" sequence. Davidite occurs in pegmatite and primary quartz veins in the main granitic rocks.

The age of the absite (brannerite) is $^{206}/238$, 610 ± 11 m.y.; $^{207}/235$, 674 ± 3 m.y.; $^{207}/206$, 895 ± 15 m.y.; $^{208}/232$, 675 ± 5 m.y. (the precise meaning of the uncertainties is unknown).

The davidite age is, in the same order, 1628 ± 10 m.y.; 1660 ± 25 m.y.; 1702 ± 60 m.y.; 1252 ± 150 m.y.

Greenhalgh and Jeffery also reported a biotite K-Ar age of 520 m.y. on a biotite hand picked from the thorium brannerite.

Radium Hill : This is 50 miles south-east of Crocker's Well in pre-Adelaide system schists and gneisses identical to those at Crocker's Well. Greenhalgh and Jeffery report a lead age on a davidite at 787 ± 10 m.y., 764 ± 35 m.y., 691 ± 20 m.y. (no Th-Pb age). This contrasts with a $^{207}/206$ determination of 1510 m.y. by Collins et. al. on davidite.

These results, if confirmed by further work, show at least two periods of uranium mineralisation, (unless the brannerite result is a massive Pb-loss effect of a later metamorphic event upon material formed at the earlier time).

F. K-AR AGES OF WILLYAMA SERIES ROCKS.

Evernden and Richards (1961) reported two K-Ar biotite ages of 504 m.y. and 526 m.y. from the granitic gneisses in the vicinity of the Broken Hill lodes. Binns and Miller (1963) measured a series of K-Ar ages on Willyama rocks in order to date petrologically defined metamorphic events. Binns' conclusions are based on his own measurements and also on the measurements of Evernden and Richards (1961) and Russell (op. cit).

Binns' (1963) proposed the following events

- M1 : High-grade metamorphism - 1500 m.y.
- M2 : Potash metasomatism - 1300 m.y.
- M3 : Andalusite grade metamorphism

The intrusion of the Mundi Mundi granite is probably related to M2 and M3.

- M4 : Folding and metamorphism of the Torrowangee Series - 920 m.y.
- Darling Range type metamorphism ; a low grade metamorphism recorded by Evernden and Richards - 520 m.y.

Dr. McDougall and Dr. Richards have made further analyses of samples donated by Dr. Binns and have kindly allowed me to quote their results. (Table 13). Richards has determined K-Ar ages in a number of other micas from Willyama rocks and I have carried out Rb-Sr age determinations on a number of these. The results have been reported in Richards and Pidgeon (1963) which is included as Appendix

Broken Hill Results on Samples Supplied by R.A. Binns

Sample Number	Cambridge Reference	Mineral	K content (%)	*Ar ⁴⁰ /K ⁴⁰	Air Correction %	Calculated Age (m.y.)	Binns and Miller
679	143-2 (84367)	Muscovite	7.69	.1288		1460	(1230 (1345
679	"	Biotite	4.64	.0515	1.9	724	762
680	122-4 (91394)	Hornblende	0.212	.1572	7.6	1670	-
681	190-4 (84332)	Hornblende	0.328	.0718	10.3	950	890
682	178-1 (84327)	C-pyroxene				2300	
683	123-11 (84336)	Hornblende	0.500	.0917	5.3	1140	990
684	113-3 (84324)	Hornblende	0.57	.1581	2.0	1680	-
685	101-1 (84322)	Hornblende	0.105	.3520	11.8	2700	-
		O-pyroxene	.0066	1.754	19.3	5330	-

$$\lambda_e = 0.584 \times 10^{-10} \text{ y.}^{-1}$$

$$\lambda_\beta = 4.72 \times 10^{-10} \text{ y.}^{-1}$$

2. A discussion of these biotite ages is presented in Chapter VIII of this thesis.

G. SULPHUR ISOTOPES.

Lawrence and Rafter (1962) have determined the isotopic composition of sulphur from galena and sphalerite in primary and supergene enriched sections of the Broken Hill ore-body. Their results show that the isotopic composition of Broken Hill primary sulphur is similar to meteoritic sulphur. The authors make no statement on the implications of these measurements though it may be inferred that they favour formation of the ore by a magmatic rather than a sedimentary process.

CHAPTER VII.

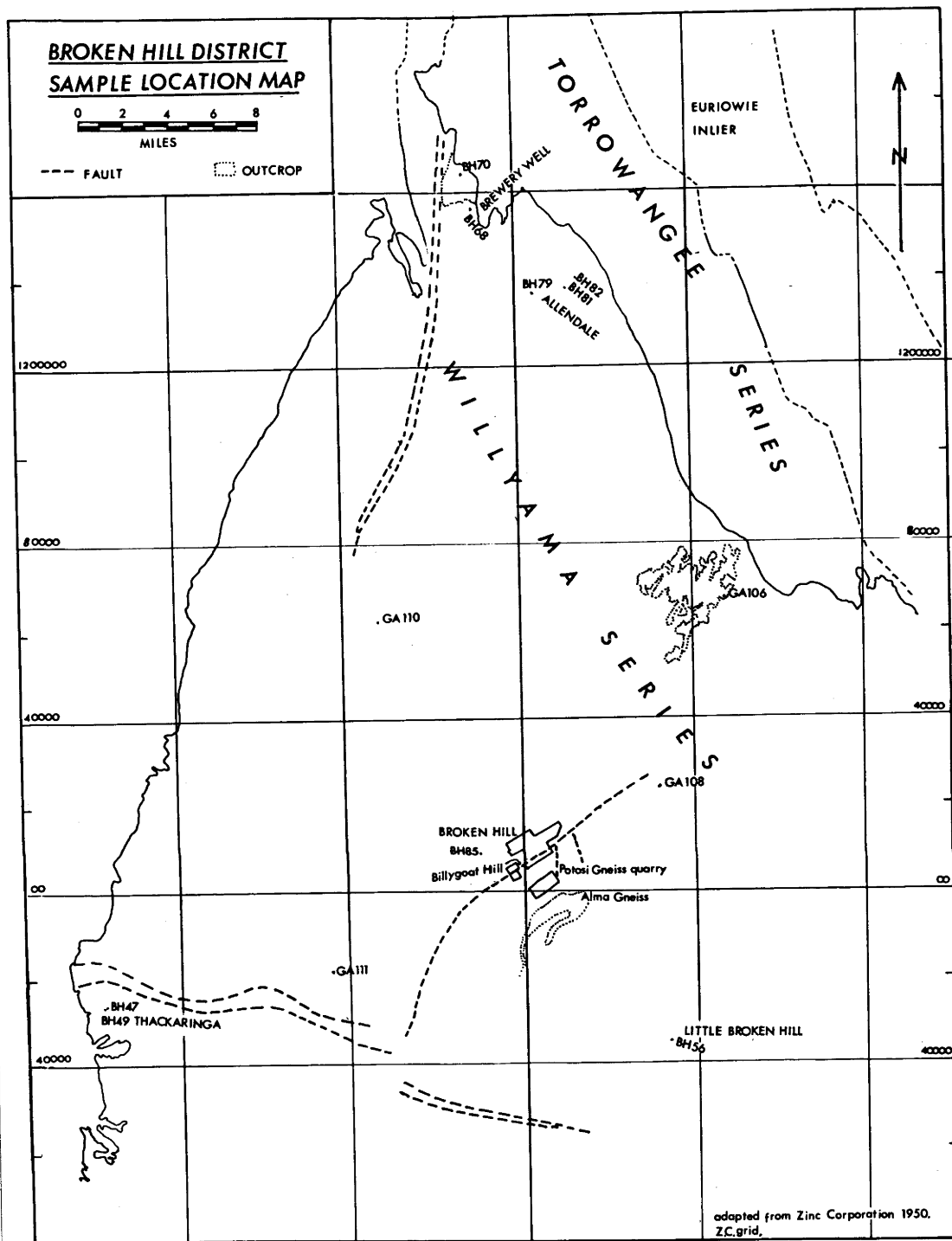
THE Rb-Sr ISOTOPIC ANALYSES.

A. INTRODUCTION.

This chapter presents the Rb-Sr isotopic analyses for Willyama rock and mineral samples other than garnet and some biotites which are recorded in Chapter VIII. It is also concerned with the samples analysed. The field relationships of samples are discussed and preliminary remarks on interpretation are given.

The experimental data is presented in tables and on $\text{Rb}^{87}/\text{Sr}^{86}$ against $\text{Sr}^{87}/\text{Sr}^{86}$ plots. The relevant table or figure is indicated in brackets near the samples being discussed. Except for Fig. 22 biotite results are not included in the figures. Ages and initial ratios are calculated by the method expressed in Chapter II and all indicated limits are 95% confidence intervals.

Samples of sillimanite gneiss, granitic gneiss and garnetiferous (Potosi) gneiss were collected from the area of high grade metamorphism (Figs. 11 and 12). Calcite xenoliths from within the sillimanite gneiss and a garnet-cordierite granulite "xenolith" from within the Alma Gneiss were sampled. No low-grade schist samples were taken. I have decided to postpone study of the lower grade rocks until geochronological information has been obtained on other material. Acid intrusive rocks have been studied from the north, north-east and the Broken Hill area. Determination of the



(Fig. 14) The location of samples distant from the town of Broken Hill.

age relationships of the pegmatites, the alkali rich granite intrusives and the metamorphic events is considered a major part of this study.

B. THE GARNET-SILLIMANITE GNEISSES.

1. Total-rock analyses.

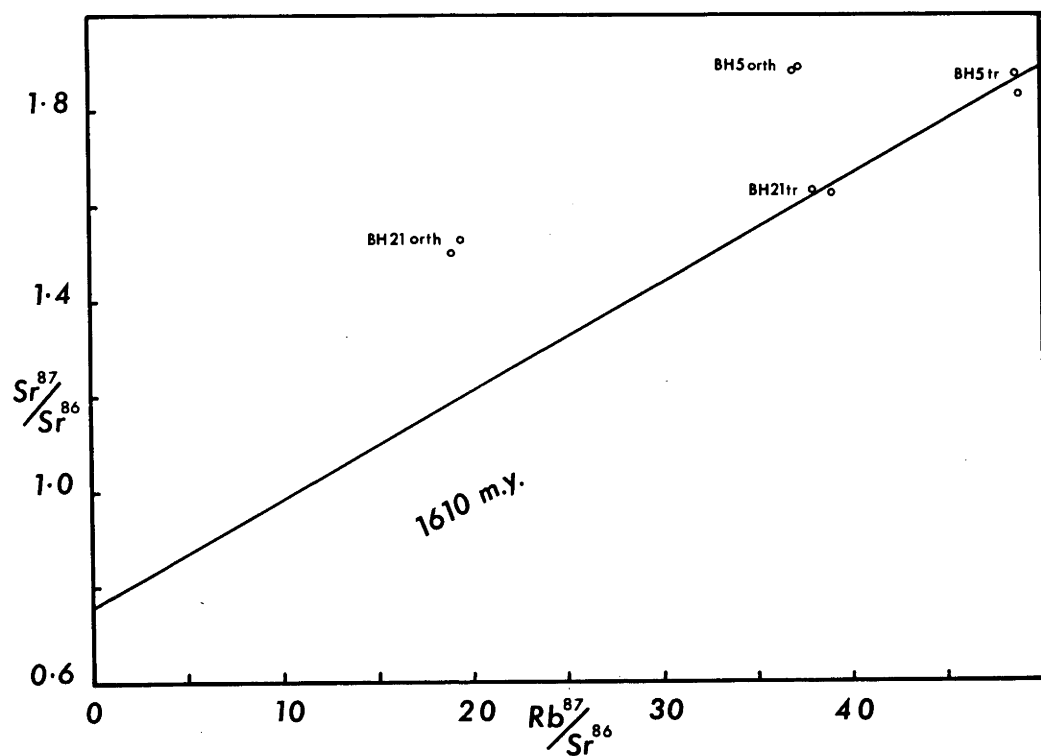
Samples of garnet-sillimanite gneiss were collected underground at New Broken Hill Consolidated Ltd (N.B.H.C.) Zinc Corporation (Z.C.) and North Broken Hill Ltd. (N.B.H.).

The garnet-sillimanite gneisses are products of the high-grade "granulite facies" metamorphism labelled M1 by Binns (1963). At least one retrogressive metamorphism has overprinted M1 and the majority of the garnet-sillimanite gneisses have retrogressive mineral assemblages (Appendix 1). To determine M1 I analysed two garnet-sillimanite gneiss samples which had only minor recrystallisation. To investigate the effect of the retrogressive metamorphism on strontium and rubidium isotopes in rock and mineral systems I have analysed a series of sillimanite-garnet gneisses with progressively increasing retrogressive recrystallization.

BH5 has no observed retrogressive recrystallization and BH21 has only minor sericitisation. These two rocks, especially

TABLE 14. Rb-Sr isotopic analyses of the garnet-sillimanite gneiss samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH5.</u>						
Total-rock	1.502	0.0308	48.82		1.878	
	1.468	0.0300	48.97		1.836	
Orthoclase	2.518	0.0679	37.09		1.885	
	2.511	0.0673	37.29		1.905	
Biotite	3.924	0.00312	1259.3		10.620	
	3.966	0.00324	1224.7		10.182	
<u>BH21.</u>						
Total-rock	1.118	0.0297	37.97		1.636	
	1.143	0.0293	38.96		1.632	
Orthoclase	1.745	0.0894	19.52		1.532	
	1.754	0.0926	18.95		1.496	



(Fig. 15) Isochron plot of the unretrogressed garnet-sillimanite gneiss samples.
t.r. - total rock, orth. - orthoclase.

TABLE 15. Rb-Sr isotopic analyses of the sericite-garnet-sillimanite gneiss samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalise $\text{Sr}^{87}/\text{Sr}^{86}$
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BH25.

Total-rock	0.5150	0.1021	5.0441	8.323	0.8711	0.8726
	0.5104	0.1069	4.776		0.8717	
Sericite	0.6024	0.2114			0.8668	
	0.7740	0.2092	3.700		0.8686	
	0.7850					

BH23.

Total-rock	1.0962	0.0732	14.98		1.1004	
Sericite	1.5443	0.1442	10.709		1.0784	
	1.6797	0.1410	10.738		1.0804	
	1.5141					

BH135.

Total-rock	0.9106	0.0629	14.460		0.9506	
Sericite	0.9650	0.0734	13.154		0.9527	
	0.9792	0.0731	13.393		0.9480	

BH137.

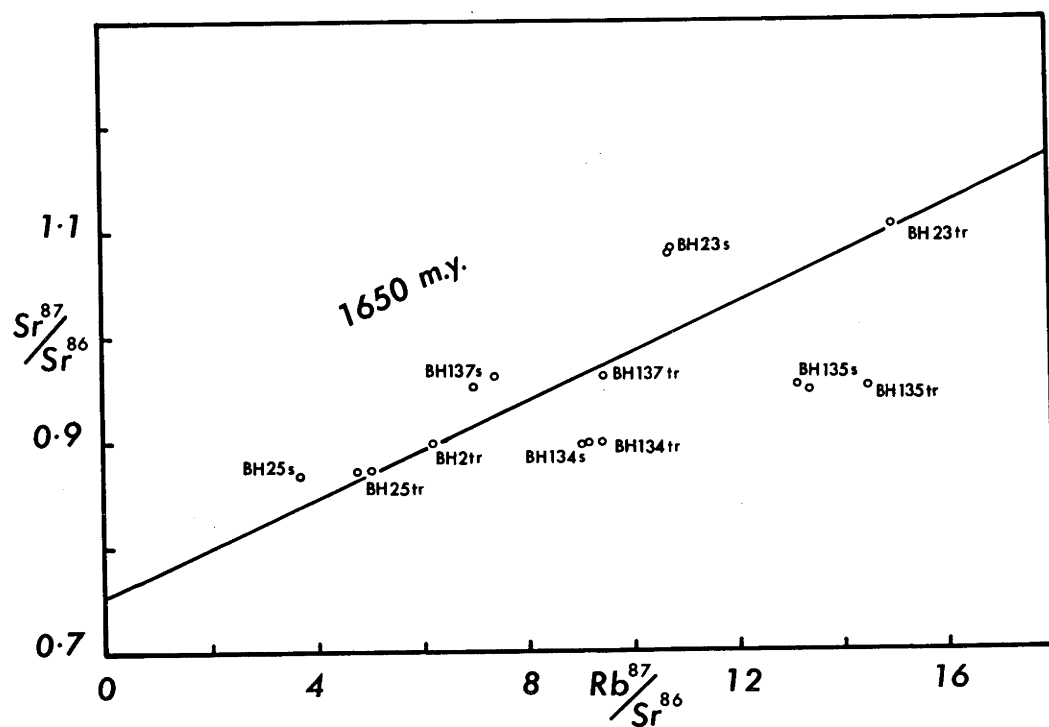
Total-rock	0.8527	0.0904	9.435		0.9615	
Sericite	0.7523	0.1018	7.390		0.9633	
	0.7381	0.1138	6.485		0.9520	

BH134.

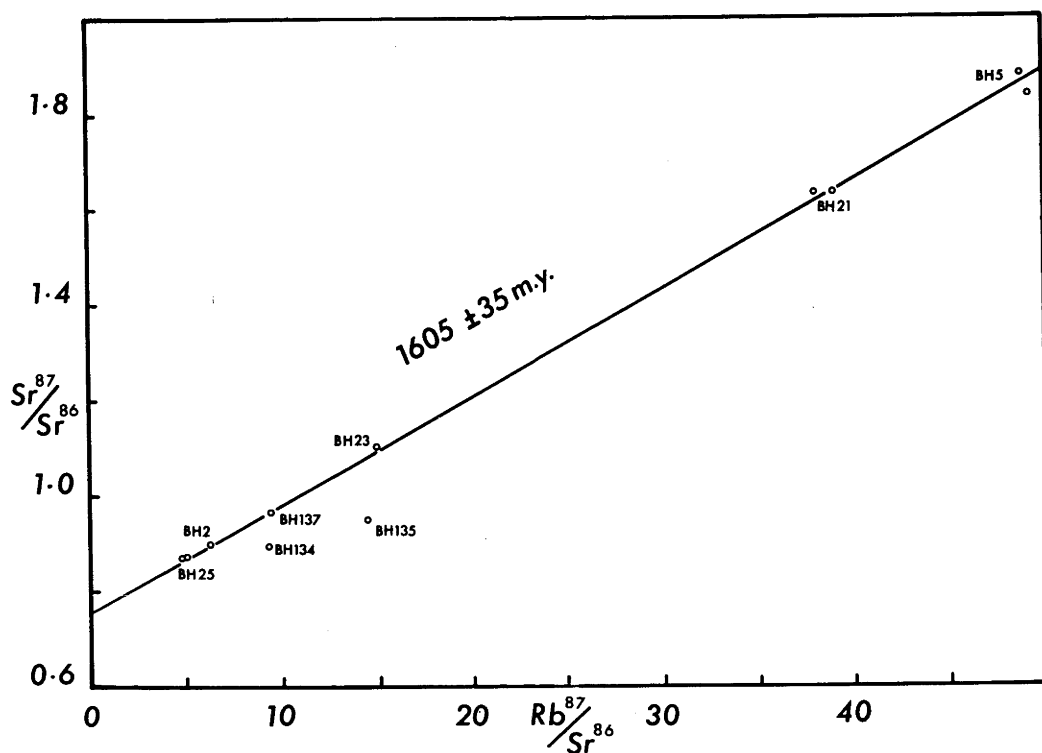
Total-rock	0.7688	0.0817	9.411	8.320	0.8978	0.8958
Sericite	1.0465	0.1139	9.188		0.8953	
	1.7243	0.1149	9.002		0.8933	
	1.0344					

BH2.

Total-rock	0.7222	0.1166	6.190	8.320	0.9007	0.8990
Sericite	1.0229	0.1490	6.865		0.9590	



(Fig. 16) Isochron plot of the retrogressed garnet-sillimanite gneiss samples.
t.r. - total-rock, s. - sericite.



(Fig. 17) Isochron plot of the combined garnet-sillimanite gneiss total-rock samples.

BH5, are pure M1 products and no petrological evidence should have remained a closed system to Rb and Sr isotopes since the M1 event. (results Table 14, Fig. 15). From Fig. 13 the apparent age is 1610 m.y. and the initial $\text{Sr}^{87}/\text{Sr}^{86}$ is 0.73.

BH2, BH23, BH25 and BH137 are sericitised sillimanite gneisses. (Table 15, Fig. 16). Total-rock data points are linearly correlated and have an apparent age of 1650 m.y. and initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.755.

Total-rock samples of shears in the sillimanite gneiss were analysed. BH134 was from the Lord's Hill Fault and BH135 from the "main shear" (Henderson, pers. comm. 1963). (results, Table 15, Fig. 16). It is noted that data-points of these samples do not fall on the 1650 m.y. isochron. Unsheared sillimanite gneiss data-points are plotted on Fig. 17. The least squares age is 1605 ± 35 m.y. and the intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis is 0.759 ± 0.13 .

2. The Mineral Analyses.

Rb-Sr isotopic analyses of BH5 orthoclase and biotite and BH21 orthoclase were made (Table 14, Fig. 15). From Fig. 15 the total-rock-orthoclase lines are not parallel and cannot be interpreted as isochrons. Also the BH5 orthoclase-total-rock line does not intersect the biotite data-point. This differs from Cooma where total-rock and minerals of the high grade metamorphics define a single apparent isochron.

Rb-Sr isotopic analyses were made on sericites from the sericitised sillimanite-garnet gneisses. (Table 15, Fig. 16). Total-rock-sericite lines are not parallel and cannot be interpreted as isochrons.

Mineral analyses are discussed further in Chapter VIII.

C. THE ALMA GNEISS.

The Alma Gneiss is a N.N.E. trending body of granitic gneiss outcropping about two miles east of Broken Hill (Fig. 14) (see map, King and Thompson, 1953). It is composed of a number of distinct granitic rock-types, it includes basic lenses and it is transgressed by pegmatites.

King and Thompson (1953) consider the Alma Gneiss to be closely related to the Hanging Wall Basin gneiss. They believe these granitic gneisses were products of granitisation whereas Andrews (1922) proposed a pre-folding igneous origin. Binns (1963) suggests they were a "sequence of acid volcanic lavas and pyroclastics akin to the leptites of the Scandinavian Pre-Cambrian". He considers that their present form is the result of the M1 metamorphism.

Some of the distinct rock-types composing the gneiss are a medium even grained granite, a garnetiferous augen gneiss, a foliated biotitic augen gneiss and a coarse grained biotite-feldspar gneiss. Strong folding is present in parts of the Alma Gneiss.

BH31 is a sample of muscovite pegmatite which transgresses the Alma Gneiss. Rb-Sr isotopic analyses of minerals from this pegmatite are reported in the section on "acid intrusives".

The main mass of the Alma Gneiss is a strongly foliated granitic gneiss with feldspar porphyroblasts lying in preferred orientation, e.g. GA439. Occasionally this rock-type develops "eyes" with a central biotitic mass surrounded by leucocratic minerals. Areas of this augen gneiss have been sheared and recrystallized with the development of feldspar porphyroblasts. In these biotite forms recrystallized aggregates in a leucocratic matrix.

There are small areas of medium grained foliated granitic gneiss of entirely different texture to GA439 which appear to be residual patches of gneiss which has escaped later deformation and recrystallization. Even so recrystallization appears to have occurred at the margins of these smaller bodies as evidenced by apparent intrusive acid veins containing small biotite aggregates in a leucocratic groundmass.

BH37 is a specimen of a granitic gneiss which is surrounded by sheared and recrystallized granitic gneiss. BH39 is a sample of a medium grained granitic gneiss which exists in the southern portion of the outcrop. It appears that BH39 and BH37 represent older phases in a sheared and recrystallized granitic mass.

BH35 is a sample of a garnet-cordierite-plagioclase-quartz gneiss which forms a "xenolithic" outcrop some ten yards square in the augen gneiss.

In all samples retrogressive recrystallization is present though generally not extensive. (Appendix 1).

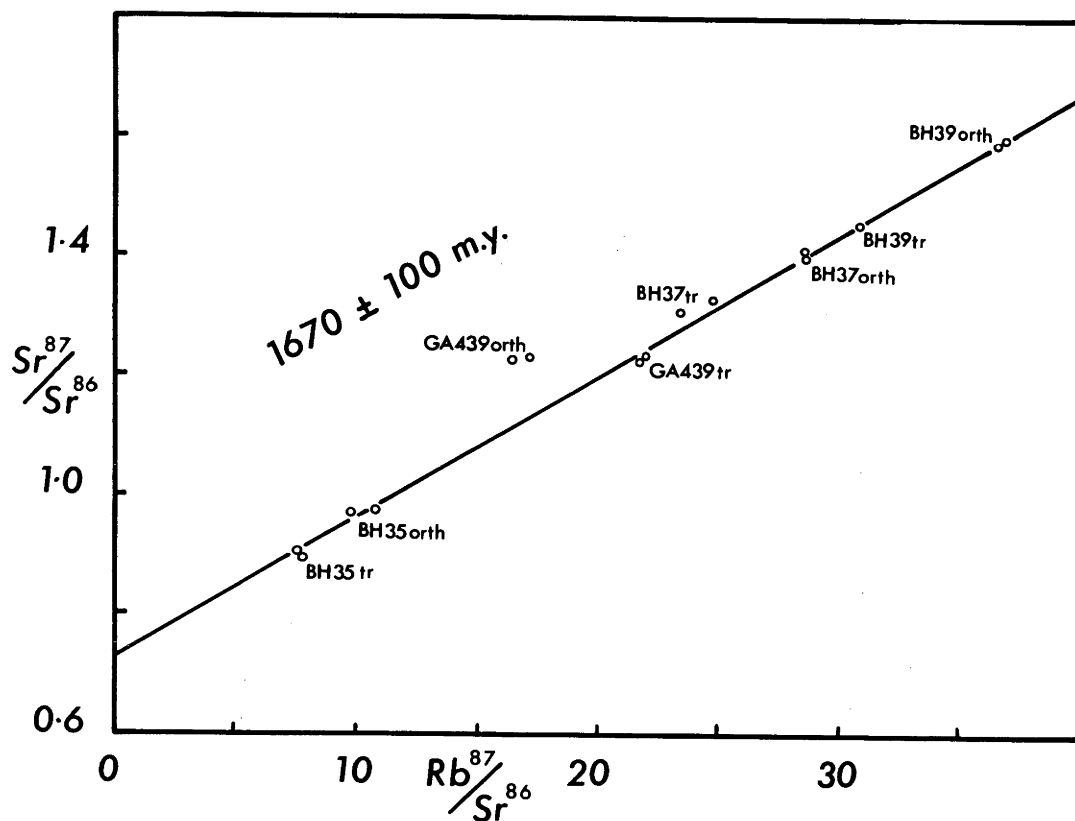
Rb-Sr isotopic analyses were made on total-rock samples of BH39, BH37, BH35 and GA439. (Table, 16, Fig.18). The high linear correlation of total-rock data-points suggests that the total-rocks have the same age and similar initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios. A small uncertainty in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio is not critical to the age determined from individual samples except in the case of BH5.

Rb-Sr isotopic analyses were made on separated mineral fractions. K-feldspar was analysed from all samples and biotite from GA439. (Table 16, Fig. 18). The data-points of orthoclase from BH39, BH37 and BH35 appear to be linearly correlated with the total-rock data-points whereas GA439 K-feldspar is anomalous.

A least squares line through total-rock data-points and K-feldspars from BH39, BH37 and BH35 has an apparent age of 1670 ± 100 m.y. and an intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.732 ± 0.036 .

TABLE 16. Rb-Sr isotopic analyses of the Alma Gneiss samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH37.</u>						
Total-rock	0.8614	0.0369	23.33		1.3077	
	0.8580	0.0345	24.87		1.3268	
K-feldspar	1.5655	0.0548	28.55		1.3996	
	1.5342	0.0535	28.66		1.4150	
<u>BH39.</u>						
Total-rock	1.084	0.0387	28.04		1.389	
	1.069	0.0319	33.50		1.505	
k-feldspar	1.854	0.0507	36.58		1.589	
	1.859	0.0504	36.91		1.605	
<u>BH35.</u>						
Total-rock	0.552	0.0706	7.814		0.9014	
	0.557	0.0699	7.962		0.9062	
K-feldspar	1.470	0.1460	10.07		0.9798	
	1.440	0.1486	9.72		0.9782	
<u>GA439.</u>						
Total-rock	0.9149	0.0416	21.99	8.295		1.2341
	0.9273	0.0427	21.70	8.390		1.2283
K-feldspar	1.232	0.0715	17.23	8.311		1.2309
	1.168	0.0710	16.44	8.332		1.2307
Biotite	3.756					
	3.839	0.0043	892.8		6.979	
	3.512	0.0036	975.5		8.093	



(Fig. 18) Isochron plot of the Alma Gneiss samples.
t.r. - total rock, orth. - orthoclase.

D. THE HANGING WALL BASIN GNEISS or UPPER GRANITIC GNEISS.

This gneiss forms the upper member of the Carruthers and Pratten Mine Sequence (Fig. 13) (Carruthers and Pratten, 1961). It outcrops a little west of, and parallel to, the ore bodies.

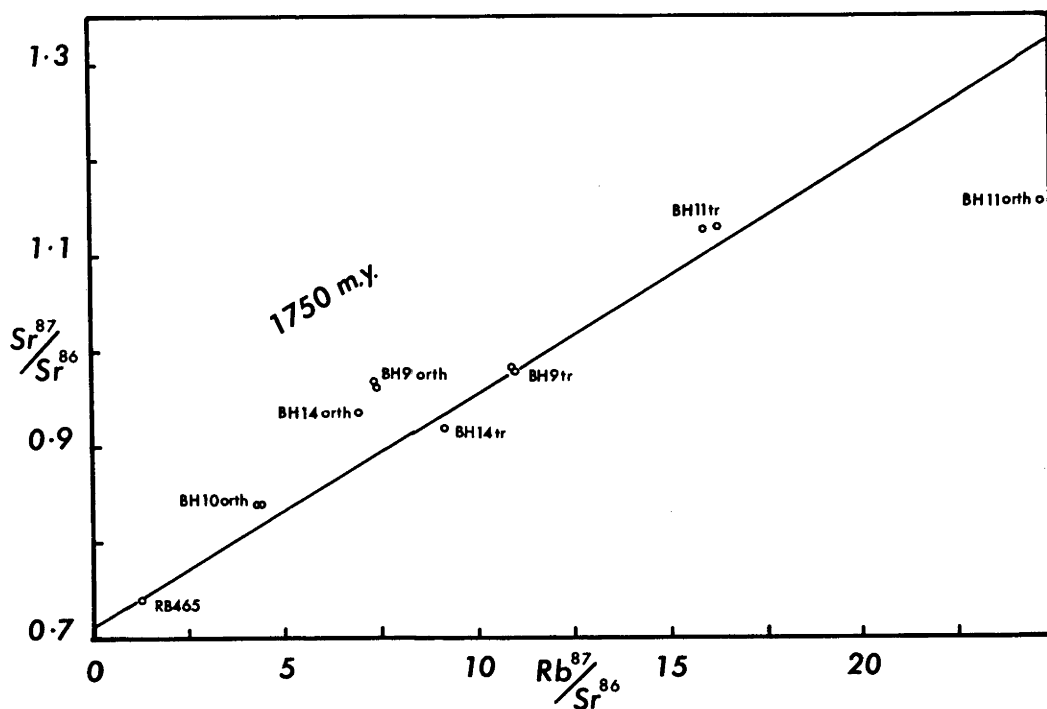
Where sampled the gneiss was a foliated quartz-feldspar-biotite gneiss. The foliation, due to biotite bands, is concentrically folded with a south plunging axis at Block 10 Hill. Axial plane slip is common and often these shears contain pegmatites which are themselves folded. Muscovite (sericite) occurs in shears and in the pegmatite, and biotite shows secondary recrystallization in slip planes. Other rock types present in the gneissic body, such as a leucocratic phase, were not sampled.

BH14 is a specimen of granitic gneiss from Block 10 Hill. It is slightly sericitised and was considered by Dr. Binns (Pers. comm. 1962) to be a slightly altered M1 product. BH11 is a similar specimen with minor pegmatite segregations and BH9 is similar except that it has small shears with secondary biotite and sericite. BH10 is a sample of pegmatite occurring in axial slip planes. It was hoped that the age of this pegmatite would reflect a period of movement in the axial planes.

Rubidium and strontium isotopic analyses were made on total-rock samples from BH14, BH11, BH9 and RB465 and K-feldspar from BH10, BH14, BH11 and BH9 and on biotite from BH11, BH14 and

TABLE 17. Rb-Sr isotopic analyses of the Hanging Wall Basin Gneiss samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH11.</u>						
Total-rock	0.9697	0.0597	16.25		1.1296	
	0.9704	0.0610	15.89		1.1293	
Biotite	4.313	0.0032	135.4		9.936	
K-feldspar	1.5185	0.0613	24.77	8.270		1.154
<u>BH14.</u>						
Total-rock	0.9287	0.0923		8.318		0.9200
	0.9216	0.1006	9.159		0.9208	
K-feldspar	1.258	0.1812	6.94		0.9337	
Biotite	3.685	0.0051	729.7		5.621	
<u>BH9.</u>						
Total-rock	0.9100	0.0825	11.03	8.339	0.9853	0.9793
	0.9674	0.0797	12.13		1.0046	
	0.8970	0.0824	10.88		0.9814	
K-feldspar	1.2365	0.1697	7.288		0.9616	
	1.2454	0.1696	7.345		0.9592	
Biotite	3.713	0.0041	915.0		6.900	
<u>BH10.</u>						
K-feldspar	0.8992	0.2052	4.382		0.8413	
	0.8929	0.2090	4.271		0.8400	
<u>RB465.</u>						
Total-rock	0.3972	0.3141	1.264		0.7409	



(Fig. 19) Isochron plot of the Hanging Wall Gneiss samples.
t.r. - total-rock, orth. - orthoclase.

BH9. (Table 17, Fig. 19).

K-feldspar-total-rock lines do not pass through their coexisting biotite data-points.

E. THE POTOSI GNEISS.

Andrews (1922, p.86) described the Potosi or Footwall Gneiss as a medium grained, grey gneiss, distinctly granular and composed chiefly of feldspar (orthoclase and plagioclase) quartz, biotite and garnet an eighth to half an inch in diameter. Sillimanite is conspicuously absent. Convolute pegmatite stringers are common.

Andrews and Browne (1922) regarded the Potosi Gneiss as an intrusive whereas Stillwell (1922) considered it sedimentary.

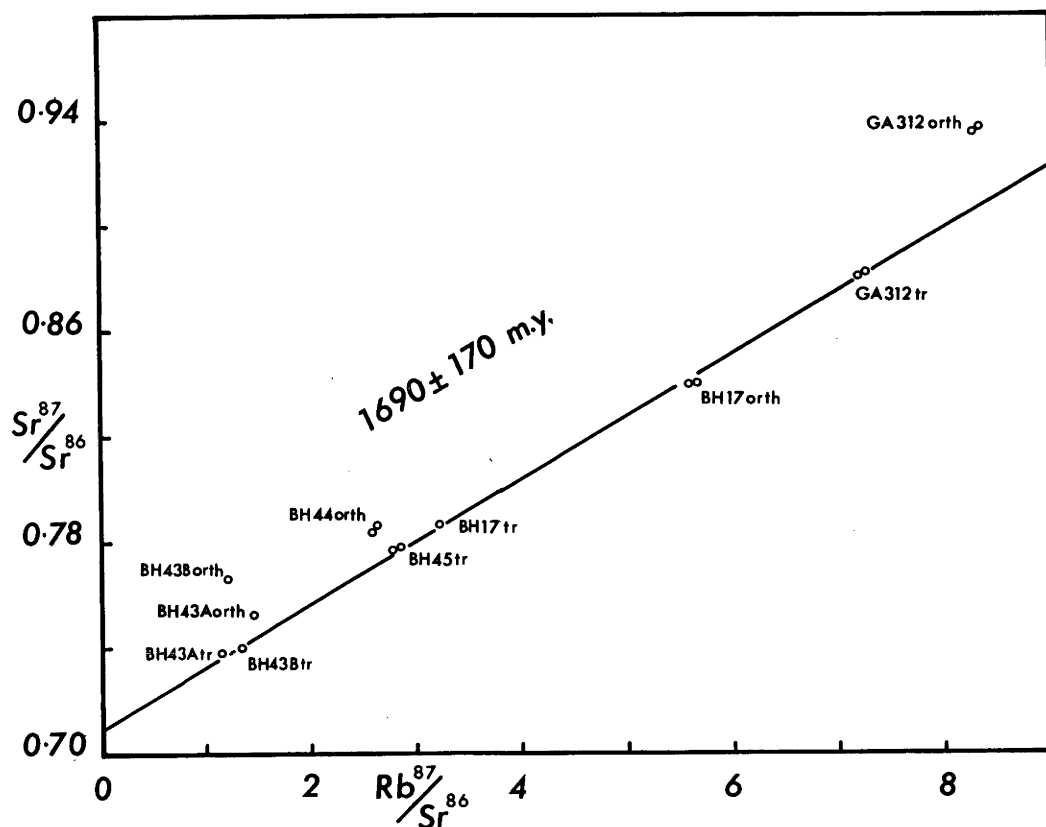
Outcrops of the Potosi Gneiss occur a little east of and parallel to the ore-bodies and also at Little Broken Hill. It is formation No. 5 in the Mine Sequence of Carruthers and Pratten (1961) (Fig. 13).

Specimens of Potosi Gneiss BH43, BH44 and BH45 were collected from the Australian Blue Metal Ltd. quarry. The gneiss here was coarse-grained foliated and associated with numerous ptygmatic veins of leucocratic rock.

Specimen BH43 was split into BH43B consisting of leucocratic vein material and BH43A actual Potosi Gneiss (Appendix 1).

TABLE 18. Rb-Sr isotopic analyses of the Potosi Gneiss samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH 43A.</u>						
Total-rock	0.3638	0.3155	1.153	8.309	0.7366	0.7374
Orthoclase	1.0968	0.7401	1.482		0.7534	
	1.0915	0.7477	1.460		0.7524	
<u>BH43B.</u>						
Total-rock	0.4794	0.3583	1.337	8.337	0.7417	0.7393
Orthoclase	1.0368	0.8566	1.210		0.7662	
<u>BH 44.</u>						
Orthoclase	1.0556	0.4004	2.637		0.7864	
	1.0531	0.4050	2.600		0.7847	
<u>BH17.</u>						
Total-rock	0.4550	0.1412	3.222	8.324	0.7881	0.7872
	0.5764	0.1455	3.962		0.7860	
	0.4439	0.1430	3.104		0.7873	
Orthoclase	1.3152	0.2331	5.643		0.8403	
	1.2966	0.2304	5.628		0.8402	
<u>BH45.</u>						
Total-rock	0.5953	0.2072	2.873		0.7779	
	0.4699	0.2137	2.199		0.7756	
	0.5892	0.2127	2.770	8.321	0.7776	0.7768
<u>GA312.</u>						
Total-rock	0.6469	0.0890	7.267	8.335		0.8824
	0.6527	0.0905	7.210	8.330		0.8814
Orthoclase	1.4963	0.1927	7.765	8.333		0.9365
	1.5275	0.2075	7.361	8.328		0.9360
Biotite	3.484	0.00367	949.37		7.184	



(Fig. 20) Isochron plot of the Potosi Gneiss samples.
t.r. - total-rock, orth. - orthoclase.

BH44 was a sample of leucocratic vein material and BH45 was a sample of Potosi Gneiss which had suffered a later east-west shearing.

GA312 is a specimen of Potosi Gneiss from this quarry presented originally to Dr. J.R. Richards by Z.C..

Potosi Gneiss sample BH17 was collected from No. 6 level Z.C..

Rb-Sr isotopic analyses were made on total-rocks BH43A, BH43B, BH45, BH17 and GA312, orthoclase from BH43A, BH43B, BH44, BH17 and GA312 and biotite from GA312 (Table 18, Fig. 20).

A least squares line through total-rock data-points in Fig. 20 has an apparent age of 1690 ± 170 m.y., and an intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.7099 ± 0.0092 . It is notable that the sheared total-rock BH45 nearly lies on this line.

The orthoclase total-rock lines are not parallel and cannot be interpreted as isochrons. This line for GA312 does not pass through the coexisting biotite point. The total-rock apparent isochron suggests that Potosi Gneiss total-rocks have remained closed systems to Rb and Sr isotopes for a similar period of time and also had similar initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios.

F. FORMATION No. 1 (CARRUTHERS AND PRATTEN, 1961).

Granitic gneiss specimen GA314 is a sample of the formation originally presented to Dr. J.R. Richards by Z.C. Its

TABLE 19. Rb-Sr isotopic analyses of Formation No. 1

(Carruthers and Prattern, op cit.) samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{Moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>GA 314.</u>						
Total-rock	1.2704	0.0752	16.88	8.324		1.1271
	1.2994	0.0783	16.60	8.326		1.1238
Biotite	6.6042	0.00339	1948.1		15.181	

location and petrography are described in Richards and Pidgeon (1963) and are included in Appendix 1.

Rb-Sr isotopic analyses were made on the total-rock and biotite (Table 19, Fig. 27). As the total-rock has a $\text{Rb}^{87}/\text{Sr}^{86}$ ratio of 16.7 small errors in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ will not greatly alter the calculated age. Assuming an initial ratio of 0.73 (found by compounding all reliable gneiss data) the calculated age is 1680 m.y.

G. THE PEGMATITES.

Pegmatites are ubiquitous throughout the Broken Hill region. They are found concordant with, and transgressing the high grade gneisses. Stillwell (1959) notes that lenses of pegmatite both large and small often lie along the cleavage planes of the sericite schist so that it can be inferred that the introduction of the pegmatite at least in part follows the formation of the sericite. The mineralogy and structural relationships of the pegmatites are extremely variable; some pegmatites are folded, others are transgressive and I have seen pegmatites cutting pegmatites.

In the granulite facies gneisses at Broken Hill the pegmatites may be divided into those with coarse muscovite and those without. Under granulite facies conditions it is expected that muscovite would be unstable (Turner and Verhoogen, 1960) and

therefore -

Age of the granulite facies metamorphism	>	Age of formation of the muscovite pegmatites.
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This is in accord with field evidence as muscovite pegmatites are thought by mine geologists to transgress the gneisses. Pegmatites which have garnet and K-feldspar but no coarse muscovite, appear to be concordant with the gneisses and the ore-bodies (King and Thompson op. cit.) and it is possible that they experienced the granulite facies metamorphism.

1. Lode pegmatites.

Examples from the "lode pegmatites" are characterised by a green or grey K-feldspar and the absence of primary muscovite.

Rb-Sr isotopic analyses were made on a total-rock sample from BH90, orthoclase from BH90, BH56, and BH27 and garnet from BH90 (Table 20, Fig. 21). BH56 is a sample of green-feldspar pegmatite from Little Broken Hill.

If the line joining BH56 and BH27 is interpreted as an isochron the apparent age is 1650 m.y. and the intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis is 0.77. The data from BH90 does not fit this interpretation. There is further discussion of this in Chapter VIII.

2. Muscovite pegmatites.

Four muscovite pegmatites were studied from the Broken Hill area. BH31 is a sample of a muscovite pegmatite transgressing

the Alma Gneiss. BH91 and BH94 (from N.B.H.C.) are samples of muscovite pegmatites which cut the sillimanite gneiss and BH85 is a sample of muscovite pegmatite from a large mass one mile west of Broken Hill.

Two samples of muscovite pegmatite, BH79 and BH81, were collected from the north of the Willyama complex. BH81 cropped out one mile east along the track from the Allandale Mine whereas BH79 was from a concordant pegmatite in the shear zone which appears to contain the Allandale ore-bodies.

Two muscovite pegmatite samples, BH47 and BH49, were taken from a shear zone in the Thackaringa area. These were concordant with the shear zone and showed no effects of stress.

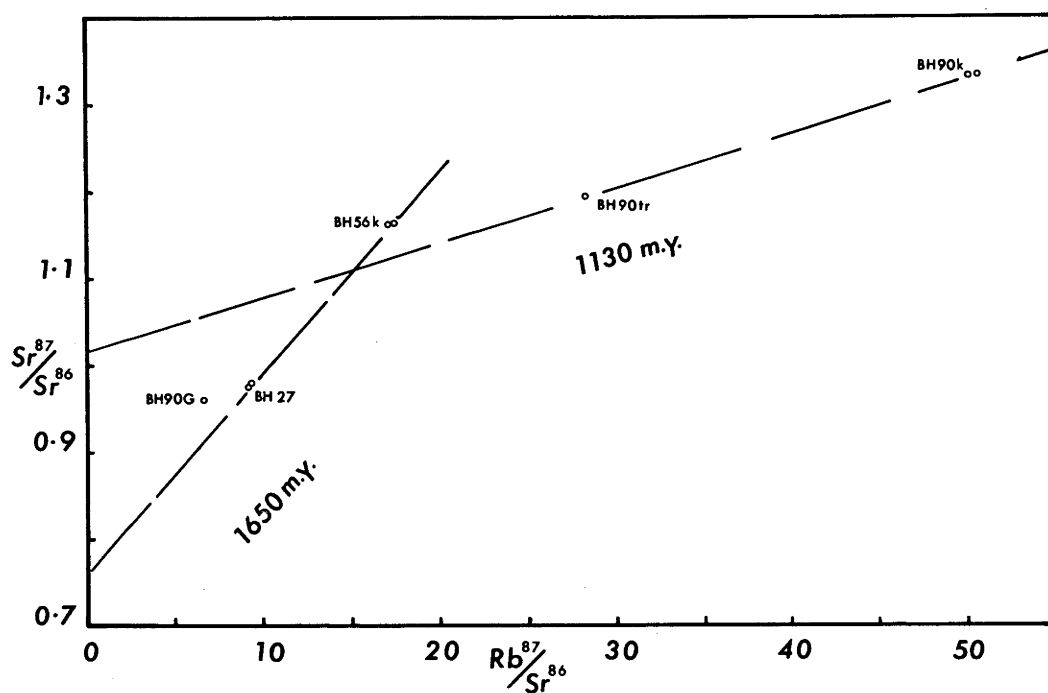
Rb-Sr isotopic analyses were made on muscovite from BH81, BH31, BH85, BH94, BH91, BH79, BH49 and BH47, on microcline from BH81, BH31, sericite from BH81, BH85 and plagioclase from BH85, BH47 and BH49 (Table 20, Fig. 22).

A least squares line through the muscovite and BH85 plagioclase and BH31 microcline data-points (excepting BH47 and BH49 muscovite) has an apparent age of 1560 ± 40 m.y. and an intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.74 ± 0.14 . Microcline from samples which show extensive sericitisation e.g. BH85 has not been included in the least squares calculation. The muscovite data-points are strongly correlated and it is obvious that small

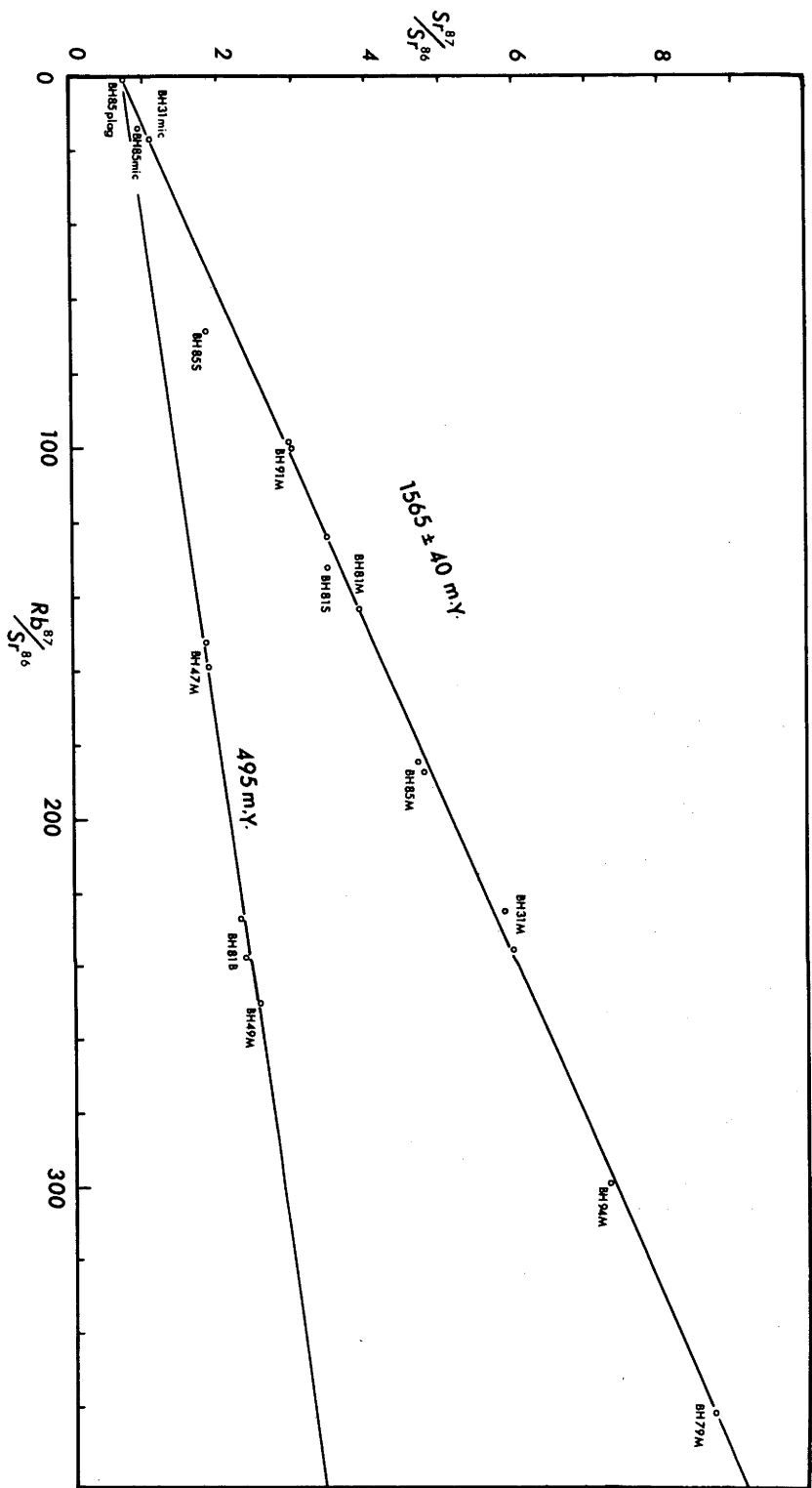
TABLE 20. Rb-Sr isotopic analyses of the pegmatite samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH81.</u>						
Muscovite	2.107	0.0148	142.8		3.892	
	2.080	0.0168	123.6		3.482	
Biotite	2.803	0.0118	237.2		2.323	
	2.748	0.0121	226.3		2.263	
Sericite	1.974	0.0149	132.2		3.475	
<u>BH31.</u>						
Muscovite	2.437	0.0104	235.5		5.960	
	2.379	0.0106	224.2		5.880	
Microcline	0.8772	0.0514	17.063	8.331		1.102
<u>BH85.</u>						
Muscovite	1.877	0.0102	184.6		4.688	
	1.891	0.0100	188.4		4.748	
Microcline	1.478	0.1055	14.01		4.688	
	1.478	0.1058	14.00		4.748	
Plagioclase	0.1376	0.1102	1.249	8.380	0.7758	
	0.1382	0.1102	1.254	8.345	0.7742	
Sericite	1.286	0.0188	68.28		1.864	
	1.312	0.0192	68.21		1.823	
<u>BH94.</u>						
Muscovite	2.352	0.00786	299.0		7.248	
<u>BH91.</u>						
Muscovite	2.443	0.0249	98.24		2.964	
	2.426	0.0243	99.97		2.993	
<u>BH56.</u>						
K-feldspar	1.511	0.0874	17.29		1.162	
	1.483	0.0848	17.49		1.164	
<u>BH27.</u>						
K-feldspar	1.949	0.2098	9.287		0.9792	
	1.918	0.2117	9.060		0.9786	

Biotite	2.803	0.0118	237.2		2.323	
	2.748	0.0121	226.3		2.263	
Sericite	1.974	0.0149	132.2		3.475	
<u>BH31.</u>						
Muscovite	2.437	0.0104	235.5		5.960	
	2.379	0.0106	224.2		5.880	
Microcline	0.8772	0.0514	17.063	8.331		1.102
<u>BH85.</u>						
Muscovite	1.877	0.0102	184.6		4.688	
	1.891	0.0100	188.4		4.748	
Microcline	1.478	0.1055	14.01		4.688	
	1.478	0.1058	14.00		4.748	
Plagioclase	0.1376	0.1102	1.249	8.380	0.7758	
	0.1382	0.1102	1.254	8.345	0.7742	
Sericite	1.286	0.0188	68.28		1.864	
	1.312	0.0192	68.21		1.823	
<u>BH94.</u>						
Muscovite	2.352	0.00786	299.0		7.248	
<u>BH91.</u>						
Muscovite	2.443	0.0249	98.24		2.964	
	2.426	0.0243	99.97		2.993	
<u>BH56.</u>						
K-feldspar	1.511	0.0874	17.29		1.162	
	1.483	0.0848	17.49		1.164	
<u>BH27.</u>						
K-feldspar	1.949	0.2098	9.287		0.9792	
	1.918	0.2117	9.060		0.9786	
<u>BH90.</u>						
Total-rock	0.7180	0.0252	28.44	8.365	1.1899	1.1967
K-feldspar	1.544	0.0307	50.31		1.335	
	1.551	0.0304	51.01		1.340	
<u>BH47.</u>						
Muscovite	1.487	0.00977	152.21		1.829	
	1.480	0.00932	158.73		1.866	
Albite				8.329		0.7927
<u>BH49.</u>						
Muscovite	1.606	0.00641	250.42		2.518	
Albite				8.309		0.7689
<u>BH79.</u>						
Muscovite	2.600	0.00722	359.87		8.698	



(Fig. 21) Isochron plot of the lode pegmatite samples.
t.r. - total-rock, orth. - orthoclase,
g. - garnet.



(Fig. 22)

Isochron plot of the muscovite-bearing pegmatites.
 mic. - microcline, m. - muscovite, b. - biotite,
 s. - sericite.

variations in the initial ratio of $\text{Sr}^{87}/\text{Sr}^{86}$ will have little effect on the apparent age (Table 20). The biotite and sericite data-points do not lie on the apparent 1560 m.y. isochron. The significance of these results is discussed further in Chapter VIII.

BH47 and BH49 muscovites define a distinctly younger apparent age. If the initial ratio of the pegmatite is assumed to be the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the coexisting albites this age is near 495 m.y. The Rb/Sr ratio of the albites, by x-ray fluorescence, is less than 0.1. Because there are only two muscovite limits on this age have not been estimated by a least squares calculation. I would expect the uncertainty in this age to be within $\pm 3\%$.

H. THE MUNDI MUNDI GRANITE.

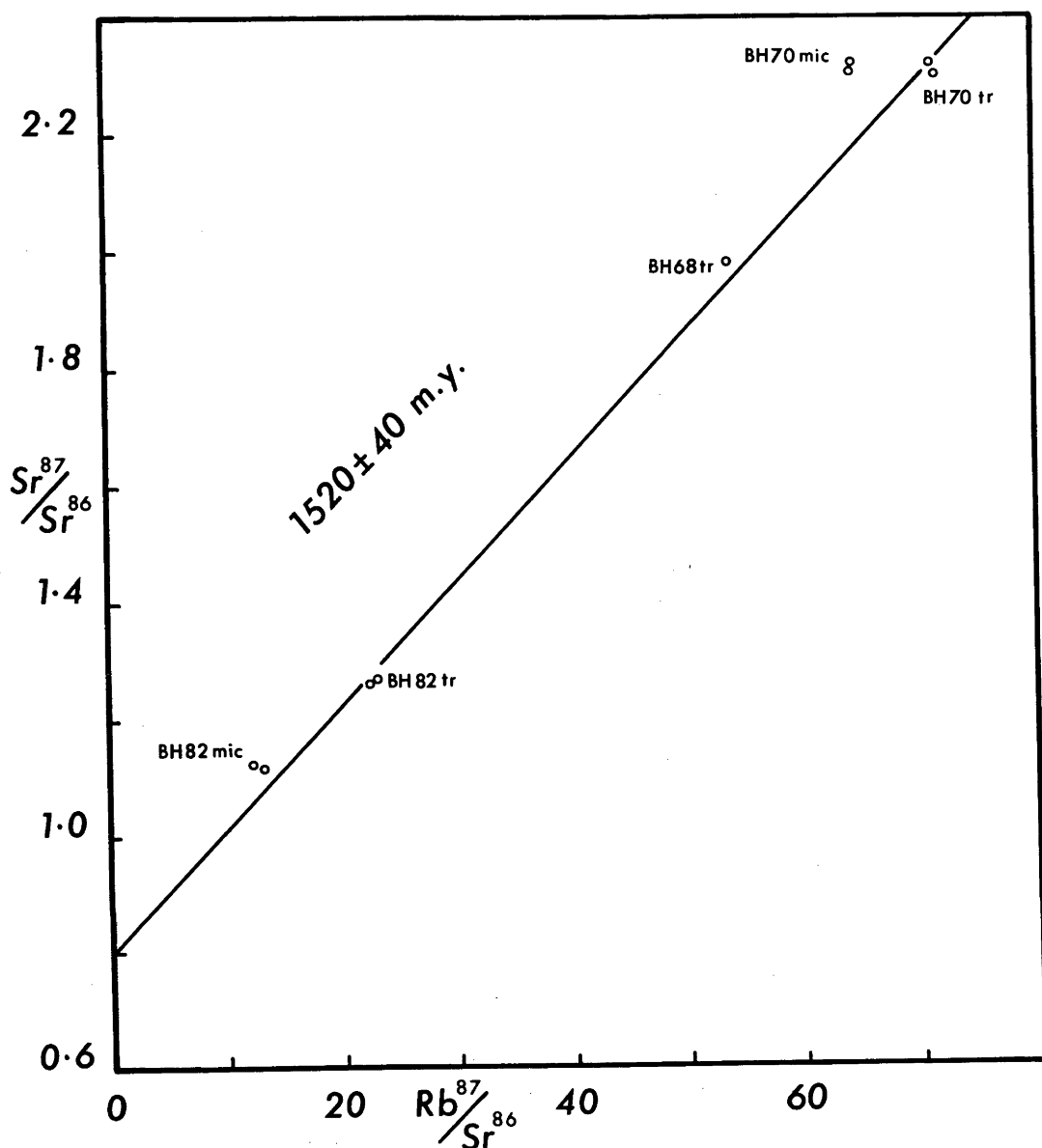
White (Pers. comm. 1964) notes contact metamorphic effects in the metasediments surrounding the largest of the intrusive bosses at Brewery Well. The relative age of the Mundi Mundi Granite on geological evidence is :-

Age of Willyama schist		Age of Torrowangee
formation in the north	> granite >	folding.
- possibly M1	age	

Granite samples collected were BH68 a muscovite granite from a dyke near the Brewery Well stock yards and wind mill, BH70, a muscovite granite from the Brewery Well pluton and BH82, a

TABLE 21. Rb-Sr isotopic analyses of the Mundi Mundi Granite samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
<u>BH70.</u>						
Total-rock	1.203	0.0168	71.71	8.415	2.297	2.318
	1.207					
	1.193	0.0167	71.39		2.325	
Microcline	2.763	0.0428	64.51		2.324	
		0.0429				
	2.789	0.0433	64.47		2.310	
Muscovite	3.444	0.00487	707.4		15.603	
	3.364	0.00499	674.3		15.271	
<u>BH82.</u>						
Total-rock	1.024	0.0446	22.96	8.340	1.308	1.272
	1.020	0.0456	22.36		1.271	
Microcline	1.550	0.1086	14.27		1.125	
	1.572	0.1297	12.12		1.127	
Muscovite	3.197	0.00467	685.1		15.621	
<u>BH68.</u>						
Total-rock	1.155	0.0216	53.35	8.340	1.982	1.983



(Fig. 23) Isochron plot of the Mundi Mundi Granite samples.
t.r. - total-rock, mic. - microcline. Although not included in the Figure the muscovite samples were used in calculating the apparent isochron.

muscovite granite from a dyke one and a half miles east of the Allandale Mine. This dyke clearly cuts a pegmatite and is discordant to the schist.

Rb-Sr isotopic analyses were made on total-rock samples from BH68, BH70 and BH82, and microcline and muscovite samples from BH70 and BH82. (Table 21, Fig. 23).

The muscovite and total-rock points are highly correlated and a least squares line through these data-points has an indicated age of 1520 ± 40 m.y. and an intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.81 ± 0.25 .

The lines joining total-rock and corresponding microcline data-points are not parallel and cannot be interpreted as isochrons.

I. SHEARS AND XENOLITHS IN THE GARNET-SILLIMANITE GNEISS.

Sericite samples were analysed from the Lord's Hill Fault, BH135, and the main shear, BH134, and the British Fault, BH40, and the Adam Fault, BH139 (Table 15 and 22).

Two carbonate rocks were collected from the vicinity of the Broken Hill ore-bodies. The first, BH31, was a low grade lead ore with calcite gangue. The second sample, BH138, was a specimen of "epidosite eye" composed largely of clinozoisite and quartz. The crushed rock was leached with 2.5 N HCl and the strontium

TABLE 22. Rb-Sr isotopic analyses of shear zone samples.

Specimen	$\mu\text{moles/gm}$ Rb^{87}	$\mu\text{moles/gm}$ Sr^{86}	$\text{Rb}^{87}/\text{Sr}^{86}$	$\text{Sr}^{88}/\text{Sr}^{86}$	Calculated $\text{Sr}^{87}/\text{Sr}^{86}$	Normalised $\text{Sr}^{87}/\text{Sr}^{86}$
----------	--	--	---------------------------------	---------------------------------	---	---

BH40.

Biotite-sericite

mix#	1.1905	0.0594	20.03		1.152	
Sericite	0.2362	0.0170	13.90		1.027	

BH139.

Sericite	1.009	0.1097	9.20		0.8740	
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The carbonate rock samples

BH 3C.

HCl dissolution

0.00116	0.5300	8.322	0.7170
		8.319	0.7151

BH138.

HCl dissolution

8.317	0.7812
-------	--------

isotopic ratios were measured on the elutant. (Table 22). The $\text{Sr}^{87}/\text{Sr}^{86}$ ratios in both cases are unusually high however more samples must be measured before a satisfactory interpretation of these results can be attempted.

CHAPTER VIII.

THE MINERAL AGES.

A. INTRODUCTION.

The object of this chapter is to assess the apparent ages measured on minerals from the Willyama Complex.

B. THE BIOTITE AGES.

1. Areal extent of the samples.

The locations of biotite samples are shown in Fig. 14 which is an adaptation of the map by King and Thomson (1953). The majority of samples are from the Broken Hill area but some have been collected from further afield. GA111 is from a sheared granitic rock located near the North Pinnacle. GA106 and GA108 are from granitic gneisses in the vicinity of the Stephens Creek Reservoir. GA110 is a sample of Mundi Mundi granite from one mile north of the Hen and Chicken smelters and Day Dream Mine 14 miles N.W. of Broken Hill. BH81 is a sample of muscovite pegmatite from near the Allandale Mine some twenty miles north of Broken Hill.

Although a complete areal coverage has not been achieved the biotite samples represent a considerable portion of the region.

2. The rock-types sampled.

Biotite fractions have been analysed from most of the

rock-types investigated in this thesis. These include a variety of gneisses, the Hanging Wall gneiss, the Potosi gneiss, the sillimanite gneiss and a gneiss from Formation No. 1 (Carruthers and Pratten, 1961), in the Mine Sequence and also granitic gneisses from other areas. Biotite has been analysed from a muscovite pegmatite (BH81) and a sample of Mundi Mundi granite GA110.

3. Retrogressive metamorphism of samples.

The rocks from which the analysed biotites were obtained have varying degrees of retrogressive metamorphism. Petrographic descriptions are given in Appendix 1, except for GA106, GA107, GA108, GA109, GA110, GA111 and GA439 which are described in Richards and Pidgeon (1963) (Appendix 2). The rocks may be classified approximately in terms of the extent of their reaction products.

- (a) Most altered; sericitised feldspars, minerals strained and possibly recrystallized. GA106, GA107, GA110, GA314.
- (b) Less altered; slightly sericitised feldspar, minerals strained and possibly recrystallized. GA111, GA312, BH81, BH11, BH14, BH9.
- (c) Slightly altered; some sericitised feldspar and strained minerals. GA439, GA109.
- (d) Unaltered; no sericite or apparent strain. BH5.

4. Experimental results.

The results of rubidium and strontium isotopic analyses of biotites BH11, BH14, BH9, GA312, GA439, GA314, BH5, BH81 are recorded in Chapter VII. Rb-Sr isotopic analyses of GA106, GA107, GA108, GA109, GA110, GA111 are recorded in Richards and Pidgeon (1963) (Appendix 2).

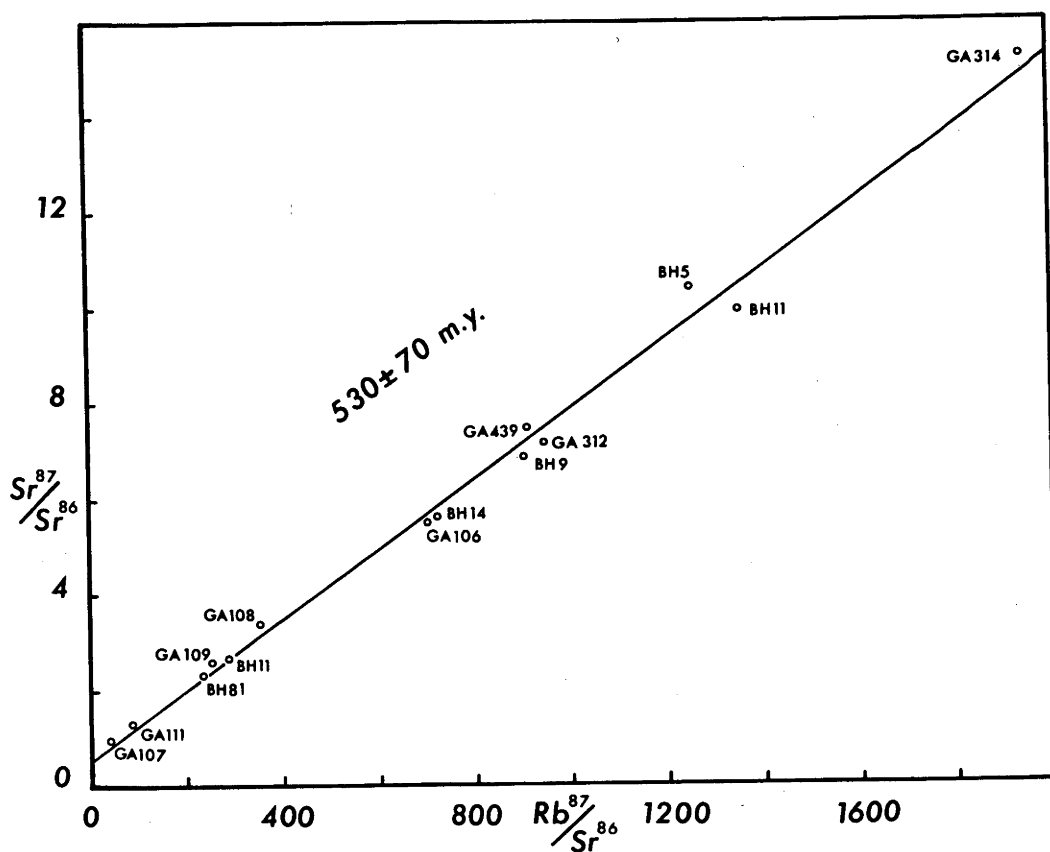
The calculated Rb-Sr age and K-Ar age where available, are presented in Table 23. For each biotite two Rb-Sr ages are presented. Each age is calculated using one of two extreme values for the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio. The lowest value 0.700 represents the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio found in basic rocks. Only meteorites and rocks of great age have lower measured $\text{Sr}^{87}/\text{Sr}^{86}$ ratios. This value therefore represents a lower limit to the possible initial $\text{Sr}^{87}/\text{Sr}^{86}$. The higher value of $\text{Sr}^{87}/\text{Sr}^{86}$, 0.800 is a higher initial ratio than that generally found in any rock (e.g. Hedge and Walthall, 1963). Actually it may be regarded as an extreme upper limit.

Except for BH107bi and GA111bi, biotite ages calculated on the basis of an initial $\text{Sr}^{87}/\text{Sr}^{86} = 0.700$ are within 5% of those calculated using an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.800. The calculated biotite ages are therefore largely independent of the choice of the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio.

The biotite data-points are plotted on a $\text{Rb}^{87}/\text{Sr}^{86}$ against $\text{Sr}^{87}/\text{Sr}^{86}$ diagram in Fig. 24.

TABLE 23. The biotite Rb-Sr and K-Ar ages.

Specimen	Rb-Sr age (m.y.)		K-Ar age m.y.
	$R_i = 0.70$	$R_i = 0.80$	
The Hanging Wall Basin			
BH11 bi	491	486	518
BH14 bi	485	477	
BH9 bi	487	479	524
The Potosi Gneiss			
GA312 bi	443	436	810
Garnet-sillimanite gneiss			
BH5 hi	567	561	
	557	551	
Alma Gneiss			
GA439 bi	506	498	455
	545	538	
GA107 bi	571	385	434
	549	384	
GA109 bi	539	511	1059
	533	506	1032
Formation No. 1			
GA314 bi	535	531	462
Granodiorite gneiss			
GA106 bi	490	480	459
Granitic gneiss			
GA108 bi	549	529	463
Granitic gneiss			
GA111 bi	495	415	562
	517	432	
Muscovite pegmatite			
BH81 bi	492	462	
	497	465	
Mundi Mundi Granite			
GA110 bi	487	462	581
	502	476	



(Fig. 24) Isochron plot of the combined biotite samples.

5. The biotite ages.

One great well known disadvantage of biotite ages is that biotite is particularly susceptible to a later metamorphism and easily loses "age" (e.g. Hart, 1964). The biotite age therefore represents a minimum age of formation of the host rock and it must be confirmed by ages on total-rock and mineral samples. (c.f. Pidgeon and Compston, 1965).

All the Rb-Sr biotite ages I have measured lie (at the 95% level) within 530 ± 70 m.y. (Fig. 24) regardless of rock-type, geographical position, extent of retrogressive metamorphism, and, largely, assumption of initial $\text{Sr}^{87}/\text{Sr}^{86}$.

A number of models may be proposed to explain the biotite ages and their spread.

The first and most obvious explanation for the wide biotite-age limits is that this spread is apparent and is a consequence of experimental error. An analysis of variance of the duplicate biotite ages (at $0.700 = \text{Sr}^{87}/\text{Sr}^{86}$ initial), shows that even at the 99% level the age differences cannot be explained by experimental error. The calculated least significant difference between means at the 95% level was 34 m.y. This infers that biotite ages from the Mundi Mundi Granite and the pegmatite to the North of Broken Hill are significantly younger than biotite ages in the vicinity of Broken Hill. This result may, however, be only apparent,

as in GA107 bi and GA110bi the initial $\text{Sr}^{87}/\text{Sr}^{86}$ becomes critical to the argument. Also single biotite age measurements from Broken Hill specimens not included in the statistical calculation are close to the younger ages.

In conclusion the experimental error alone cannot explain the spread of biotite ages in the rocks. Some added "geological" variance must be introduced. Also it cannot be proved that biotite ages of any two rock types are significantly different.

There are many explanations for the age of 530 ± 70 m.y. It can represent nearly complete removal of radiogenic strontium during a single geological event, or it may reflect two or more distinct geological events closely spaced in time but randomly varying in intensity. The observed ages could also be the result of some slow leakage process during which radiogenic strontium has constantly leaked from the biotite since its formation.

The biotite ages of the Mine Series rocks range from 560 m.y. for BH5bi to 440 m.y. for GA312bi. As these two rocks are among the least altered of all the samples the degree of retrogressive metamorphism does not appear to be significant in explaining the wide age spread. It does however indicate that slow diffusion is not a mechanism as consistent apparent ages resulting from this would be altered by the varying degrees of recrystallization of the biotites.

It appears therefore that the observed ages are the result of a geological event at 530 ± 70 m.y. The biotite ages from elsewhere in the Willyama Complex are in the range 530 ± 70 m.y. This could indicate that the intensity of this geological event was similar over the region. I consider the spread of ages to be a function of the distribution of radiogenic strontium between biotite and other mineral phases under low temperature conditions. A discussion of this statement is given in Chapter X.

As a first hypothesis the biotite age is interpreted to be the result of a geological event at 530 ± 70 m.y. This appears to be younger than the large scale retrogressive recrystallization which has no apparent effect on the biotite ages.

6. Comparison with the total-rock ages.

The total-rock ages presented in Chapter VII lie between 1450 m.y. and 1750 m.y. The Potosi Gneiss has a total-rock age of 1690 ± 170 m.y. whereas its biotite age is 440 m.y. The garnet-sillimanite gneiss has a total-rock age of 1605 ± 35 m.y. whereas its biotite age is 560 m.y. and the Mundi Mundi Granite has a total-rock and muscovite age of 1520 ± 40 m.y. and a biotite age of 495 m.y.

The biotite apparent ages are distinctly younger than their corresponding total-rock age. They do not reflect the age of

their host rocks but record a later period of isotopic rearrangement.

7. Geological evidence for a Lower Palaeozoic metamorphism.

At present there is only fragmentary geological evidence for a Lower Palaeozoic metamorphism in the Broken Hill district. During a symposium in 1956, Daily (1956) referred to a Middle Cambrian orogeny which marks the end in South Australia of sedimentation in the Adelaide Geosyncline. Öpik (1956) gave evidence of a possible unconformity in the same period at Cobar, some 250 miles to the east of Broken Hill, and also that folding in the South Australian Kanmantoo Series may have occurred somewhere in the time interval Middle Cambrian to Lower Ordovician. In 1961 Warner and Harrison (1961) found Middle Cambrian fossils in a gently folded structure in the Mootwingee Ranges some 60 miles to the north-east of Broken Hill. More recently, Öpik (pers. comm. to J.R. Richards, Richards and Pidgeon, 1963) has observed deformed Lower Ordovician deposits resting unconformably on folded early Middle Cambrian strata in the same region. Thus by extrapolation over comparatively large distances it is possible to interpret the geological evidence as lending support to the concept of some tectonic event in the period Middle Cambrian to Lower Ordovician.

This evidence supports but does not completely justify the correlation of the isotopic movement at 530 m.y. with a

metamorphic event. This correlation may be made if, by metamorphic event, is meant a period of heating, or an increase in pressure-temperature conditions reorganising isotopes within the minerals, but not necessarily producing observable mineralogical changes. However, metamorphism is defined by mineralogical and structural adjustment not isotopic movement. (Turner and Verhoogen, 1961). The fact that the isotopes have recorded an event not apparent in the mineralogy does not mean that this "metamorphism" will not become obvious in another specimen or another locality. Even if individual samples do not appear to have undergone a later metamorphism, geological and isotopic evidence indicates that the region as a whole was at least folded at 530 ± 70 m.y.

8. Comparison with K-Ar analyses.

Table 23 presents the results of K-Ar and Rb-Sr age determinations on nine biotite samples. The K-Ar analyses were carried out by Dr. J.R. Richards. Other K-Ar analyses not presented in this thesis are recorded in Richards and Pidgeon (1963) (appendix 2).

Fourteen out of eighteen biotite K-Ar ages presented in this paper lie between 430 and 530 m.y. The other four are significantly older than the upper 95% limit of 580 m.y. for the Rb-Sr biotite ages. The most striking of these is GA109, a biotite

from the Alma Gneiss, which has a reproducible K-Ar age of 1045 m.y. and a Rb-Sr age of 530 m.y. Another sample, GA439, collected near GA109 several years later had a biotite K-Ar age of 455 m.y. and a Rb-Sr age of 520 m.y. GA107 and GA405 also from the Alma Gneiss have biotite K-Ar and Rb-Sr ages between 430 and 540 m.y. The Potosi Gneiss biotite (GA312) has an older apparent K-Ar age than the Rb-Sr determination and so to a lesser degree have biotites from GA110 and GA111. Signs of a similar pattern can be detected in other results published on metamorphic areas (Wetherill et. al. 1957, Wasserburg et. al. 1959, Fairbairn et. al. 1960, Gerling and Ovchinnikova 1961.)

A detailed discussion of the reasons for these high K-Ar ages has been developed by Dr. J.R. Richards and is included in Richards and Pidgeon (1963).

It is noted here that the potassium content of the anomalous biotites is not depleted as would be expected under Kulp and Engel's (1963) theory of base exchange. Richards prefers the hypothesis that the high ages are the result of argon, released from high potassium minerals during metamorphism, being trapped in the immediate environment. This argon would either be absorbed into low potassium minerals or would hinder further diffusion from high potassium minerals. In the first case the observed age would be unrealistically old whereas in the second case the age would be a

minimum for the rock.

The majority of biotites appear to have lost all their radiogenic argon $500 \pm$ about 50 m.y. ago. This age is similar to the Rb-Sr age of 530 ± 70 m.y. and it is postulated as a first hypothesis that they record the same geological event.

C. THE MUSCOVITE AGES.

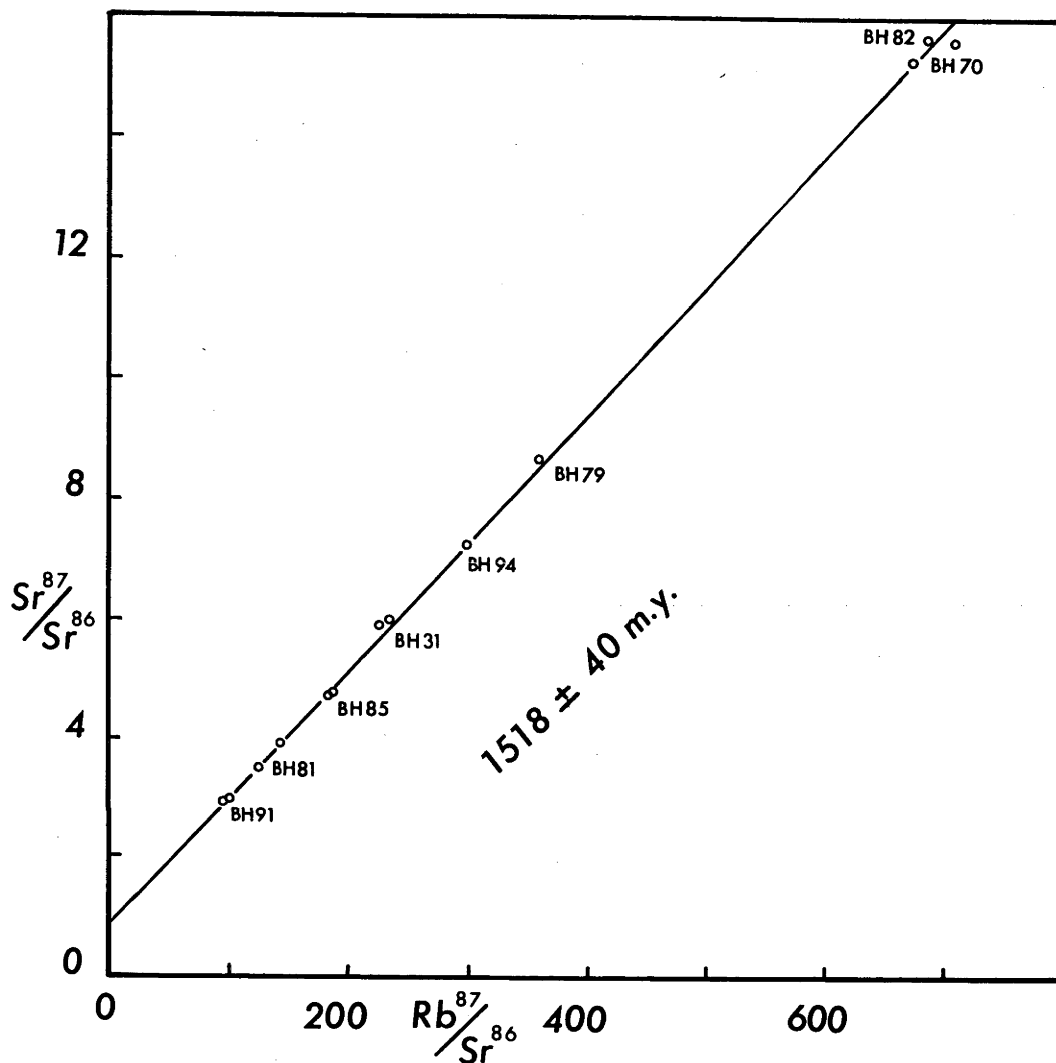
1. The ages.

This section discusses the Rb-Sr age determinations of Willyama rocks using primary muscovite. Primary muscovite occurs as books about one centimeter across in some pegmatites and as large flakes in the Mundi Mundi Granite masses. In thin section individual flakes are occasionally bent, frayed, and slightly recrystallized to fine sericite. The apparent ages of sericites and secondary muscovites are discussed in the section headed "sericite ages".

The experimental results of Rb-Sr isotopic analyses on primary muscovite from the Mundi Mundi Granite and the pegmatites are included in Chapter VII. Table 24 shows the effect on the muscovite ages of an uncertainty in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio. "Ages" are recorded using hypothetical values for the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.70 and 0.80. The reasons for the choice of these values are given in the section on biotite ages. Table 24

TABLE 24. The muscovite ages.

Specimen	Age (m.y.)	
	$R_1 = 0.70$	$R_1 = 0.80$
BH70 muscovite	1543	1533
	1504	1494
BH82 muscovite	1555	1545
BH81 muscovite	1595	1546
	1608	1550
BH31 muscovite	1596	1565
	1650	1619
BH85 muscovite	1543	1504
	1535	1497
BH94 muscovite	1564	1540
BH91 muscovite	1647	1573
	1639	1567
BH79 muscovite	1581	1561
BH47 muscovite	531	484
	526	481
BH49 muscovite	520	491



(Fig. 25) Isochron plot of the combined primary muscovite samples.

shows that there is no significant difference between the ages of the pegmatite muscovites (excluding BH47 and BH49) and those of the Mundi Mundi Granite. The Mundi Mundi Granite muscovite ages lie between 1494 m.y. and 1545 m.y. and the pegmatite muscovites have ages between 1497 m.y. and 1567 m.y.

The combined muscovite data-points, excluding BH47 and BH49 muscovite, are plotted on a Rb^{87}/Sr^{86} against Sr^{87}/Sr^{86} diagram in Fig. 25. These data-points are extremely well correlated and a least squares line through these has an apparent age of 1520 ± 40 m.y. and an intercept on the Sr^{87}/Sr^{86} axis of 0.88 ± 0.21 .

The primary muscovite from concordant unmetamorphosed pegmatites in a shear plane at Thackaringa (BH47, BH49) have a distinctly younger apparent age of approximately 4.95 m.y.

2. Interpretation of the Primary muscovite age.

The muscovite "ages" may be interpreted in two ways. They could represent the age of emplacement or crystallization of the host rock, or they could reflect an isotopic movement later than the original emplacement. Petrologically there is little doubt that the muscovite is primary but it has been noted that primary biotite loses "age" under a later heating without apparent recrystallization. The Mundi Mundi Granite has slight retrogressive alteration to sericite and is slightly strained. However, the

muscovite ages are, within experimental error, identical to the age of the total-rocks. Assuming the total-rocks have remained closed systems since formation (consistency of total-rock ages between Mundi Mundi Granite masses lends strong support to this hypothesis as does previous experience; see Part I), then the muscovites are also likely to have remained closed systems to rubidium and strontium since the formation of the granite.

The age found for muscovite from one set of muscovite-bearing pegmatites is identical to that of the Mundi Mundi Granite. It has been noted that in one outcrop (track to Allandale Mine) granite cuts pegmatite although in others the contact appears gradational indicating

muscovite pegmatite	>	Mundi Mundi Granite
age		age

This evidence strongly suggests that the muscovites from these pegmatites have remained closed systems to Rb and Sr since formation.

Muscovite pegmatites occur in the high-grade gneisses as discordant dykes. This discordance and the presence of muscovite indicates that these pegmatites were post granulite facies metamorphism. The age of the granulite facies metamorphism, 1640 ± 40 m.y. is only slightly younger than this maximum age suggesting that little if any loss of age has occurred in the muscovites.

Varying amounts of sericite alteration is present in these pegmatites. The maximum possible age of sericitisation for BH85 can be estimated by assuming an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.70. This is 1200 m.y., significantly lower than the muscovite ages, and is strong evidence that this slight retrogressive alteration has not affected the muscovite age.

It is concluded that the muscovite age represents the age of formation of the Mundi Mundi Granite and the muscovite-bearing pegmatites.

This conclusion may be applied to the primary muscovite from BH47 and BH49. These muscovite-bearing pegmatites occur in shear planes but show no signs of crushing or retrogressive alteration. There is no evidence to suggest that these primary muscovites have lost their daughter strontium indicating that their age of formation is 495 m.y.

These conclusions support observations by others (e.g. Compston, Jeffery and Riley, 1960) that muscovite is considerably more retentive of its age than biotite.

Richards (Richards and Pidgeon, 1963) made K-Ar age determinations on muscovites from the Mundi Mundi Granite sample GA407 and a specimen of biotitic lode material GA313 (there is little doubt that this muscovite is secondary). Muscovite from GA407 gave 1360 m.y. whereas the apparent age of GA313 muscovite was

470 m.y. Both ages are significantly lower than the Rb-Sr muscovite ages; the second is within the limits of the Palaeozoic metamorphism defined by the biotite ages. Binns and Miller (1963) analysed muscovites in an attempt to date separate metamorphisms proposed by Binns on petrological grounds. Their K-Ar ages on Mundi Mundi Granite muscovites were 985 ± 38 m.y. and 1307 ± 56 m.y. These ages are in approximate agreement with Richard's results if the low age is ignored, but they are inconsistent and significantly lower than the Rb-Sr muscovite age for the granite. I interpret these K-Ar results to be due to argon loss from the muscovite, possibly by slow diffusion, but more likely by episodic loss during a later metamorphism, as for instance the Palaeozoic event registered by the biotites.

To summarise the Rb-Sr results it appears, from isotopic and geological evidence, that muscovite has remained a closed system to Rb and Sr since its formation. It is concluded that within experimental error the older pegmatite and Mundi Mundi Granite muscovite-ages are identical and that they are significantly younger than the total-rock ages of the Mine Sequence granulite facies rocks. It is also concluded that, within experimental error, the muscovites from pegmatites in the shear zones at Thackaringa were formed by the same metamorphic event registered by the biotite ages and that these pegmatites provide a petrological expression of this metamorphism which has hitherto been lacking.

D. THE SERICITE AGES.

1. Introduction.

This section presents the results of Rb and Sr isotopic analyses of sericites and fine grained secondary muscovites. The secondary white micas are here referred to collectively as sericites in order to distinguish them from the primary muscovites previously discussed.

Throughout the region the Willyama rocks appear to have suffered varying degrees of retrogressive metamorphism. Whether this has resulted from one or more metamorphic events has not been satisfactorily established, but the retrogressive mineral assemblages are similar in that they generally include sericite.

The aim in studying sericitised rocks and their sericites was firstly to investigate the behaviour of the isotopes of Rb and Sr in a total-rock during sericitisation and secondly, to determine the age or ages of formation of the sericite.

In this study the sericite-bearing samples are mainly from the sillimanite-garnet gneiss of the Mine Sequence. This rock type was selected because its age has been established and also because, in a limited study such as this, uniformity of rock type is desirable in the interpretation of results. Even so the gneisses vary one from another (Appendix 1).

The samples investigated have also been selected on the basis of varying intensity of retrogressive metamorphism. The criteria for this are the extent of sericitisation and recrystallization and the retention of original textures and minerals. It is possible to list the samples in approximate order of increasing retrogressive alteration. BH2, BH25, and BH23 are strongly sericitised but still retain some measure of the pre-existing texture. BH137 is more extensively altered. BH134, BH135, BH139 and BH40 are specimens from known shears (Chapter VII) and are by far the most altered rocks in this suite. BH40 is a surface sample of the British Fault and may have suffered leaching through weathering.

Rb and Sr isotopic analyses were made on total-rock and sericite samples from BH2, BH25, BH23, BH137, BH134, BH135 and sericite from BH139 and BH40, (Chapter VII) and from BH81 and BH85, two sericitised muscovite-feldspar pegmatites.

The only previous work on secondary muscovite that I am aware of is by Allsopp (1961) and Allsopp et. al. (1962). They found that muscovite, apparently mostly secondary (Allsopp, pers. comm. 1964) gave an older "age" than that of the total-rocks. They interpreted this result to be due to the secondary muscovite gaining radiogenic Sr^{87} which has been lost from the biotite and feldspar. They also found that although the minerals were unreliable age indicators

the total-rock samples remained closed systems to Rb and Sr.

2. The sericitised total-rock.

It has been shown that sericitised total-rock samples BH23, BH2 and BH25 define an apparent age of 1650 m.y. (Fig. 16). This is essentially the same as the age of unretrogressed garnet-sillimanite gneiss samples BH5 and BH21. (Fig. 15). BH137 lies slightly off this isochron (Fig. 17). It may be concluded that sericitised samples BH25, BH2, BH23 and possibly BH137 have remained closed systems to Rb and Sr for the same time as the comparatively unsericitised rocks BH5 and BH21. This supports the observations of Allsopp et. al. (1962).

The most altered total-rock samples BH134 and BH135 do not lie on this isochron but reflect a significantly younger "age" (Fig. 16). As there are only two discordant results it is impossible to exclude the possibility that the data-points lie on a 720 m.y. isochron and have an anomalously high initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.8. However there is no independent support for such a hypothesis. All that can be concluded is that these total-rock samples became open systems to Rb and Sr some time after 1604 ± 50 m.y. and that this cannot be established from the present total-rock evidence.

The mechanism by which this loss of "age" was accomplished, whether by loss of radiogenic strontium or some other process is not

certain and there is no evidence to prove it reached completion. The maximum radiogenic strontium in these rocks can be calculated assuming an initial ratio of 0.70. On this assumption the maximum age for BH134 is 1490 m.y. and for BH135 is 1240 m.y. These ages represent the maximum time the rock has remained closed to Rb and Sr isotopes. Assuming that both shearings were of the same age the last event(s) which opened these rocks to Rb and Sr occurred at or more recently than 1240 m.y. ago.

3. The sericites (including secondary muscovite).

In the sericitised sillimanite gneisses the sericite has an older apparent age than that of its corresponding total-rock, assuming the same initial $\text{Sr}^{87}/\text{Sr}^{86}$. This is identical with the observations of Allsopp et. al., 1962. Other than this the position of the sericite data-point relative to the total-rock is unpredictable. It is not related to the extent of deformation or recrystallization.

The mechanism or rearrangement of Rb and Sr during sericitisation is not known. However in four of the samples studied this has proceeded under closed system conditions. Sericitisation involves the breakdown of the feldspars and probably the partial recrystallization of the pre-existing micas, and therefore the sericite apparent age and Rb and Sr concentrations are interpreted as functions of the composition of the rock, the extent of the

breakdown of the feldspars and micas, and also the age.

Two sericite samples have been analysed from pegmatites BH85 and BH81 (Fig. 22, Table 20). Fig. 22 shows that these sericites have apparent ages younger than the pegmatite isochron (1560 m.y.) which is the reverse of the behaviour of the sericite from the garnet-sillimanite gneisses. If an initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of 0.700 is assumed for BH85 sericite the calculated maximum age is 1200 m.y. The age of the metamorphism producing the sericite must be equal to or less than 1200 m.y.

4. Conclusions.

The most extensively metamorphosed garnet-sillimanite gneiss total-rock samples have lost "age" whereas sericitised samples which have retained their gneissic texture have also retained their old age. It was found from these total-rock samples that the age of sericitisation of the strongly metamorphosed samples cannot be older than 1240 m.y.

It has not been possible to establish the age of the sericites because the apparent ages are functions of the rock composition and the extent and age of the recrystallization.

E. THE POTASSIUM FELDSPAR AGES.

Previous investigators have found Rb-Sr potassium feldspar

ages to be reliable (c.f. Jeffery 1956, Wetherill et. al. 1957), and this section is aimed at assessing the reliability of potassium feldspar age determinations on Willyama rocks.

Potassium feldspar occurs in 1) the pegmatites, 2) the granites and 3) the high-grade gneisses.

1. The pegmatites.

It has already been shown that the pegmatites can be divided into two classes: those with primary muscovite and those without.

Firstly, I wish to consider potassium feldspar from the "lode pegmatites". These pegmatites have been shown to contain a grey or green orthoclase and no primary muscovite. Structurally they are concordant with the gneisses and also the ore-bodies. The green feldspar is considered by some authors (Stillwell, 1959) to be genetically related to the ore. Stillwell (1959) suggests that the high lead content in the potassium feldspar could be the reason for the green colour, and also it could indicate that the ultimate source of the orthoclase and the sulphide is identical. This is in agreement with Andrews' view (1922, p.183) that the "lode pegmatites" are the forerunners of the ore deposits. The possibility that this pegmatite formed before or during the granulite facies metamorphism cannot be overlooked however.

Rb-Sr isotopic analyses were made on lode pegmatite potassium feldspar samples BH27, from No.12 level Z.C., BH56, from Little Broken Hill and BH90, from No.14 level N.B.H.C. (Appendix 1). (Chapter VII). BH27 and BH90 have strong retrogressive alteration and the orthoclase shows signs of crosshatched twinning.

Assuming initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of 0.70 and 0.78, (reasonable limits on previous experience, also Hedge and Walthall, 1963) ages calculated for BH56 potassium feldspar are 1900 m.y. and 1570 m.y. respectively and for BH27 the ages are 2140 m.y. and 1520 m.y. These ranges are similar, and providing the feldspars have remained closed systems, their time of formation can be placed between 2200 m.y. and 1500 m.y. Assuming the two feldspars had similar initial ratios an isochron may be empirically fitted (Fig. 21) which is 1610 m.y. with an intercept on the $\text{Sr}^{87}/\text{Sr}^{86}$ axis of 0.77. This is remarkably close to the age and initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of the sillimanite gneisses which surround BH27. This result may be fortuitous as BH56 and BH27 are miles apart but it suggests a relationship between the green feldspar and the granulite facies metamorphism. Possibly the pegmatites were formed during or before this metamorphism. This would be one explanation for the absence of muscovite from the pegmatite (Turner and Verhoogen, 1960) and the presence of orthoclase (Heir, 1961) in place of microcline.

The analytical results of BH90 orthoclase are at variance

with those just discussed. This feldspar has "ages" of 904 m.y. and 790 m.y. calculated using initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios of 0.70 and 0.78. Binns and Miller postulated the metamorphism and folding of the Torrowangee to be 920 m.y. but except for BH90 orthoclase I have no indications of an event at this time. Age determinations on BH90 total-rock and garnet do not support the orthoclase result, (Fig. 21), nor do they lie near the 1640 m.y. isochron. It is possible to explain the low orthoclase and total-rock "age" by postulating a movement of Sr and Rb isotopes after the 1640 m.y. event which is thought to be the time of formation of this pegmatite. This is not unlikely if the strong retrogressive metamorphism seen in the section is considered, but if this is the case there is no obvious reason why the equally retrogressed BH27 should retain its age and remain on the "gneiss" isochron. The feldspar age of 904 m.y., calculated using an initial ratio of 0.70, represents a maximum age for the retrogressive metamorphism.

Rb-Sr isotopic analyses have been made on microclines from two muscovite-bearing pegmatites BH31 and BH85. (Table 20, Fig. 22). The data-point for BH31 microcline lies on the muscovite pegmatite and Mundi Mundi granite isochron, behaving as a closed system. The BH85 microcline data-point lies below the isochron and if an initial ratio of 0.70 is assumed its calculated age is 1220 m.y. This low age may be related to sericitisation in the pegmatites. The

calculated maximum age for BH85 sericite (assuming $R_1 = 0.70$) is 1200 m.y.

2. The Mundi Mundi Granite microcline.

Rb and Sr isotopic analyses have been made on microcline from the Mundi Mundi Granite samples BH70 and BH82. Both microclines have older apparent ages than the total-rock-muscovite isochron. To explain this it must be assumed that the microcline gained radiogenic strontium from, or lost rubidium to, another phase within the rock. The exact mechanism by which the microcline gained "age" has not been established.

3. Potassium feldspar from the high-grade gneisses.

Rb and Sr isotopic analyses have been made on potassium feldspar from a number of high grade gneisses. The analytical results are recorded in Chapter VII. It can be seen from Fig. 15 that the sillimanite gneiss orthoclase samples have older apparent ages than the total-rocks. Also the two orthoclase "ages" are different. Rb and Sr isotopes appear to have reached equilibrium between rocks during the granulite facies metamorphism and the total-rocks have remained closed since. The high orthoclase "age" must be the result of a gain of radiogenic strontium or loss of rubidium under closed system conditions at a time later than the granulite facies metamorphism.

If certain assumptions are made it is possible, in the case of BH5, to test whether the orthoclase apparent age is the result of a movement of radiogenic strontium during a later metamorphism.

The first assumption is that all the Rb and Sr is contained in the biotite and orthoclase. This is reasonable as the rock consists of quartz, orthoclase, sillimanite, biotite, garnet and muscovite (1%) (Appendix 1). Following this assumption the following table gives the distribution of Rb^{87} and Sr^{86} in the rock.

	$\text{Rb}^{87} \mu\text{moles/gm}$	$\text{Sr}^{86} \mu\text{moles/gm}$	R_p
T.R.	1.49	0.030	1.865
orthoclase	2.51	0.067	1.890
biotite	3.94	0.0032	10.40

If it is assumed that the orthoclase and biotite have remained closed systems to Rb^{87} and Sr^{86} since the time of closure of the total-rock it is possible to calculate the concentrations of orthoclase and biotite in the rock.

Let x be the fraction of orthoclase in the rock.

Let y be the fraction of biotite in the rock.

This leads to the following equations -

$$2.51 x + 3.94 y = 1.49$$

$$0.067 x + 0.0032 y = 0.030$$

from which $x = 0.096$ and $y = 0.443$.

These calculated percentages of biotite, 9.6%, and orthoclase, 44.3%, are reasonably close to the concentration estimated from the thin section; biotite about 10% and orthoclase about 60%. If a total-rock age of 1680 m.y. is assumed (from the combined gneiss data) (Fig.27) it is possible to calculate the radiogenic strontium lost from the biotite and compare this with the Sr^{87} needed to move the orthoclase data-point from the total-rock isochron to its present position (Fig. 15).

The total-rock age corresponds to a $\text{Sr}^{87}/\text{Rb}^{87}$ of 0.02361. The biotite has a present day $\text{Sr}^{87}/\text{Rb}^{87}$ of 0.0077. The difference represents the loss in "age" of the biotite and is expressed as

$$\frac{\text{Sr}^{87}_*}{\text{Rb}^{87}} = 0.01591. \quad \text{The Rb}^{87} \text{ concentration in the biotite is } 3.94$$

μ moles/gm therefore

$$\begin{aligned} \text{Sr}^{87}_* &= 0.0627 \mu\text{moles/gm of biotite} \\ &= 0.00602 \mu\text{moles/gm of rock.} \end{aligned}$$

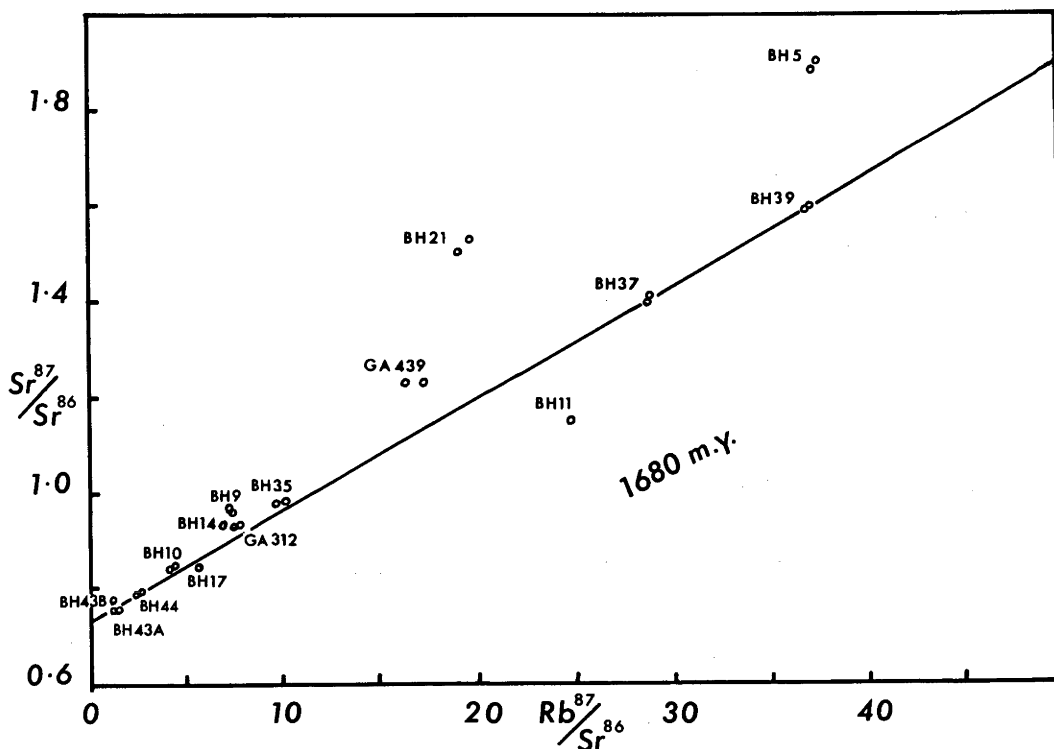
For the orthoclase to plot on its present position entirely by the addition of extra radiogenic strontium (Sr^{87}_*), its ($\text{Sr}^{87}/\text{Sr}^{86}$) must have increased by 0.29. The corresponding change in the amount of Sr^{87} is given by:-

$$\begin{aligned} \text{Sr}^{87} &= (0.29 \times 0.067) = 0.0194 \mu\text{moles/gm of orthoclase} \\ &= 0.0086 \mu\text{moles/gm of rock.} \end{aligned}$$

Considering the assumptions which have been made, this required Sr^{87} is very close to the radiogenic strontium available from the biotite. Consequently the high orthoclase "age" can be explained by the hypothesis that it absorbed radiogenic strontium lost from the biotite, probably during the 530 m.y. event.

Age determinations have been made on potassium feldspar from other gneissic rocks. The data-points of Alma Gneiss potassium feldspars, BH39K, BH37K, and BH35K lie close to the total-rock isochron (Fig. 26). These potassium feldspars appear to have remained closed systems to Rb and Sr since the granulite facies metamorphism. GA439 potassium feldspar however has a distinctly "older age" than the total-rocks and has possibly absorbed radiogenic strontium released from the biotite as in the case of BH5. The Hanging Wall Basin potassium feldspar samples also have data-points which lie off the total-rock isochron. BH14 and BH9 potassium feldspars have older apparent ages whereas BH11 potassium feldspar has a younger apparent age than that of the total-rocks (Fig. 19).

Dr. A.J. White has kindly measured the triclinicities, by x-ray technique, of some of the analysed potassium feldspars. BH5 and BH21 potassium feldspar were found to be orthoclase. BH14 potassium feldspar from the Hanging Wall Gneiss was also confirmed as orthoclase whereas BH11 was a mixture of orthoclase and microcline. GA439 potassium feldspar from the Alma Gneiss was distinctly a



(Fig. 26) Isochron plot of the combined orthoclase samples.

mixture of orthoclase and microcline. There is some suggestion that the degree of triclinicity can be related to the potassium feldspar anomalous ages. However the Potosi Gneiss feldspar sample GA312, determined as orthoclase is distinctly older than BH17, also determined as orthoclase, which lies close to the total-rock isochron. It is concluded that at present there is no definite evidence to relate degree of triclinicity with anomalous "ages" in potassium feldspar.

4. Conclusions.

In this section it has been found that many of the potassium feldspars behave as if they have been open systems to Rb and Sr at some time more recent than the total-rock age. They have suffered varying intensities of later metamorphism and in one sample the anomalous "age" of the potassium feldspar has been shown to be quantitatively consistent with the model of the selective absorption of radiogenic strontium lost from the associated biotite during metamorphism.

F. THE GARNET AGES.

1. Introduction.

These measurements were undertaken in an attempt to find the age of the granulite facies metamorphism, since petrographically garnet is a stable mineral in the granulite facies metamorphic assembly

(Appendix 1). Under retrogressive metamorphism thought to be lower amphibolite facies, garnet shows alteration to biotite (in the Potosi Gneiss). In some retrogressed gneisses it could be inferred that euhedral garnet has recrystallized under the retrogressive metamorphic conditions. No recrystallization of the garnet was observed in the samples analysed.

2. Chemical technique.

Because of the low concentration of Rb and Sr in the garnet extreme care was taken to minimise contamination in the chemical procedure. The garnet was purified to > 99% by ordinary techniques but even so composite garnet-biotite grains remained ($\sim 0.2\%$). The purified garnet was crushed in a hand mortar, to pass through a -120 cloth sieve, and then further crushed under analar acetone.

A one gram sample was weighed into a platinum dish, moistened with water and 10 mls of HF were added. The sample was left cold for some hours and then heated gently on the water bath. A blank solution was run with every sample. Further reagents were added to the sample and blank solution in the following aliquots over about 8 hours:- 5 mls HClO_4 , 5 mls HF, 5 mls HF, 5 mls HF, 5 mls HClO_4 .

The dissolved sample was evaporated to dryness,

redissolved in 30 mls 2.5 N HCl and transferred to a weighed platinum beaker with the addition of no more than 30 mls of distilled water. The solution was homogenised by heating and then left standing for 24 hours. The amount of added spike solution was found by

(i) weighing the amount added to the sample and

(ii) by weighing the spike lost from the spike bottle.

At best these two spike weights (about 0.04 gms) agreed to within one percent. Because of the relative size of exposed surfaces the second weight was assumed to be nearest the true weight of spike solution added.

The spiked samples were evaporated to dryness, baked, leached with hot water, dried, taken up in HCl and passed through cation exchange columns.

3. The analytical results.

The results of Rb and Sr isotopic analyses are recorded in Table 25.

Total strontium contamination is about $0.00015 \mu\text{mole Sr}^{86}/\text{gm}$ for all reagents and one pass through the column (the blank generally preceded the sample through the column). From blank E data it is seen that every pass through the column adds $0.00008 \mu\text{moles Sr}^{86}$. No sample passed through the column more than once; the contamination of Sr^{86} was therefore about one tenth of the sample Sr^{86} .

TABLE 25. Rb-Sr isotopic analyses of garnets (corrected for reagent contamination).

Specimen	μ moles/gm Sr ⁸⁶	μ moles/gm Rb ⁸⁷	R _p	Age (m.y.)	
				R _i = 0.70	R _i = 0.78
BH90	0.00166	0.0108	0.976	3043	2161
BH35	0.00228	0.0482	0.860	544	272
	0.00124	0.0509	1.000	526	386
	0.00093		0.947		
BH21	0.00100	0.0563	1.280	741	639
	0.00129	0.0571	1.434	1192	1062
	0.00116	0.0600	1.224	729	618
BH5	0.00080	0.0340	1.188	826	660
	0.00085	0.0358	1.235	915	777
BH137	0.00414	0.1453	1.123	867	703
	0.00430	0.1572	1.140	867	708
Blank determinations					
A	0.00015	0.00009			
B	0.00013				
C	0.00012				
D	0.00018				
E	0.000076	(run without passing through the column.)			

Garnet "ages" are generally a lot lower than 1600 m.y. This can not be explained by reagent contamination. This could be near the true garnet age or it could be an apparent "age" resulting from garnet plus biotite contamination.

Assuming the garnet age to be 1650 m.y. and the biotite contamination to be 0.2% it is possible to test whether the low garnet age is completely the result of biotite contamination.

Assume the Rb^{87} concentration of BH5 garnet is 0.027 μ moles/gm (found by subtracting 0.2% biotite Rb^{87}). At $R_1 = 0.70$ the measured garnet age is 850 m.y. Consider the loss in age to be the result of x grams of biotite contamination then,

$$\frac{*_{\text{Sr}}^{87}_{\text{G}} + *_{\text{Sr}}^{87}_{\text{B}}}{\text{Rb}^{87}_{\text{G}} + \text{Rb}^{87}_{\text{B}}} = 0.0118$$

$$\frac{0.000620 + 0.0305 x}{0.027 + 3.94 x} = 0.0118$$

$$x = 1.96\%$$

More biotite is required than is available showing that the age of BH5 garnet is significantly less than 1650 m.y.

The biotite contamination has been estimated at 0.2%. A maximum possible garnet age can be calculated by subtracting a hypothetical 0.5% biotite

$$\begin{aligned}
 \text{age (m.y.)} &= \frac{1}{1.39 \times 10^{-11}} \times \frac{\frac{{}^{87}\text{Sr}_{\text{mix}} - {}^{87}\text{Sr}_{\text{biotite}}}{{}^{87}\text{Rb}_{\text{mix}} - {}^{87}\text{Rb}_{\text{biotite}}}}{\frac{0.00045 - 0.00015}{0.035 - 0.020}} \\
 &= 1.39 \times 10^{-11} \frac{0.00045 - 0.00015}{0.035 - 0.020} \\
 &= 1440 \text{ m.y.}
 \end{aligned}$$

The maximum possible BH5 garnet "age" is 1440 m.y. This is significantly "younger" than the gneiss total-rock age whereas the indicated age for BH90 garnet is significantly "older".

It is concluded that the garnet ages are the result of a later movement of Rb and/or Sr isotopes as well as biotite contamination.

CHAPTER IX.

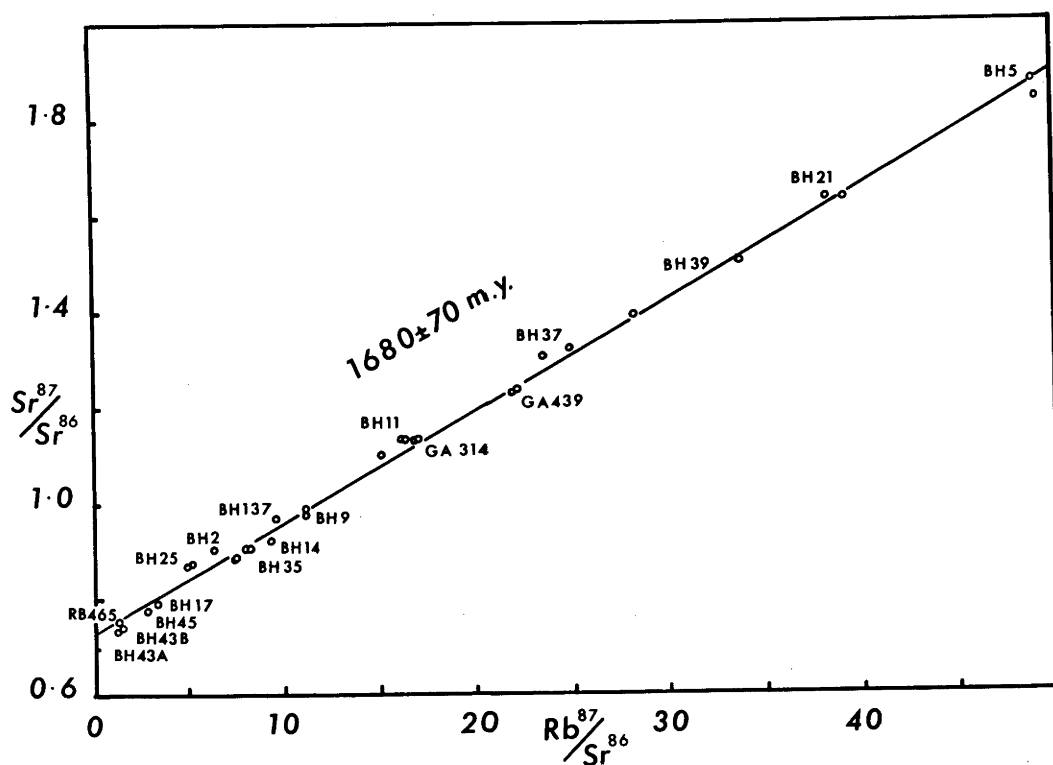
DISCUSSION AND CONCLUSIONS.

A. THE AGE OF THE GNEISSES.

Geological evidence indicates that the gneisses included in Carruthers and Pratten's Mine Sequence have had similar metamorphic histories. They have experienced a metamorphism to low granulite facies and subsequently have undergone similar retrogressive metamorphisms.

It has been demonstrated (Chapter VII) that the gneiss total-rock samples have behaved as closed systems to Rb and Sr for a similar time. The slope of total-rock isochrons defined by the garnet-sillimanite gneiss, the Potosi Gneiss, the Alma Gneiss, the Hanging Wall Gneiss and Formation No.1 granitic gneiss are not significantly different. A "t" test for the difference between two means demonstrates this for the Alma, Potosi and sillimanite gneisses. The data-points of the Alma Gneiss potassium feldspars BH39, BH35 and BH37 lie close to the total-rock isochron indicating that they have remained closed to Rb and Sr for the same period of time.

The data-points of these feldspars and all gneiss total-rocks except BH134 and BH135 are plotted on a Rb^{87}/Sr^{86} against Sr^{87}/Sr^{86} diagram in Fig. 27. A least squares line through the points defines a 1680 ± 70 m.y. isochron and an initial Sr^{87}/Sr^{86} ratio of 0.729 ± 0.019 .



(Fig. 27) Isochron plot of the combined total-rock samples.

This calculation implies -

- (i) The rocks had similar $\text{Sr}^{87}/\text{Sr}^{86}$ ratios 1680 m.y. ago.
- (ii) The rocks have remained closed systems to Rb and Sr for 1680 m.y.

As regards (i) the Rb/Sr ratios in these gneisses are high enough to allow considerable variation in the initial ratios without severely altering the measured age. (Chapter VII). However statistical calculations indicate that real differences exist, for instance between the Potosi Gneiss initial ratio 0.710 ± 0.009 and the sillimanite gneiss 0.759 ± 0.013 , and a better estimate of the gneiss age can be calculated by taking this into account. Alma, sillimanite and Potosi samples were normalised to the Potosi initial ratio and the least squares age and 95% limits were then determined to be 1640 ± 40 m.y. This age will hereafter be used as the best estimate of the age of the gneisses.

The interpretation of the gneiss age.

The conclusion (ii) that the gneisses have remained closed to Rb and Sr isotopes for 1640 m.y. is the most satisfactory explanation for the correlated data-points. The geological time of closure however is not obvious and the age may refer to 1) the deposition of the original sediments, 2) the recrystallization at granulite facies or 3) a later retrogressive metamorphism.

1). It is noted that a number of potassium feldspars are precisely correlated with the total-rock isochron and that the combined potassium feldspars have data-points whose mean isochron closely approximates that of the combined total-rocks. As the potassium feldspars are products of the granulite facies recrystallization this evidence strongly suggests that the total-rock age is that of this recrystallization and is not the age of deposition. It is also noted that apparent initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios defined by the gneisses are generally significantly higher than seawater $\text{Sr}^{87}/\text{Sr}^{86}$. This suggests that appreciable time has elapsed after deposition before the rocks were finally closed to Rb and Sr isotopes.

I conclude from this evidence that the gneiss total-rock age is not the age of deposition but is more likely to be the age of the granulite facies recrystallization.

2). The possibility must be considered that the gneiss total-rock and feldspar age is really the age of a later geological event. This implies that at some time after the granulite facies recrystallization the strontium isotopes were completely mixed (see Part I) between minerals and total-rocks. It is reasonable to correlate this hypothetical later mixing with the observed retrogressive alteration. It has been shown that the gneisses have varying amounts of retrogressive recrystallization and that this becomes extreme in

shear zones.

It has also been shown (Chapter VII) that the age of gneisses with progressively increasing retrogressive alteration is not significantly different from the unaltered total-rock age provided the gneissic fabric is retained. It was found for the sillimanite gneisses however that in shear zones where severe crushing and destruction of the gneissic fabric occurred the total-rocks lost "age". The two shear zones considered were the northerly trending "main shear" and the easterly trending Lord's Hill Fault. These shears may be younger than the retrogressive recrystallization which has not altered the gneissic fabric. However it is noted that the data-point of sheared Potosi Gneiss sample BH45 lies very close to the Potosi Gneiss isochron. In this case shearing has not opened the total-rock to Rb and Sr isotopic movement. This evidence strongly suggests that the gneisses have not become open systems to Rb and Sr isotopes during later retrogressive recrystallization, including the introduction of water, until the onset of severe deformation.

Additional evidence against the interpretation of the gneiss age as that of a later metamorphism is the necessary rearrangement of strontium isotopes. To achieve such highly correlated data-points it has been shown in Part I that complete mixing of strontium isotopes is the most probable mechanism. In the unretrogressed gneisses there is no petrographic evidence to suggest

such a severe process. Also it is noted that similar sericitisation to that in the gneisses is found in the nearby muscovite pegmatites and that these pegmatites are significantly younger than the gneiss total-rocks.

3). It is concluded that the gneiss total-rock age is the age of the granulite facies metamorphism. The K-Ar ages, 1680 m.y. (Table 13) of two hornblendes, products of this metamorphism, support the above conclusion.

B. THE MUNDI MUNDI GRANITE AGE.

The Mundi Mundi Granite masses investigated varied from dykes one chain across to stocks miles in diameter. It was found (Chapter VII) that data-points from total-rock samples from these masses fell on the same isochron and because of the varying size of the bodies and the insignificance of the alteration, which could be a later stage effect, it is concluded that the total-rock age is the age of emplacement or cooling of these granitic masses. It has also been demonstrated (Chapter VII) that the muscovites from these granites have remained closed systems to Rb and Sr isotopes since the time of formation of the granite 1520 ± 40 m.y. ago.

C. THE AGE OF THE MUSCOVITE-BEARING PEGMATITES.

The age of one set of muscovite pegmatites has been shown to be 1560 ± 40 m.y. This age is not significantly different from

that of the Mundi Mundi Granite.

It is concluded that one period of pegmatite formation, which includes muscovite pegmatites in the vicinity of Broken Hill, occurred at the same time as the Mundi Mundi Granite formation.

An age of 495 m.y. has been obtained on muscovites and albites from unmetamorphosed muscovite pegmatites from within the foliation planes of a shear zone at Thackaringa. It is considered likely that these pegmatites were nearly contemporaneous with the shearing. As there is no retrogressive alteration in these pegmatites and considering the known age retention properties of muscovite in this region it is concluded that this age represents an age of pegmatite formation and a period of shearing.

The 495 m.y. muscovite age is similar to the 530 ± 70 m.y. age registered by the biotites.

D. THE BIOTITE AGES.

It has been shown (Chapter VIII) that all the biotite Rb-Sr ages regardless of rock-type or degree of alteration lie between 530 ± 70 m.y. This has been interpreted by Richards and Pidgeon (1963) (Appendix 2) as evidence for a Palaeozoic metamorphism and is in accord with slight geological evidence and is similar to the anomalous lead age of the Thackaringa lead found by Kanasewich (1963) and also with the age of formation of pegmatites in shear

zones at Thackaringa.

It is concluded that the biotite age results from a definite metamorphic event at about 495 m.y. and that at this time the biotite lost nearly all memory of its previous age.

E. THE AGE OF EMPLACEMENT AND SEDIMENTATION OF THE WILLYAMA ROCKS.

The possibility of commenting on the origin of the Willyama rocks in the light of recent developments in the interpretation of initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios (Chapter I) is restricted at Broken Hill because of the relatively large uncertainties in the initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios in most of the rocks. This is the result of a long extrapolation of data-points defining an isochron to the $\text{Sr}^{87}/\text{Sr}^{86}$ axis. The Mundi Mundi Granite for instance has an initial ratio of 0.80 ± 0.25 ; also in the case of the gneissic rocks it is possible that redistribution of $\text{Sr}^{87}/\text{Sr}^{86}$ at the time of granulite facies metamorphism has obscured previous initial strontium isotopic ratios in the individual rock units, however it has been noted that apparent differences in initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios do exist between rock units.

It is possible to estimate the original age of the gneisses if the following assumptions are made:-

- 1) Each rock unit, e.g. Potosi Gneiss has remained a closed system to Rb and Sr since deposition or emplacement.
- 2) The least squares initial ratio for each rock unit is

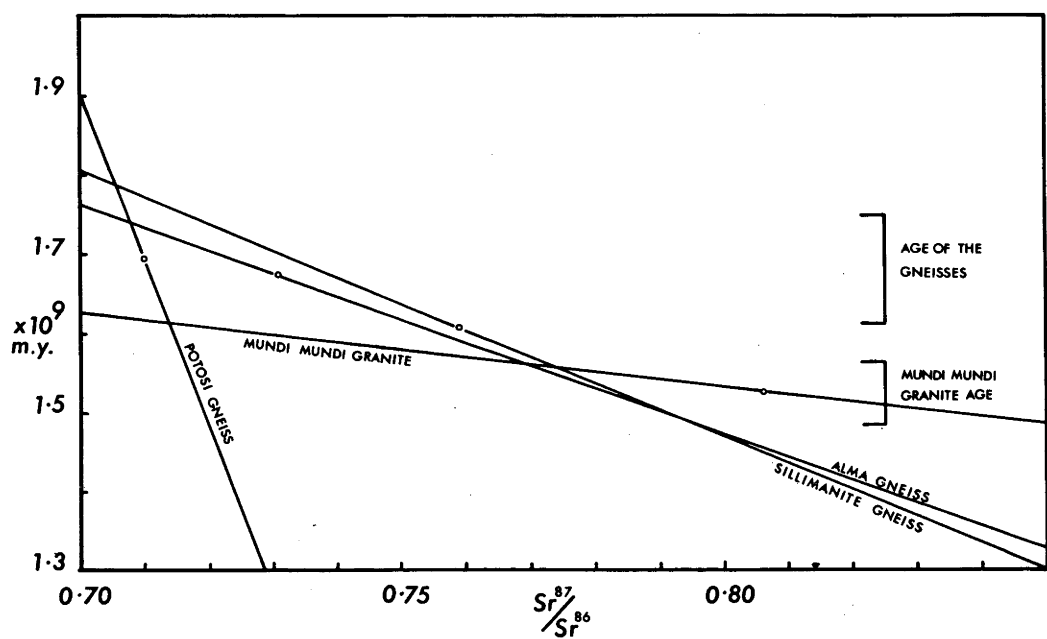
the $\text{Sr}^{87}/\text{Sr}^{86}$ ratio for that unit at the least squares age.

- 3) The average total-rock present day $\text{Sr}^{87}/\text{Sr}^{86}$ ratio of total-rock samples of a particular rock unit represents the present day ratio of that unit.

These assumptions imply that the average Rb/Sr ratio of the total-rock samples is the Rb/Sr ratio of the rock unit and that this has remained constant since deposition or emplacement.

The least squares initial ratios and age and the average present day ratios of the Alma Gneiss, Potosi Gneiss, sillimanite gneiss and Mundi Mundi Granite are plotted on a time against $\text{Sr}^{87}/\text{Sr}^{86}$ diagram in Fig. 28. Extrapolations are made to an initial $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.702 for each rock unit. The gneiss age estimated at 0.702 on this model is 1780 ± 25 m.y. The ± 25 m.y. is the uncertainty estimated from Fig. 28 and 0.702 is the estimated sea water $\text{Sr}^{87}/\text{Sr}^{86}$ at this age (normalised to $\text{Sr}^{88}/\text{Sr}^{86} = 8.34$) (Hedge and Walthall, 1963). The results of individual rock units are consistent indicating that the age of 1780 m.y. is of the correct order. It is stressed that large uncertainties are inherent in the assumptions and that this age is at best an approximation.

Under the same assumptions the Mundi Mundi Granite can be extrapolated to a $\text{Sr}^{87}/\text{Sr}^{86}$ of 0.700, where it indicates a maximum possible age of approximately 1630 m.y. At approximately 1600 m.y. ago the average $\text{Sr}^{87}/\text{Sr}^{86}$ of the gneisses corresponded to that of



(Fig. 28) Time - R_i plot of the evolution of some Willyama rock types.

the Mundi Mundi Granite, suggesting that the granite may have been genetically related to the gneisses.

A period of pegmatite emplacement accompanied the granite intrusion and crystallization.

F. COMPARISON WITH PREVIOUS WORK.

Lead ages.

It has been demonstrated in Chapter VI that the lead age of the conformable lead deposits has an uncertainty of approximately $\pm 10\%$ due to the uncertainty in the value of t_0 (the age of the earth). This coupled with the relatively short time interval of approximately 300 m.y. covering deposition of sediments, metamorphism to granulite facies and granite intrusion, makes correlation of the model lead age with any one of these events very speculative.

The 500 m.y. event determined by Kanasewich (1963) on his two stage model for the Thackaringa leads is remarkably close to the 495 m.y. determined for the shearing in the Thackaringa area. It is noted that the veins containing the Thackaringa leads transgress the shear planes in the area.

Assuming Kanasewich's model is near the truth and assuming 495 m.y. is the age of the Thackaringa leads an estimate of the age of the Broken Hill lead is very close to 1610 m.y. It is difficult to determine the precision of this estimate but if $\pm 5\%$ is assumed

as the 95% confidence limits for the 495 m.y. event the Broken Hill lead age becomes 1610 ± 8 (0.5%) m.y. These limits are markedly narrower than the previously determined $\pm 10\%$. It follows that under the assumptions of the model the Broken Hill lead age may be tentatively assigned a position in time between the metamorphism to granulite facies and the invasion of acid intrusive rocks; however as the lead age is within the 95% limits of the M1 metamorphism these may not be significantly different in time.

K-Ar ages.

The work of Richards and Pidgeon (1963) shows that the biotite K-Ar ages reflect a Palaeozoic geological event, indicating that K-Ar ages in this region are affected by argon loss. Where argon loss has been complete, as for most biotites, the age of these minerals is similar to the Rb-Sr biotite age. The unpublished K-Ar analyses by Dr. McDougall (Table 13) on samples donated by Dr. Binns generally support these conclusions though hornblende is noticeably retentive of its old age.

The K-Ar ages reported by Binns and Miller (1963) do not fit the results established by this work. However I have not analysed many samples from the north-west of the Broken Hill region and it remains to test this area for Binn's other petrologically determined metamorphic events. Binns and Miller determined the

Mundi Mundi Granite age at 1350 m.y. This is significantly younger than the Rb-Sr age indicating that in this example at least the K-Ar ages reflect a partial loss of argon.

Comparison with known geological relationships.

Throughout this thesis geological criteria have been used where possible to form a framework for the age results. Where age results contradict field relationships, as in the case of the biotite ages, alternative explanations are proposed to explain the ages.

One important assumption that the pegmatites in the shears at Thackaringa are the same age as the lead appears to contradict field relationships which clearly show the lead-bearing veins are later. This time interval may not be great.

TABLE 26. Summary of geological events whose ages have been determined in this study.

Age of deposition intrusion or extrusion of the original Willyama rocks (estimation only)	1780 m.y.
The metamorphism to granulite facies (M1)	1640 $\pm$ 40 m.y.
The emplacement of muscovite pegmatite (sericitised)	1560 $\pm$ 40 m.y.
The intrusion of Mundi Mundi Granite	1520 $\pm$ 40 m.y.
A period of shearing and muscovite (unsericitised) pegmatite formation	495 m.y.
This is similar to the biotite age	530 $\pm$ 70 m.y.

TABLE 27. Tentative geological history based on geochronological determinations.

Deposition of sediments (estimate)	1780 m.y.
Metamorphism to granulite facies	1640 $\pm$ 40 m.y.
Emplacement of lead deposits	1610 m.y.
Emplacement of muscovite pegmatite	1560 $\pm$ 40 m.y.
Intrusion of Mundi Mundi Granite	1520 $\pm$ 40 m.y.
A period of shearing and muscovite pegmatite (unsericitised) formation	495 m.y.
Metamorphism affecting biotite age	530 $\pm$ 70 m.y.
Kanasewich's age of formation of Thackaringa leads	510 $\pm$ 80 m.y. (S.D.)

PART II - APPENDIX 1.

THE PETROGRAPHY OF THE ANALYSED ROCKS.

A. The garnet-sillimanite-feldspar gneisses.

BH5. Orthoclase-sillimanite-garnet-biotite gneiss.

This specimen was collected from between No. 2 and No. 3 lenses No. 17 level Z.C. (Z.C. is an abbreviation of Zinc Corporation Ltd.)

The rock is medium grained granoblastic with poikiloblastic orthoclase and small lenses (approx. 10 mm. x 1 mm.) of sillimanite.

Constituent Minerals.

Orthoclase (approx. 50%): Anhedral untwinned crystals about 3 mm. x 2.5 mm.; contains numerous small poikiloblastic inclusions of subhedral garnet, quartz and biotite. The inclusions tend to concentrate toward the centre of grains. The crystals have an undulose extinction and contain some fine dust.

Quartz (approx. 25%): Anhedral crystals about 0.6 mm. x 0.4 mm. with slightly undulose extinction.

Sillimanite (approx. 10%): Anhedral to subhedral crystals about 1 mm. x 0.03 mm. generally in small veins.

Biotite (approx. 10%): Anhedral crystals about 1 mm. x 0.6 mm., pleochroic with Z red brown, Y, light brown, X, colourless to fawn.

Pleochroic halos and zircons are present, the crystal edges are frayed slightly and grains lie in a preferred plane.

Garnet (approx. 5%): Pink subhedral crystals about 0.5 mm. x 0.5 mm.

Alteration to muscovite plus iron ore and sericite make up about 1% of the rock.

BH21. Orthoclase-garnet-sillimanite-biotite gneiss.

This specimen was collected from No. 6 level Z.C.

In hand specimen this is grey with lenses about 20 mm. x 1 mm. of sillimanite and alteration products. In thin section the rock is medium grained granoblastic with areas of recrystallization to phyllosilicates.

Constituent Minerals.

Orthoclase (approx. 50%): Anhedral crystals about 3.5 mm. x 3 mm., only some have poikiloblastic inclusions as in BH5. Crystals are untwinned but possess an undulose extinction less marked than in BH5. There is alteration to sericite and a few patches of dust sized opaque material.

Quartz (approx. 15%): Anhedral crystals about 0.5 mm. x 0.4 mm. with undulose extinction.

Garnet (approx. 10%): Subhedral crystals about 2 mm. x 2 mm., broken up in reaction zones.

Biotite (approx. 10%): Anhedral crystals about 1 mm. x 0.4 mm.

Generally has frayed edges and exsolved iron oxide. Pleochroic Z = red brown, X = light brown to colourless. Biotite is recrystallized in the reaction zones to form crystals interleaved with colourless phyllosilicates.

Sillimanite (approx. 5%): Anhedral crystals about 3 mm. x 0.5 mm. generally occur in small veins. These appear to be a focus for deformation. There is minor stable gahnite.

These reaction zones make up some 10% of the rock.

BH21 Orthoclase concentrate.

Consists of untwinned poikiloblastic crystals with a few composite with biotite and quartz ($< 1\%$). Most grains have areas of opaque dust, some are nearly half covered.

The stable initial assemblage in the above rocks appears to be garnet, sillimanite, orthoclase, biotite and quartz. This assemblage is very similar to the pelitic assemblage in the sillimanite-almandine-orthoclase subfacies of the Almandine-Amphibolite Facies of Turner and Verhoogen (1960). It is also identical to the Hornblende-Granulite subfacies of the Granulite Facies of these authors.

The mineral assemblage is undergoing retrogressive alteration. Stable alteration minerals are sericite and biotite and an unknown phyllosilicate which is pseudomorphing sillimanite.

B. The altered garnet-sillimanite gneisses.

BH2. Muscovite-feldspar-biotite-garnet gneiss.

From No.17 level Z.C.

This rock is medium grained, grey, granoblastic with considerable retrogressive recrystallization.

Constituent Minerals.

Quartz (approx. 45%): Clusters of anhedral crystals 0.4 mm. x 0.3 mm. with undulose extinction. Appears to have recrystallized from larger crystals.

Muscovite (approx. 25%): Anhedral crystals about 1 mm. x 0.4 mm. Crystals occur with random orientation in groups giving the appearance of being secondary.

Biotite (approx. 10%): Anhedral crystals about 0.3 x 0.1 mm. and smaller. Crystals occur randomly oriented in clusters and are secondary.

Feldspar (approx. 10%): Anhedral crystals about 0.8 mm. x 0.5 mm. Drastic alteration by sericite and replacement by quartz and alkali-feldspar obscures the identity of this mineral though both plagioclase and orthoclase are suspected.

Accessory zircon, iron ore, rutile and apatite are present.

BH2. Muscovite concentration.

About 65-75% is clear muscovite. About 25% is a mat of

fine sericite composites. Quartz and sillimanite make up 3%.

BH23. Sericite-garnet gneiss.

From No. 6 level Z.C.

This is a grey medium grained granoblastic rock heavily altered to sericite and biotite.

Constituent minerals.

Sericite (approx. 70%): Anhedral crystals up to 0.1 mm. showing preferred orientation. This secondary mica is well crystallized and could be called muscovite.

Quartz (approx. 8%): Dissected crystals about 1 mm. x 0.8 mm., distends sericite planes.

Biotite (approx. 2%): Secondary crystals similar in size and habit to the sericite.

A few dissected iron ore crystals and some relic feldspar crystals are present.

BH23. Sericite concentrate.

The sample is 85% fine sericite aggregates and 15% flakes of coarse sericite or muscovite.

BH25. Sericite-garnet-biotite-feldspar gneiss.

From No.12 level Z.C.

This is a grey medium grained granoblastic rock which has

been considerably recrystallized.

Constituent Minerals.

Quartz (approx. 60%): Anhedral crystals about 0.3 mm. x 0.3 mm. with undulose extinction; this appears to have recrystallized.

Sericite (approx. 15%): Anhedral crystals about 0.1 mm. x 0.05 mm. generally well crystallized but occurs in clusters with preferred orientation and is obviously secondary.

Garnet (approx. 10%): Broken crystals about 0.6 mm. x 0.5 mm. These do not appear to have been chemically altered.

Biotite (approx. 10%): Secondary anhedral crystals about 0.1 mm. x 0.2 mm. similar in habit to sericite. (It is pleochroic brown (z) to light fawn (x) and is well crystallized.

Feldspar (approx. 5%): Extensively altered potassium feldspar and andesine, $X^{\wedge} 010 \perp a = 15^{\circ} \pm 4^{\circ}$. Dissected crystals are altered to biotite, sericite and opaque dust.

Opaque iron ore (approx. 1%): Anhedral crystals about 0.4 mm. x 0.4 mm.

BH25. Sericite concentrate.

60% is clear flakes, the rest is sericite quartz composites. Biotite composites make up about 0.1%.

BH134. Sericite-garnet schist.

This is a specimen of the "main-lode shear" (J. Henderson,

pers. comm.) from No.23 level North Broken Hill Ltd.

The rock is medium grained allotriomorphic and consists mainly of a mat of sericite.

Constituent Minerals.

Sericite (approx. 60%): Occurs as a fine mat of crystals with a strong preferred orientation.

Quartz (approx. 25%): Anhedral crystals about 0.1 mm. x 0.2 mm. These have an undulose extinction and appear to have recrystallized.

Garnet (approx. 10%): Anhedral crystals about 0.9 mm. x 0.8 mm. These have indented margins and are showing chemical alteration to brown-green mica.

Biotite (approx. 5%): Pleochroic green-brown crystals similar in habit to the sericite occur in patches.

BH134. Sericite concentrate.

90-95% sericite aggregates, 10% quartz. There are a few biotite composites.

BH135. Sericite-garnet-feldspar schist.

This is a specimen of the Lord's Hill Fault from No.23 level, North Broken Hill Ltd.

The original gneiss has been extensively altered to a mat of sericite, serpentinous chlorite and biotite. An unusual feature of this rock is the presence of euhedral staurolite, now pseudo-

morphed by chloritic mica.

Constituent Minerals.

Sericite Mat (approx. 45%): This consists of fine crystals of mainly sericite but also biotite. There is a preferred orientation.

Quartz (approx. 20%): Anhedral crystals 0.2 mm. x 0.2 mm. occur in groups and appear to have recrystallized from larger crystals.

Garnet (approx. 25%): Anhedral slightly crushed crystals about 0.3 mm. x 0.4 mm. altering to biotite.

Staurolite (approx. 10%): Euhedral crystals about 0.7 mm. x 0.3 mm., some twinned, are now pseudomorphed by chloritic mica. These appear to have been randomly oriented in the sericite mass.

A few crystal clusters with high relief may be epidote.

BH135. Sericite concentrate.

Contains 10-20% quartz. Some sericite crystals are semi-opaque.

BH137. Sericite-sillimanite-garnet-biotite schist

From No.23 level North Broken Hill Ltd.

The hand specimen is inhomogeneous and banded and has clots of quartz, biotite and garnet.

Constituent Minerals.

Quartz (approx. 45%): Anhedral crystals about 1.0 mm. x 0.6 mm. with a distinct undulose extinction.

Sericite (approx. 36%): Occurs as a fine mat with occasional large

crystals with a radiating texture suggesting an origin from sillimanite.

Sillimanite (approx. 8%): Anhedral crystals up to 1 mm. x 0.4 mm. Crystals are bent, crushed and sericitised.

Garnet (approx. 5%): Poikilitic broken crystals with slight alteration to biotite.

Biotite (approx. 5%): Broken and frayed crystals 0.5 mm. x 0.4 mm. Larger crystals appear to have been present before the sericite alteration. Smaller crystals behave similarly to the sericite.

Epidote (approx. 1%): Anhedral dissected clinozoisite with anomalous blue birefringence.

A little secondary iron ore is present plus about 1% of relic feldspar.

BH137. Sericite concentrate.

The fine sericite occurs as composites with sillimanite and residual feldspar. Two weight fractions were recorded -

1) $SG > 2.75$, 2) $S.G. > 2.71 < 2.75$

It was assumed that these fractions contained mainly sillimanite-sericite composites.

BH139. Sericite-garnet schist.

This is a specimen of the Adam Fault No. 9 cross cut No.24 level North Broken Hill Ltd.

In hand specimen this is a grey-green knotted quartz-garnet-mica schist. In thin section the rock is considerably recrystallized and originally was probably a granoblastic garnet-biotite-feldspar gneiss.

Constituent Minerals.

Garnet (approx. 40%): unaltered crystals about 4 mm. x 4 mm. Some are euhedral indicating considerable recrystallization of the garnet.

Quartz (approx. 25%): Anhedral crystals about 0.4 mm. x 0.4 mm. with undulose extinction; appears recrystallized.

Sericite (approx. 35%): Mass of anhedral crystals up to 0.3 mm. x 0.2 mm.

Biotite (approx. 10%): Anhedral crystals 0.6 mm. x 0.3 mm. being recrystallized to fine biotite, of similar habit to the sericite and green chlorite?, plus iron ore.

Accessory crystals of iron ore are present together with rutile and epidote or more likely sphene. A few relic feldspar grains occur.

BH139. Sericite concentrate.

This consists of well crystallized sericite with approx. 1% biotite. 5% of the grains are composites with quartz.

BH40. Sericite-sillimanite-garnet schist.

This is a specimen from a surface outcrop of the British Fault at the turnoff from the main road to North Broken Hill Ltd.

In hand specimen it is a white micaceous schist with small pink garnets (about 10%). Iron staining and weathering are evident.

In thin section the rock shows strong deformation and partial recrystallization. There is a strong preferred direction.

Constituent Minerals.

Sericite (approx. 60%): Nearly covers the rock in a fine mat.

Sillimanite (approx. 15%): Crushed and smeared crystal fragments with weak undulose extinction.

Garnet (approx. 10%): Residual rounded grains of pink garnet with marginal orange alteration.

About 10% of the rock is coated with opaque brown dust; probably clay.

BH40. Sericite and biotite concentrate.

Two separates were made. One consisted of well crystallized sericite with about 5% biotite. The other consisted of sericite plus about 20% biotite.

The stable assemblage in these retrogressive members of the garnet-sillimanite gneiss rocks of the mine sequence appear to be, sericite, (muscovite), biotite, epidote, quartz, staurolite and garnet. No stable feldspar was observed. Rutile and possibly sphene appear also in minor amounts. Albite has not been recognised but I am not confident that this does not exist in the quartz groundmass.

The assemblage appears to be similar to the Staurolite Almandine Subfacies of the Almandine-Amphibolite Facies of Turner and Verhoogen (1960).

C. Formation No. 1 of Carruthers and Pratten (1961).

GA314. Granitic gneiss.

This specimen is from an outcrop just east of the De Bavay Fault. Z.C. Co-ordinates, 8800N, 14000E. Collected by Z.C.

This rock is medium grained granoblastic with considerable sericite alteration and some development of myrmekite. Crystal margins show considerable indentation.

Constituent Minerals.

Quartz (approx. 60%): Anhedral crystals about 1 mm. x 0.8 mm. with strong undulose extinction.

Potassium feldspar (approx. 20%): Anhedral crystals about 1 mm. x 0.6 mm. Although some crystals are untwinned with a slightly undulose extinction the majority have microcline twinning and have a strong wavy extinction. Alteration to sericite is proceeding along grain boundaries, and replacement by albite and quartz is present.

Plagioclase (approx. 15%): Oligoclase, An_{13} , $X'AO10 \perp a = 9^\circ \pm 6^\circ$, R.I. > quartz, dissected crystals about 1 mm. x 0.6 mm. In some instances appears to be replacing potassium feldspar through myrmekite.

Biotite (approx. 5%): Anhedral frayed crystals about 0.4 mm. x 0.5 mm., occurs mainly as small secondary crystals with sericite.

Sericite (approx. 1%): Randomly scattered small groups of crystals cluster round grain boundaries. A few subhedral apatites and some zircon are present.

This rock appears to have undergone considerable strain and recrystallization. The presence of triclinic potassium feldspar is noteworthy.

D. The Potosi Gneiss.

BH17. Garnet-feldspar gneiss.

This is a specimen of Potosi Gneiss from No. 6 level Z.C.

The rock is medium grained granoblastic. Reaction texture is present in the feldspars and garnet is showing alteration to biotite.

Constituent Minerals.

Quartz (approx. 45%): Anhedral crystals about 6 mm. x 6 mm. with a strong undulose extinction.

Plagioclase (approx. 25%): Andesine, An_{35} . Anhedral twinned crystals about 0.6 mm. x 0.6 mm. $X' \wedge O10 \underline{1} \underline{a} = 15^\circ \pm 5^\circ$. This has a slightly undulose extinction and appears to be unstable with respect to orthoclase.

Potassium feldspar (approx. 15%): Untwinned anhedral crystals about

1 mm. x 0.6 mm. Some grains have microperthitic inclusions.

Garnet (approx. 10%): Subhedral dissected poikilitic crystals about 3 mm. x 2.5 mm. altering to biotite and iron ore.

Biotite (approx. 2%): Recrystallized anhedral crystals about 0.2 mm. x 0.1 mm.

Iron Ore (approx. 1%): Occurs as rounded crystals about 0.2 mm. x 0.2 mm., zircon (1%) occurs as small rounded crystals, apatite and epidote? form accessories. There is a small concentration of sericite.

BH17. Potassium feldspar concentrate.

Untwinned perthitic crystals with about 35% quartz. About 5% of the feldspar has a clay dust coating. There is < $\frac{1}{2}$ % biotite.

BH44. Acid pygmatic vein in the Potosi Gneiss from the Potosi Gneiss quarry, Broken Hill.

This is coarse grained granoblastic with indication of a later crushing. Grain boundaries are indented.

Constituent Minerals.

Quartz (approx. 40%): Anhedral crystals about 4 mm. x 3 mm. Some potassium feldspar may be present but none is evident in the thin section. The feldspar is slightly sericitised and antiperthitic in spots.

Biotite (approx. 5%): Occurs as anhedral crystals 3 mm. x 2 mm. with

frayed edges and as recrystallized clusters of small grains.

Zircon occurs as an accessory.

BH44. Potassium feldspar concentrate.

Untwinned perthitic crystals. About 70% of the grains have a moderate clay coating. The sample is > 98% potassium feldspar.

BH45. Sheared Potosi Gneiss.

This sample is from a shear zone (trend 45°) located in the Potosi Gneiss Quarry.

The rock has been strongly deformed and has a schistose fabric. In section it is medium grained with evidence of strong cataclasis and recrystallization.

Constituent Minerals.

Quartz (approx. 60%): Strained anhedral crystals about 2 mm. x 2 mm. are being broken down and recrystallized as smaller grains. Small recrystallized subhedral grains about 0.1 mm. x 0.1 mm. occur in the groundmass.

Biotite (approx. 16%): Subhedral greeny-brown pleochroic crystals about 0.2 mm. x 0.1 mm. of secondary origin.

Feldspar (approx. 10%): Highly dissected relic grains mainly plagioclase occur in the ground mass.

Sericite (approx. 7%): Subhedral crystals about 0.2 mm. x 0.1 mm.

have a strong preferred orientation.

Garnet (approx. 5%): Small crystal fragments occur in trails.

Epidote (approx. 2%): Anhedral crystals about 0.1 mm. x 0.1 mm.

Iron Ore (approx. 1%): Anhedral to subhedral crystals about 0.1 mm. x 0.1 mm.

Apatite is accessory.

BH43. Feldspar-biotite-garnet gneiss.

This is a specimen of Potosi Gneiss from the Potosi Gneiss quarry, Broken Hill.

In hand specimen this is a garnet biotite gneiss with acid bands. 43A is the garnet gneiss, 43B is a leucocratic band. The texture is medium grained granoblastic though considerable indentation of crystal margins is present.

Constituent Minerals in 43A.

Quartz (approx. 40%): Anhedral crystals about 8 mm. x 6 mm. with pronounced undulose extinction.

Plagioclase (approx. 40%): Andesine, An_{33} well twinned anhedral crystals about 0.6 mm. x 0.5 mm. with a zoned extinction. $X' \wedge 010 \pm a = 16^\circ \pm 5^\circ$.

Biotite (approx. 8%): Anhedral crystals 0.3 mm. x 0.2 mm. with frayed ends. These often occur in groups and are often recrystallizing

to smaller crystals. Garnet appears to be unstable with respect to biotite and a colourless mica.

Garnet (approx. 5%): Anhedral crystals about 3 mm. x 3 mm.

extensively altered to green mica, biotite and sericite in cracks.

Associated with apatite and iron ore.

Potassium feldspar (approx. 5%): Anhedral untwinned orthoclase

0.6 mm. x 0.4 mm. with inclusions of euhedral garnet and other colourless crystals; has undulose extinction.

Apatite (approx. 1%): Rounded crystals about 1 mm. x 1 mm. often associated with garnet.

Iron ore, zircon and calcite are accessories.

BH43A. Potassium feldspar concentrate.

Untwinned perthitic crystals with inclusions of biotite (< 1%) and quartz. About 10% of the grains have a minor dust coating. The sample is about 97% pure.

BH43B. Potassium feldspar concentrate.

Untwinned perthitic crystals with a total of 3% inclusions with < 1% biotite. There is a minor clay coating. The purity is > 97%.

GA312. Garnet-feldspar gneiss.

This is also from the Potosi Gneiss quarry, Broken Hill.

It is medium grained granoblastic with considerable

recrystallization.

Constituent Minerals.

Quartz (approx. 45%): Anhedral crystals about 1 mm. x 1 mm. with undulose extinction.

Plagioclase (approx. 20%): Andesine, An_{45} , anhedral crystals about 0.5 mm. x 0.6 mm. One subhedral crystal was noticed. $X^{\wedge} 010 \perp a = 25^{\circ} \pm 5^{\circ}$; zoned; twinned; and has dust sized inclusions.

Potassium feldspar (approx. 14%): Anhedral untwinned slightly perthitic crystals about 1 mm. x 0.6 mm. Has an undulose extinction and a light dust sized clay coating.

Garnet (approx. 5%): Subhedral poikilitic crystals about 1.5 mm. x 1 mm. heavily altered to biotite and colourless micas along cracks.

Biotite (approx. 10%): Anhedral frayed crystals 0.3 mm. x 0.1 mm. and recrystallized clumps.

Iron ore (approx. 1%). Zircon and apatite are accessories.

GA312. Potassium feldspar concentrate.

Unaltered, untwinned crystals with a minor amount of composites including rare biotite. The purity is approx. 98%.

E. The Hanging Wall Basin.

The following samples are from Formation No. 13 after Carruthers and Pratten, 1961.

RB465. Plagioclase-biotite-garnet gneiss.

This was presented by Dr. R.A. Binns and is from the "Hanging Wall Basin" Billygoat Hill, Broken Hill.

This is a medium grained granoblastic somewhat inhomogeneous in hand specimen with isolated patches of garnet. Alteration products are essentially absent.

Constituent Minerals.

Plagioclase (approx. 60%): Andesine, An_{32} , anhedral crystals 1 mm. x 0.6 mm. with well developed twinning. $X' \wedge 010 \perp a = 17^\circ \pm 5^\circ$.

The extinction is zoned and crystals are fractured.

Quartz (approx. 25%): Anhedral crystals about 0.8 mm. x 0.4 mm. with undulose extinction.

Biotite (approx. 10%): Anhedral crystals about 8 mm. x 3 mm., includes zircon and dots of iron ore.

Orthoclase (approx. 3%): Poikilitic porphyroblasts 3.5 mm. x 3.0 mm. include quartz, plagioclase and biotite.

Garnet (approx. 2%): Highly dissected crystals unstable with respect to biotite.

Zircon, apatite and iron ore are accessories.

BH9. Granitic gneiss.

From Block 10 Hill, Broken Hill.

In hand specimen this is a medium grained granitic gneiss

with a strong foliation, with biotite feldspathic banding, which is itself folded.

This is a medium grained granoblastic rock which has experienced a later severe crushing and recrystallization.

Constituent Minerals.

Quartz (approx. 50%): Anhedral crystals about 0.4 mm. x 0.3 mm. recrystallized from larger grains.

Potassium feldspar (approx. 20%): Anhedral untwinned crystals about 1.0 mm. x 0.7 mm. Some microcline twinning is present.

Plagioclase (approx. 17%): Anhedral twinned crystals about 0.6 mm. x 0.5 mm.

Sericite (approx. 10%): Anhedral sharp crystals 0.5 mm. x 0.5 mm. concentrated in crush zones.

Biotite (approx. 3%): Anhedral crystals 0.2 mm. x 0.1 mm. recrystallized and concentrated in crush zones.

BH9. Potassium feldspar concentrate.

Untwinned perthitic crystals include occasional biotite (< 1%). The sample has a minor dust coating and is > 98% pure.

BH14. Granitic gneiss.

From Block 10 Hill, Broken Hill.

The rock has a foliation made up of alternating biotitic and feldspathic bands which is itself folded. Where this second

folding is intense axial plain slippage occurs and sericite develops together with occasional pegmatite. (i.e. BH10).

In section the rock is medium grained granoblastic with considerable reaction texture.

Constituent Minerals.

Potassium feldspar (approx. 50%): Anhedral perthitic crystals about 3 mm. x 2 mm. with faint microcline twinning. Altering to albite via myrmekite.

Quartz (approx. 30%): Anhedral crystals about 0.4 mm. x 0.3 mm. appear to have recrystallized from larger grains.

Biotite (approx. 5%): Anhedral crystals about 0.4 mm. x 0.2 mm. with pleochroic halos tending to recrystallize to smaller grains.

Plagioclase (approx. 5%): Oligoclase An_{26} , anhedral twinned crystals about 0.4 mm. x 0.3 mm. $X' \wedge 010 \perp a = +4^\circ + 4^\circ$.

Sericite (approx. 3%): Anhedral sharp crystals about 0.05 mm. x 0.02 mm. scattered throughout the rock.

BH14. Potassium feldspar concentrate.

Poikilitic crystals include subhedral quartz and minor biotite (< 1%). The sample has 20% of its grains with a light clay coating, and is about 97% pure.

BH11. Granitic gneiss.

This specimen is from Block 10 Hill, Broken Hill.

The hand specimen is strongly foliated with alternating bands of feldspathic and biotitic material. These bands are themselves folded. Biotite sometimes occurs in patches which have a surrounding leucocratic zone.

The rock is medium grained granoblastic with evidence of a later crushing. Crystal boundaries are indented and there has been considerable recrystallization.

Constituent Minerals.

Potassium feldspar (approx. 10%): Anhedral twinned crystals about 0.6 mm. x 0.4 mm. altering to albite via myrmekite, sericite and opaque dust sized material, possibly clay.

Quartz (approx. 45%): Anhedral crystals about 0.3 mm. x 0.4 mm., have an undulose extinction and appear to have recrystallized from larger grains.

Plagioclase (approx. 32%): Anhedral oligoclase about 1 mm. x 0.8 mm. with a zoned extinction.

Biotite (approx. 10%): Anhedral crystals about 0.4 mm. x 0.2 mm. often occur in groups; include zircon.

Sericite (approx. 3%): Anhedral sharp crystals about 0.1 mm. x 0.05 mm.

Zircon, iron ore are accessories.

BH11. Potassium feldspar concentrate.

Twinned and untwinned perthitic grains with less than 1%

biotite composites. About 5% of grains have a slight clay coating.

The sample is > 98% pure.

BH10. "Pegmatitic" vein in granitic gneiss.

From Block 10 Hill, Broken Hill.

This rock occurs in a shear parallel to the axial planes of folds in the granitic gneiss. The pegmatite itself has experienced a later deformation and recrystallization.

In thin section the rock is porphyroblastic with parallel veins of crushed and recrystallized minerals. An opaque dust coats many of the minerals.

Constituent Minerals.

Quartz (approx. 40%): Anhedral crystals about 0.3 mm. x 0.2 mm. recrystallized from larger crystals. Some crystals are larger and have undulose extinction.

Orthoclase (approx. 40%): Anhedral untwinned perthitic porphyroblasts 6 mm. x 4 mm. reacting in fractures and at margins to myrmekite. Crystals have a sparse dust coating.

Plagioclase (approx. 10%): Oligoclase, An₁₀. Anhedral twinned porphyroblasts about 6 mm. x 4 mm. has zoned extinction, is altered to sericite and has indented and crushed margins.

Biotite (approx. 7%): Occurs as clusters of anhedral crystals.

Sericite (approx. 3%): Sharp crystals concentrated in "crush veins".

F. The Alma Gneiss.

Specimen BH37 is from an outcrop of granitic gneiss which appears to be surrounded by rock type BH34, a coarse sheared and recrystallized granitic gneiss. A notable feature of BH34 is the growth of perthitic untwinned potassium feldspar porphyroblasts. BH37, a medium grained granitic gneiss has coarse grained lenses of granitic material characterised by glomeroblastic biotite. These occur near the contact of BH34 and the rock, BH37, appears to grade into rock type BH34. BH39 has a different texture from BH34 and BH37.

Indications are that these rocks

- (1) represent independent granitic masses
- (2) are the same mass but have experienced different metamorphic conditions.

BH37. Granitic gneiss.

In hand specimen the rock is a medium grained granulose leucocratic rock. Biotite ($\sim 10\%$) occurs in a preferred plane. The fabric is distinctly different from the coarser grained augen gneiss.

In thin section it is medium grained granoblastic with evidence of a later crushing.

Constituent Minerals.

Quartz (approx. 40%): Anhedral crystals about 0.8 mm. x 0.6 mm. with

undulose extinction.

Potassium feldspar (approx. 35%): Anhedral untwinned and twinned perthitic crystals about 0.8 mm. x 0.6 mm. altering to albite via myrmekite; has an undulose extinction.

Plagioclase (approx. 20%): Anhedral zoned crystals about 0.5 mm. x 0.5 mm.

Biotite (approx. 5%): Greeny-brown crystals about 0.1 mm. x 0.05 mm., frayed at edges.

Sericite (approx. 1%): Is located mainly in the plagioclase and around biotite.

There is a little iron ore and rare rounded to subhedral zircons.

BH37. Potassium feldspar concentrate.

This is perthitic untwinned and grains have an extensive coating of opaque dust; a few grains are $\frac{1}{4}$ covered. The sample is > 97% potassium feldspar.

BH39. Granitic gneiss.

This is a medium grained melanocratic granulose rock with a strong preferred orientation, defined mainly by biotite; the fabric is distinctly different from BH37.

In section the rock is medium grained granoblastic and shows evidence of being severely crushed and recrystallized.

Constituent Minerals.

Quartz (approx. 35%): Anhedral, crushed crystals about 0.5 mm. x 0.5 mm. with undulose extinction.

Microcline (approx. 55%): Anhedral crystals about 1 mm. x 0.6 mm., twinned, strained, and crushed. Recrystallization is occurring at the boundaries in the form of myrmekite. Reactions also suggest a reorientation of microcline.

Plagioclase (approx. 5%): Anhedral crystals about 0.5 mm. x 0.4 mm. reacting to form microcline and quartz.

Biotite (approx. 5%): Anhedral crystals recrystallized in the new axial plane.

Muscovite (approx. 1%): About 0.4 mm. x 0.2 mm. appears to be older than the fine sericite. Sericitisation is not extensive.

BH39. Potassium feldspar concentrate.

Crystals are untwinned strained and perthitic and have a considerable coating of dust sized opaque clay; some grains are half covered. The sample is > 99% potassium feldspar.

GA439. Alma Augen gneiss.

For petrographic description refer to GA109 Richards and Pidgeon, 1962.

GA439. Potassium feldspar concentrate.

Crosshatched twinning is well developed and there are about 3% composites with quartz. A coating of dust sized clay is

present and some crystals are $\frac{1}{4}$ covered.

BH35. Quartz-plagioclase-garnet-cordierite granulite.

This appears to be a basic xenolith in the Alma Gneiss which has suffered metamorphism possibly to hornblende granulite facies. It has suffered a later crushing.

It is coarse grained granoblastic and is considerably crushed though there appears to have been little chemical alteration accompanying crushing. The cordierite is pinitised.

Constituent Minerals.

Quartz (approx. 50%): Anhedral strained crystals about 4 mm. x 3 mm.

Plagioclase (approx. 30%): Anhedral crystals 3 mm. x 2 mm., twinned, crushed but not recrystallized.

Garnet (approx. 15%): Anhedral crystals about 1 mm. x 1 mm.

Poikilitically includes quartz and biotite.

Cordierite (approx. 5%): Anhedral twinned crystals about 0.5 mm. x 1 mm., altering to pinite.

Orthoclase (approx. 1%): Anhedral untwinned crystals about 1 mm. x 0.5 mm.

BH35. Potassium feldspar concentrate.

Perthitic untwinned crystals. The sample is > 98% potassium feldspar.

G. The Mundi Mundi Granite.

BH68. Muscovite granite.

From near the Brewery Well stockyards and windmill.

This is a leucocratic medium grained granite. In section the rock is coarse grained allotriomorphic with minor alteration and evidence of a later crushing.

Constituent Minerals.

Quartz (approx. 45%): Anhedra1 crystals about 3 mm. x 3 mm. with a distinct undulose extinction.

Microcline (approx. 30%): Anhedra1 twinned crystals about 3 mm. x 1.5 mm. Crushed with veins of albitic feldspar.

Plagioclase (approx. 20%): Albite; anhedra1 twinned crystals about 3 mm. x 1.5 mm., strained and slightly crushed, includes sericite.

Muscovite (approx. 4%): Anhedra1 strained about 3.5 mm. x 3.0 mm.

Occurs also as small crystals 0.5 mm. x 0.3 mm. in plagioclase.

Biotite (approx. 1%): Anhedra1 green crystals occur in clusters associated with muscovite.

BH70. Muscovite Granite.

From the Brewery Well pluton, Brewery Well.

In hand specimen this is a medium grained leucocratic muscovite granite.

In section it is medium grained allotriomorphic. It has

suffered a later crushing which has resulted in minor recrystallization.

Constituent Minerals.

Quartz (approx. 40%): Anhedral crystals about 2 mm. x 2 mm. which show distinct strain. Smaller crystal aggregates have recrystallized from larger grains.

Microcline (approx. 20%): Anhedral twinned dissected and strained crystals about 2 mm. x 1 mm.

Plagioclase (approx. 9%): Albite, well twinned anhedral crystals crushed with indented margins and zoned extinctions.

Muscovite (approx. 5%): Anhedral crystals about 3 mm. x 2 mm. strained and slightly recrystallized to muscovite and biotite.

Biotite (approx. 1%): Green and brown poorly recrystallized grains around muscovite.

25% of the rock is an aggregate of small recrystallized grains. An opaque brown dust lightly coats areas of the section.

BH70. Muscovite concentrate.

About 30% are crystal aggregates. Biotite is about 1% in composites. The rest is muscovite flakes.

BH70. Microcline concentrate.

Twinned crystals with 30% slightly coating with opaque clay. The sample is > 98% microcline.

BH82. Muscovite granite.

From a granite dyke in metasediments $1\frac{1}{2}$ miles east of the Allandale Mine.

The hand specimen is a leucocratic medium to coarse grained muscovite bearing granite.

In section it is medium grained allotriomorphic with evidence of a later crushing which is not as severe as in BH70.

Constituent Minerals.

Microcline (approx. 40%): Anhedral, strained, twinned crystals about 2 mm. x 1.6 mm. altered to sericite.

Quartz (approx. 30%): Anhedral strained crystals about 0.8 mm. x 0.6 mm. Altering to sericite, quartz and possibly potassium feldspar.

Muscovite (approx. 7%): Anhedral strained crystals about 0.6 mm. x 0.4 mm. slightly frayed at the edges.

Biotite (approx. 3%): Small recrystallized pleochroic brown grains. There is also a few rounded apatites, sericite along grain boundaries and a brown dust coating the feldspars.

BH82. Microcline concentrate.

Twinned crystals. 80% have a light coating of opaque clay. The sample is > 97% microcline.

H. The Pegmatites.

BH81. Pegmatite or aplite from a dyke one mile east of the Allandale Mine.

The hand specimen is coarse grained leucocratic with secondary muscovite and coarse primary muscovite.

In section this is coarse grained allotriomorphic and shows evidence of a later crushing and recrystallization.

Constituent Minerals.

Quartz (approx. 50%): Strained and crushed anhedral crystals up to 1 cm.².

Plagioclase (approx. 30%): Oligoclase crushed anhedral crystals with some sericite alteration.

Some 15% of the rock is a crushed aggregate of feldspar, quartz and coarse sericite. Some of the larger white mica is bent and strained suggesting it is original muscovite.

BH85. Pegmatite from outcrop one mile west of Broken Hill.
770N, 650". (Z.C. map)

This is coarse grained with coarse muscovite books, a fine secondary mica with a preferred orientation and phenocrysts of pink feldspar.

In section it is coarse grained with evidence of crushing and recrystallization.

The quartz occurs in stringers and is strained. The plagioclase (approx. albite) is twinned and is coated with secondary sericite. In the section potassium feldspar is rare.

BH85. Potassium feldspar concentrate.

The mineral is pink and coated with an opaque dust. Alteration has occurred to sericite and epidote. No twinning was present.

BH85. Albite concentrate.

This is altered to sericite and coated with clay to about the same extent as the potassium feldspar.

BH31. Pegmatite from a dyke transgressing the Alma Gneiss.

This is a coarse grained quartz-muscovite-microcline pegmatite. The muscovite occurs in books about one inch across with a preferred orientation.

BH31. Microcline concentrate.

Contains 15% to 20% quartz and is coated to varying degrees with opaque clay. Some grains are completely coated.

BH91. Discordant muscovite pegmatite from near the haulage shaft No.16 level N.B.H.C.

This consists of coarse crystals of quartz and muscovite together with crushed zones of smaller crystals.

The quartz (approx. 70%) is strained whereas the muscovite (approx. 15%) is slightly frayed and bent. The rock has a sheared appearance.

BH94. Muscovite pegmatite from No.14 level N.B.H.C. This could be the same rock as BH91.

The rock consists of muscovite (2 cm.² books) and quartz. The muscovite has no preferred orientation and is not altered. The rock does not appear to have experienced the strong crushing of BH91.

BH79. Muscovite pegmatite from the shear zone through the Allandale Mine area.

This consists of quartz, microcline, albite and muscovite. The quartz is strained and primary muscovite is frayed and bent. Some secondary muscovite occurs in the microcline.

The rock is slightly weathered. The feldspars are altering to clay.

BH47 and BH49. Muscovite pegmatites from a shear zone at Thackaringa.

These two pegmatites consist of coarse muscovite, albite and quartz. They show no weathering and no retrogressive alteration.

BH27. "Concordant" green feldspar pegmatite from No.12 level Z.C.

This is coarse grained with considerable recrystallization. The mineral margins are very indented.

Constituent Minerals.

Quartz (approx. 50%): Anhedral crystals about 4 mm. x 3 mm. and smaller when recrystallized.

Microcline (approx. 40%): Anhedral crystals about 3 mm. x 2 mm., extensively crushed and altered to clay sericite and zoisite.

Alteration products (approx. 10%) are sericite, zoisite, clay and calcite.

BH90. Green feldspar pegmatite.

This is coarse grained granoblastic with considerable alteration of the feldspars found between A and B zinc lodes N.B.H.C., No.14 level.

Constituent Minerals.

Potassium feldspar (approx. 50%): Anhedral crystals about 1.5 mm. x 1.0 mm. are altered and coated with dust sized clay, but not as extensively coated as the potassium feldspar in BH27.

Quartz (approx. 35%): Anhedral strained crystals about 1.0 mm. x 0.8 mm., some recrystallized.

Plagioclase (approx. 8%): Anhedral crystals which appear to be replacing potassium feldspar with the formation of muscovite.

Alteration Products.

Zoisite (approx. 1%): Anhedral crystals about 2 mm. x 1 mm. with blue birefringence.

Calcite with subhedral crystals against quartz.

Prehnite (approx. 3%): Biaxial + ve crystals with fan texture, in veins.

Scapolite (approx. $\frac{1}{2}\%$): Uniaxial - ve birefringence 0.007.

Garnet (approx. 2%): Anhedral broken crystals about 30 mm. x 20 mm.

BH56. Green feldspar pegmatite from the Bendigo Rockwell Mine, Little Broken Hill.

Feldspar was chipped from this rock. It was coarse grained and consisted of greenish feldspar, quartz and also green ghanite and sphalerite.

I. Other rocks.

BH3. Low grade ore.

From stope, No. 2 lens, No.17 level Z.C.

The rock is medium grained granoblastic.

Constituent Minerals.

Calcite (approx. 80%): Subhedral to euhedral about 5 mm. x 4 mm.

Rhodonite (approx. 15%): Anhedral crystals about 3.5 mm. x 3.0 mm. with no strong cleavage.

Ore (approx. 5%): Anhedral about 0.1 mm. x 0.3 mm.

Garnet (approx. 0.5%): Euhedral green about 0.3 mm. x 0.2 mm.

Other minerals are apatite and an unknown (very low birefringence 0.006), RI about 1.64.

BH138. A "calcitic" lens or vein from No.23 level North Broken Hill.

This is a granoblastic aggregate of quartz and zoisite.

Quartz (approx. 60%): Anhedral strained crystals about 0.5 mm. x 0.3 mm.

Zoisite (approx. 35%): Blue birefringent anhedral crystals about 0.3 mm. x 0.2 mm.

About 5% appears to be rounded zircon.

J. Comments on the metamorphic history in the Mines area.

The small number of rocks studied make an accurate determination of the metamorphisms in this area impossible. To evaluate the age data however a knowledge of the metamorphic history is imperative.

The rock descriptions indicate that the area underwent a high grade regional metamorphism under which the following minerals were stable:- In the pelitic rocks, orthoclase, plagioclase, garnet (almandine), biotite, sillimanite, rutile and possibly gahnite; in the magnesium rich xenolith from the Alma Gneiss, garnet, plagioclase, biotite, orthoclase, cordierite, quartz; and in the granitic rocks,

biotite, plagioclase, orthoclase, quartz.

This assemblage may be assigned to the Sillimanite-Almandine-Orthoclase Subfacies of the Almandine Amphibolite Facies. The presence of cordierite and rutile (in small amounts) however indicates that the metamorphic grade is closer to the Hornblende Granulite Subfacies of the Granulite Facies.

Overprinting this paragenesis is a second mineral assemblage due to one or more retrogressive metamorphisms. Minerals which appear to be stable under this metamorphism are sericite (muscovite), biotite, garnet, staurolite, epidote, possibly microcline (the position of this mineral is not certain) and also possibly scapolite, prehnite and albite. This assemblage appears to fit the Staurolite-Almandine Subfacies of the Almandine-Amphibolite Facies.

PART II - APPENDIX 2.

Some Age Measurements on Micas From Broken Hill, Australia

by J.R. Richards and R.T. Pidgeon.

In this study I performed the Rb-Sr analyses whereas the K-Ar analyses were performed by Dr. J.R. Richards. The petrography was largely the work of Dr. G.A. Joplin.

REPRINTED FROM:

Journal of the Geological Society of Australia

Vol. 10, Pt. 2, pp. 243-260.

SOME AGE MEASUREMENTS ON MICAS FROM
BROKEN HILL, AUSTRALIA

By J. R. RICHARDS AND R. T. PIDGEON

ADELAIDE
SOUTH AUSTRALIA

1963

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By J. R. RICHARDS AND R. T. PIDGEON

(WITH 1 FIGURE)

(Received 4th January, 1963. Read at Canberra, 30th July, 1963.)

ABSTRACT

K-Ar measurements were carried out on 24 mineral concentrates, mostly biotite, from rocks in the Broken Hill district of New South Wales; Rb-Sr measurements were carried out for comparison on eight of these. The results range from 430 to 1360 m.y. for K-Ar, and from 460 to 550 m.y. for Rb-Sr. They indicate that the last event of sufficient intensity to affect the biotites of this area occurred in the Lower Palaeozoic. This may be correlated, as a first hypothesis, with the event which caused emplacement of the secondary "Thackaringa-type" lead deposits.

The well-known silver-lead-zinc mineralisation in the Broken Hill district of New South Wales occurs in the older Precambrian metamorphosed sediments of the Willyama Series (Andrews, 1922; King and Thomson, 1953; Carruthers and Pratten, 1961). Because of their high degree of metamorphism and folding, an Archaean age has often been assigned to them (King and Thomson, 1953), although it is not completely clear whether this age refers to the metamorphism or to the preceding sedimentation. Subsequent to these events, there were laid down the Proterozoic sediments and fluvio-glacial rocks of the Torrowangee Series (King and Thomson, 1953). These deposits, which have been correlated (King and Thomson, 1953) with the upper series of the Adelaide System, in their turn suffered a slighter degree of metamorphism and folding. A real understanding of the chronological sequence in this complex area has yet to be achieved. For example, the "true" granites—the Mundi Mundi Granite (Andrews, 1922) (sometimes called "Paps-type")—have been stated to be both older (Leslie and White, 1955) and younger (King and Thomson, 1953) than the deposition of the basal layers of the Torrowangee. Further, there appear to be as many schools of thought concerning the relationship of the lead mineralisation to other events in the area as there are possible mechanisms. Thus, whilst there is little doubt that the "Thackaringa-type" deposits occurred later than the main Willyama metamorphism and folding, it has not so far been possible to decide on geological grounds whether the more important "Broken Hill-type" deposits are related to the original sedimentation, to the major metamorphism, to the events which produced the Thackaringa-type deposits, or to some completely separate event.

Lead isotope studies in recent years by Russell and his co-workers (Kanasewich, 1962, pers. comm.; Kollar, Russell *et al.*, 1960; Russell, Farquhar *et al.*, 1957; Russell and Farquhar, 1960; Russell, Ulrych *et al.*, 1961) have suggested that the two types of deposit are related to two very different events. On the

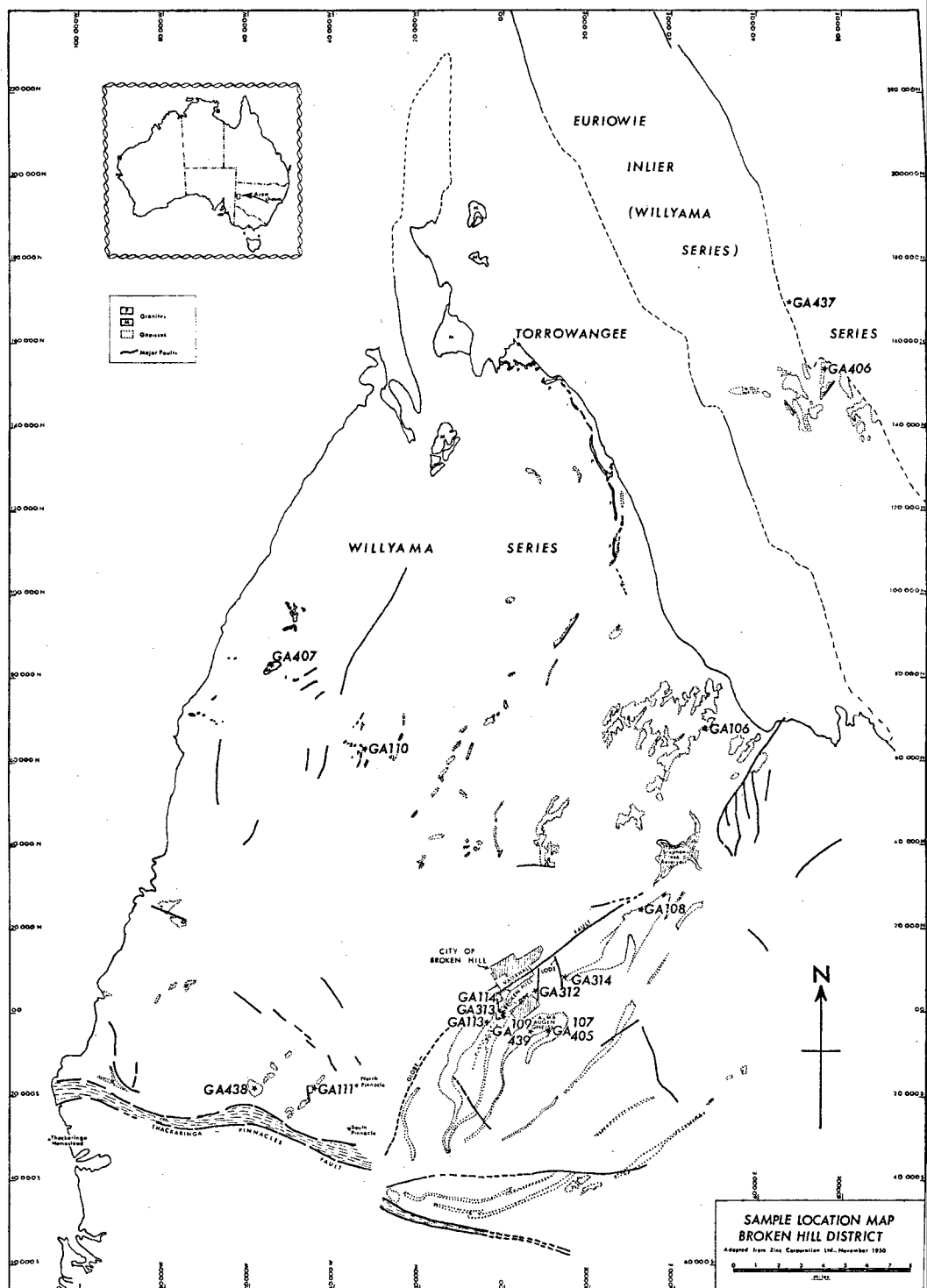


Fig. 1

models they propose, the main "conformable" ore-body represents a typical example of a "mantle" lead, with isotope ratios characteristic of lead which separated from uranium and thorium some 1600 m.y. ago. During this process it was contaminated only slightly, if at all, with "crustal" lead. The "Thackaringa-type" leads, on the other hand, represent "anomalous" behaviour, interpreted as being derived from the admixture of this "mantle" lead with varying proportions of "crustal" lead. The time of this event has been interpreted as being "less than 1000 m.y. ago" (Russell, Farquhar *et al.*, 1957; Russell and Farquhar, 1960) and, more recently, about 500 m.y. ago (Kanasewich, 1962, pers. comm.).

It is apparent that determinations of the absolute chronology of the Broken Hill district by methods not employing the decay of uranium to lead will be necessary for the interpretation of these results. The first two K-Ar measurements on biotites from the mine sequence were reported by Evernden and Richards (1961, 1962). This paper presents the complete results of the first areal survey, of K-Ar measurements on separated micas, with some Rb-Sr measurements for comparison. It can be seen that, in a metamorphic area such as this, a satisfactory interpretation will not be possible before measurements have been carried out on a wider range of minerals, using every available dating technique. Whilst this fuller investigation is now in progress, these results are presented as amplification of those already published, and to urge due caution in their geological interpretation.

EXPERIMENTAL

Mineral Separation

After crushing and sieving to close size ranges, separations were carried out by electromagnetic and heavy liquid techniques, with occasional use as required of a micro-panner with CCl_4 medium. Grain purities were estimated by microscopic examination, and were normally in the 98 p.c. plus range. Representative aliquots were taken for analysis by the use of a micro-splitter. One large portion (0.9 gm.) was pulverised in a Wig-L-Bug type ball-mill, and represented the stock from which samples (0.16 gm.) were taken for K analysis. This operation was performed to reduce the possibility of error from grain inhomogeneity. For argon analysis, however, this possibility had to be tolerated, and the sample was used as separated (60-100 B.S.) to avoid the possibility of argon loss, excessive air adsorption, and "blow-out" during vacuum handling. Thus error is to be expected on this account, although mitigated to some degree by the somewhat larger sample (0.3 gm.) taken. Since Rb and Sr measurements are made on the one dissolution, the daughter-parent ratio should remain constant even if the absolute concentrations vary. Therefore no special precautions were taken against sampling errors for these measurements.

Potassium-argon

Potassium analyses were carried out by close comparison of the unknown solution with two closely-spaced standard solutions on a Perkin-Elmer model 146 flame photometer. Reagent concentrations were kept the same for all solutions, to which were added large excesses of Li salt for internal standard,

TABLE 1.

Analytical details for the K-Ar measurements.

Sample Number GA	Rock	Mineral	% K	av K	% atm. ⁴⁰ Ar	⁴⁰ Ar*/ ⁴⁰ K
106	Granodiorite gneiss	Biotite	7.437 ± .050 7.421 ± .017	7.43	2.7	.0303 ₄
107	Alma Augen Gneiss	Biotite	6.840 ± .034 6.830 ± .046	6.84	2.0	.0285 ₁
108	Granite Gneiss	Biotite	6.936 ± .036 6.945 ± .011	6.94	2.3	.0306 ₄
109	Alma Augen Gneiss	Biotite	6.499 ± .039 6.527 ± .042	6.51	1.0	.0830 ₄
	Alma Augen Gneiss	Biotite	6.499 ± .039 6.527 ± .042	6.51	1.0	.0802 ₄
110	Mundi Mundi Granite	Biotite	7.573 ± .033 7.632 ± .040	7.60	1.8	.0397 ₇
111	Granitic Rock	Biotite	6.963 ± .067 6.982 ± .017	6.97	2.6	.0382 ₂
113	Granitic Gneiss	Biotite*	7.458 ± .025 7.298 ± .047	7.44	1.7	.0337 ₂
114	Sillimanite Gneiss	Biotite*	7.254 ± .018 7.298 ± .044	7.28	1.6	.0354 ₄
	Sillimanite Gneiss	Sericite	2.353 ± .005 2.337 ± .006	2.35	1.8	.0608 ₄
312	Potosi Gneiss	Biotite	7.645 ± .036 7.651 ± .039	7.65	2.7	.0590 ₄
313	Biotitic Lode Material	Biotite	6.786 ± .022 6.747 ± .029	6.77	2.9	.0349 ₄
	Biotitic Lode Material	Muscovite	8.683 ± .027 8.653 ± .021	8.67	2.1	.0311 ₄
314	Granitic Gneiss	Biotite	7.801 ± .043 7.832 ± .047	7.82	3.1	.0305 ₇
	Granitic Gneiss	Plagioclase	2.974 ± .007 2.991 ± .005	2.98	1.5	.0347 ₇
405	Alma Augen Gneiss	Biotite (—18 + 44 BS)	7.961 ± .016 7.928 ± .040	7.94	2.3	.0316 ₄
	Alma Augen Gneiss	Biotite (—60 + 85 BS)	7.894 ± .008 7.931 ± .004	7.91	2.5	.0327 ₄
406	Augen Gneiss	Biotite	6.752 ± .019 6.728 ± .034	6.74	3.8	.0285 ₄
407	Mundi Mundi Granite	Biotite	7.156 ± .036 7.181 ± .053	7.17	4.9	.0324 ₄
	Mundi Mundi Granite	Muscovite	8.701 ± .019 8.715 ± .020	8.71	2.3	.1153 ₄
	Mundi Mundi Granite	Muscovite	8.701 ± .019 8.715 ± .020	8.71	1.4	.1151 ₄
	(Second Separation)	Biotite	7.694 ± .019 7.702 ± .029	7.70	3.3	.0348 ₄
	(Second Separation)	Muscovite	8.766 ± .026 8.782 ± .023	8.77	0.9	.1167 ₄
437	Gneiss Boulder in Tillite	Biotite	7.012 ± .044 7.096 ± .033	7.09	4.4	.0301 ₄
438	Granitic Gneiss	Biotite	7.769 ± .041 7.713 ± .052	7.74	3.7	.0310 ₄
439	Alma Augen Gneiss	Biotite	7.547 ± .048 7.574 ± .014	7.56	3.0	.0300 ₄

*Previously reported by Evernden and Richards, 1961 and 1962. Indicated errors on K analyses represent standard deviation (RMS) of an *individual* measurement in each run, and thus may be regarded as an indication of flame photometer performance on the day.

and Na salt to buffer out stray interferences of other metals in the unknown solution. This solution is presently used directly as dissolved, without any separation steps. Precision of analysis depends to a certain extent on K content. As can be seen in Table 1, replication is almost always better than $\frac{1}{2}$ p.c. Absolute accuracy is believed to be good. From comparison with isotope dilution measurements it is believed to be within 1 p.c. for biotites (Cooper, 1963), and within somewhat wider limits for low-K minerals (McDougall, 1963).

Argon analyses were carried out on separate portions (see previous section) by isotope dilution with ^{38}Ar . The gas was extracted from the mineral by vacuum fusion, without flux, in a system based on Berkeley practice. Non-inert gases were removed by reaction with hot CuO and Ca vapour. Condensibles were removed initially with a liquid-air trap, latterly with Linde Molecular Sieve. Measurements were made on a Reynolds (1956) type all-glass mass-spectrometer, using the static run procedure. Recent experience suggests that no significance should be read into age differences of less than two to three per cent. (McDougall, 1963), even although on occasions a remarkably good replication is achieved. It is felt that absolute accuracy should also lie within these limits, apart from the usual uncertainties about decay constants and possible systematic diffusional loss of argon. There is, however, no direct evidence on this issue at present.

TABLE 2.

*Rb-Sr analytical results, showing effect of R_i on calculated age.**

Sample GA—	Rb ⁸⁷ μm/gm	Sr ⁸⁶ μm/gm	R_i	$10^2\theta$ ($R_i=0.700$)	$10^2\theta$ ($R_i=0.800$)	$10^2\theta$ ($R_i=0.715$)
106	3.65	0.00517	5.5035	0.6810	0.6668	0.6789
107	3.140	0.08148	1.0060	0.7940	0.5346	0.7551
	3.158	0.08394	1.0008	0.7638	0.5337	0.7597
108	5.153	0.01437	3.4379	0.7638	0.7359	0.7597
109	2.781	0.01091	2.6109	0.7495	0.7103	0.7437
	2.762	0.01067	2.6193	0.7414	0.7027	0.7356
110	3.728	0.01298	2.6432	0.6768	0.6420	0.6733
	3.710	0.01337	2.6374	0.6982	0.6622	0.6946
111	3.465	0.03364	1.3173	0.6882	0.5767	0.6715
	3.334	0.03936	1.3091	0.7187	0.6007	0.7010
312	3.484	0.003667	7.1837	0.6824	0.6719	0.7861
314	6.604	0.003391	15.1806	0.7436	0.7384	0.7428

To avoid confusion caused by uncertainty in decay constant, the age is given in terms of the parameter θ , which is equivalent to $\lambda T = {}^{87}\text{Sr}^/{}^{87}\text{Rb}$ (see text)

Rubidium-strontium

Rubidium and strontium were determined by isotope dilution using the triple-filament technique on a six-inch, 90°, Metropolitan-Vickers MS2-SG mass-spectrometer. Duplicate dissolutions were made for each specimen, and for each dissolution the ^{86}Sr and ^{87}Rb tracers were added to separate aliquots. Further purification was carried out using ion-exchange techniques, and the samples were analysed as chlorides (Compston and Vernon, 1962, pers. comm.).

Precision of individual age measurements generally lies within one per cent., as shown by comparison of duplicates (Table 2). Absolute accuracy is less

easily estimated. Systematic errors arising from the chemical treatment and mass-spectrometry are thought to have been reduced to insignificant levels. Other than these the absolute age is affected by possible diffusional loss of Sr, uncertainty in the ^{87}Rb decay constant λ , and the ratio $^{87}\text{Sr}/^{86}\text{Sr}$ ($= R_i$) in the rock at its formation. For Palaeozoic minerals which have remained a closed system to both Rb and Sr since formation, these quantities are related by the equation (Compston and Jeffery, 1961),

$$\lambda T = \theta = \frac{^{87}\text{Sr}^*}{^{87}\text{Rb}} = \frac{^{86}\text{Sr}}{^{87}\text{Rb}} (R_p - R_i)$$

where T = time in years, R_p = present-day ratio $^{87}\text{Sr}/^{86}\text{Sr}$, and $^{87}\text{Sr}^*$ = concentration of radiogenic strontium.

In the absence of information from co-genetic minerals of differing Sr content, a value for R_i must be assumed. For the biotites reported in this paper, R_p is so large that small variations in R_i have little effect on the calculated age. The main uncertainty therefore arises from the current lack of knowledge of the true value for λ . The two currently favoured values, $\lambda = 1.47 \times 10^{-11} \text{y}^{-1}$ (Flynn and Glendenin, 1959) and $\lambda = 1.39 \times 10^{-11} \text{y}^{-1}$ (Aldrich and Wetherill, 1958) cause differences in estimated age to the order of 6 p.c.

RESULTS

The geographical distribution of sampling points is shown in Fig. 1, which is an adaptation of the map published by King and Thomson (1953). Details of samples and suppliers are given in the appendix. In Table 1 are listed the relevant analytical details for the K-Ar determinations; those for Rb-Sr are given in Table 2. Values of the radiogenic ^{87}Sr to ^{87}Rb ratio (θ) are calculated for two extreme values of R_i , 0.700 and 0.800, and also for 0.715, considered to be near the true value. The resultant small variations in θ show that small changes in R_i scarcely affect the calculated age.

In Table 3 are presented the collected age data, those for Rb-Sr being listed for the two half-life values in current use.

DISCUSSION

The variability of results, and the non-constant trend in the differences between the Rb-Sr and the K-Ar results, shown in Table 3, are phenomena which have been reported for some other metamorphic areas (Aldrich, 1962, pers. comm.); Wetherill, Davis *et al.*, 1957; Wetherill, 1961; Gerling and Ovchinnikova, 1961). It can be seen that the disagreement between the two methods on the one sample ranges from an anomalously large excess in K-Ar ages to the more usual small deficit, even for the high value of the Rb decay constant ($\lambda = 1.47 \times 10^{-11} \text{y}^{-1}$). This value is often favoured because of the better agreement it produces between the two methods. Choice of the other λ ($1.39 \times 10^{-11} \text{y}^{-1}$) has little effect on the overall picture, although differences in detail can be seen.

When viewed separately, the results from each method may suggest the possibility of a regional grouping. Thus, for example, the Rb-Sr results could be taken to suggest two separate metamorphic events, although the small amount

of data (eight samples) would allow this interpretation to be no more than conjectural, and at least one of the eight results cannot be explained under this hypothesis. The K-Ar dates, on the other hand, indicate an entirely opposite

TABLE 3.

Comparison of K-Ar and Rb-Sr ages.

Sample Number GA—	Mineral	K-Ar age (m.y.)	Rb-Sr age in m.y. ($R_t = 0.715$)	
			$\lambda = 1.47 \times 10^{-11} \text{y}^{-1}$	$\lambda = 1.39 \times 10^{-11} \text{y}^{-1}$
106	b.	459	462	488
107	b.	434	515 } 516 }	545 } 547 }
108	b.	463	518	548
109	b.	1059 } 1032 }	506 } 500 }	535 } 529 }
110	b.	581	458 } 472 }	486 } 498 }
111	b.	562	457 } 477 }	482 } 504 }
113	b.	504		
114	b.	526		
	s.	830		
312	b.	810	463	490
313	b.	519		
	m.	470		
314	b.	462	505	534
	p.	518		
405	coarse b.	476		
	fine b.	491		
406	b.	434		
407	1st b.	487		
	1st m.	1351 } 1349 }		
	2nd b.	518		
	2nd m.	1363		
437	b.	456		
438	b.	510		
439	b.	455		

K decay constants $\lambda_\beta = 4.72 \times 10^{-10} \text{y}^{-1}$, $\lambda_K = 0.584 \times 10^{-10} \text{y}^{-1}$

^{40}K abundance, 1.19×10^{-4} mole ^{40}K /mole K

arrangement, of ages becoming progressively older from east to west. This simple pattern, also, is disturbed by the high K-Ar results to the immediate south and east of Broken Hill. The overall pattern, therefore, is complex and cannot easily be explained in terms of regional trends.

Taking the biotite results alone, all Rb-Sr ages lie between the limits 460-520 m.y., or 490-550 m.y., depending on the decay constant chosen; and 14 out of the 18 K-Ar ages lie within the limits 430-530 m.y. The other four are those anomalously higher than the Rb-Sr results. Potassium-argon ages on one plagioclase (GA314) and one muscovite (GA313) in the neighbourhood of Broken Hill support the evidence of the biotites with which they are associated, whereas one concentrate consisting largely of sericite (GA414) is anomalously "old" compared with its associated biotite. In the north-west, two distinct separations from the Mundi Mundi Granite boss (GA407, see appendix)

yielded K-Ar ages on muscovite much greater (1350 m.y.) than those for the associated biotite (500 m.y.). Thus it might seem possible to infer from the biotite data that almost complete loss of Ar and Sr was caused by a metamorphic event, or a series of events, at some time in the Lower Palaeozoic between 440 to 550 m.y. ago. Whilst thus supporting in general terms the conclusions of Evernden and Richards (1961, 1962), this wide spread of results also underlines the high possibility of drawing wrong conclusions if interpretations are attempted on the basis of only a few results in metamorphic areas.

Before this broad interpretation is accepted, there remain to be examined the few anomalously high K-Ar ages. The most striking of these is GA109, a biotite from the Alma Augen Gneiss (Fig. 1) which has a reproducible K-Ar age of 1045 m.y., and a Rb-Sr age of 500 (or 530) m.y. This is in contrast to another sample (GA439) collected nearby several years later, which has a K-Ar age of 455 m.y., and to a corresponding pair of samples from a little further east in the same mass (GA107, GA405), which have K-Ar and Rb-Sr ages between 430 and 540 m.y. The Potosi Gneiss biotite (GA312) has an older apparent K-Ar age than the Rb-Sr determination, and so to a lesser degree have biotites from GA110 and GA111. As has already been observed at the beginning of this section, signs of a similar pattern can be detected in other results published on metamorphic areas (Fairbairn, Hurley *et al.*, 1960; Hurley, Fairbairn *et al.*, 1960; Wasserburg, Wetherill *et al.*, 1959; Wetherill, Davis *et al.*, 1957; Gerling and Ovchinnikova, 1961), even if they have not always been commented upon.

Of the various possible explanations for these anomalously high K-Ar ages, it seems to the present authors that the following arguments are pertinent. Firstly, alteration of K content by leaching, in such a way as to leave unchanged the Sr/Rb ratio, appears to be unlikely because of the known tendency of Rb to follow K. Further, the experiments reported by Kulp and Bassett (1961) indicate that, contrary to what might be expected, the action of ground-waters should result in reduction both of the K content and the K-Ar age of biotites. In six cases the results in this paper show the K content to be lower than might be expected (i.e., below 7 p.c.). In only two of these (GA107, GA406) do we find an especially low K-Ar age, whereas the lowest K content of all is associated with the exceptionally high age (GA109). Hence it appears that leaching of K cannot be invoked to explain these anomalous K-Ar results. Secondly, under the conditions usually envisaged as leading to partial argon loss, it could be supposed that the radiogenic strontium ion, being of smaller radius than the argon atom, might escape more easily. This, however, is difficult to reconcile with the general experience in most areas that K-Ar ages tend to be lower than Rb-Sr ages, which suggests that argon escapes more easily than strontium. There remains, however, the possibility that during metamorphism under conditions such as, say, deep burial, there may occur localities where radiogenic argon is released from the high-K minerals where it developed, but remains trapped in the immediate environment. Thus it could be possible to have localised regions where there is not only a high general pressure but also a higher than usual pressure of argon. This argon would then be available either for absorption into low-K minerals, or to hinder the diffusional loss of argon from minerals in which it has accumulated. Although in physical principle there

is scant difference between these two alternatives, there is a practical geological distinction. For the one case (low K) a high K-Ar age may be found which has little chronological significance; for the other (high K) it could be argued in most cases that the original biotite age is not less than the result obtained, since it is from these very minerals that the radiogenic argon pressure is generated. The laboratory experiments which will make it possible to draw this distinction have not yet come to our notice. There is, however, mounting evidence, at present only fragmentary, that argon can indeed be absorbed under conditions of high pressure and temperature by beryl (Damon and Kulp, 1958), cordierite (Aldrich, 1962, pers. comm.; Damon and Kulp, 1958), pyroxene (Hart and Dodd, 1962), and muscovite (Karpinskaya, Ostrovskii *et al.*, 1961). It therefore seems to the present authors that this suggestion of high local concentrations of argon during metamorphism is the most satisfactory interpretation of the divergent biotite results, even although it cannot on present knowledge explain all the phenomena found in this area, such as, for example, the large difference in biotite and sericite "ages" in GA114, or the vast difference in age between two samples (GA109, GA439) supposedly from the same site. Therefore although comparison with the 1600 m.y. lead model age (Russell, Farquhar *et al.*, 1957; Russell and Farquhar, 1960) makes it reasonable to suggest that 1060 m.y. represents a minimum original age for the biotite, this must remain a provisional conclusion. These arguments would, however, tend to suggest that the true time of the last event should lie closer to the younger ages recorded.

There has recently come to our notice a set of K-Ar measurements made by Dr. J. A. Miller of Cambridge University, which are to be reported in the near future (Binns, 1962, pers. comm.). Whereas there is satisfactory agreement on the apparent age (approx. 1300 m.y.) of the Mundi Mundi Granite muscovite, there appears at first sight to be a discrepancy between the Palaeozoic event indicated in this work and the lowest age (700-900 m.y.) reported in the other set of results. Dr. Binns has kindly inspected our thin sections, and has reported that only GA109 and GA312 come close to satisfying the criteria used by him in the selection of samples for dating. His selection was based on the comparative absence of signs of low grade metamorphic alteration. Therefore it seems that the discrepancy lies in the choice of samples. Thus of our samples there are only GA109 and GA312 which may not have been strongly affected by the later metamorphism, and which could therefore have retained indications of an older age (i.e., the "partial argon loss" effect). It may be significant, however, that the two samples thus selected proved to be both anomalous. Hence a satisfactory assessment of the discrepancy is not possible without Rb-Sr check on the Cambridge results. This further illustrates the need for caution in the interpretation of results in metamorphic areas.

A further complication, the possibility of weathering or groundwater alteration, cannot be entirely overlooked. Evidence accumulating in this laboratory suggests that this effect can sometimes be appreciable, particularly where signs are visible in hand-specimen of iron-staining around the biotites. A brief petrographic description of the analysed samples is given in the appendix, where it

will appear that it is difficult to find any factor with which to correlate the apparent low K and low age of GA114 and GA406.

Taking all factors into account, it appears likely that a metamorphic event, or a metamorphic period, occurred between 550 m.y. and 440 m.y., narrower limits depending on an assessment of the relative importance of the effects discussed above. Considerable evidence is now available (Aldrich, 1962, pers. comm.) to show that biotite is probably the mineral most liable to loss of both Sr and Ar. This early Palaeozoic event, signs of which are said to be not easily seen in hand specimen (*cf.* Evernden and Richards, 1961), is therefore considered to be the last metamorphic event of recordable magnitude in the Broken Hill region. This conclusion is in accord with the scanty geological evidence available. Thus, in a symposium in 1956, references were made by Daily (1956) to a Middle Cambrian orogeny which marks the end in South Australia of sedimentation in the Adelaidean geosyncline; and by Öpik (1956) to evidences of a possible unconformity in the same period at Cobar, some 250 miles to the east of Broken Hill, and also of the possibility that folding in the South Australian Kanmantoo Series occurred somewhere in the time interval Middle Cambrian to Lower Ordovician. In 1961 Warner and Harrison found Middle Cambrian fossils in a gently folded structure in the Mootwingee Ranges, some 60 miles to the north-east of Broken Hill. More recently, Öpik (pers. comm.) has observed deformed Lower Ordovician deposits resting with an unconformity on folded early Middle Cambrian strata in the same region. Thus by extrapolation over comparatively large distances, it is possible to interpret the geological evidence as lending support to the concept of some tectonic event in the period Middle Cambrian to Lower Ordovician, which could have been responsible for the apparent losses of Ar and radiogenic Sr.

The time of this event is close to the re-calculated value deduced by Kanasewich (1962, pers. comm.) for the Thackaringa-type leads, and as a first hypothesis may be correlated with them. Lack of conclusive geological evidence, and uncertainties in the lead age calculation (Richards, 1963) would make this hypothesis tentative at present.

Other conclusions which might be drawn on the data concern, firstly, the possibility of correlating a gneissic boulder in the tillite from the Torrowangee Series (GA437) and the gneiss in the Euriowie Inlier of older Willyama age (GA406). The K-Ar analyses made so far indicate only that these two rocks were subject to the same metamorphism. The evidence is not sufficient by itself to enable any deductions about the Torrowangee. Secondly, some comment must be made about the results on GA407, a sample from the southernmost of the five recorded Mundi Mundi Granite bosses, reported to be somewhat more foliated than its more northerly counterparts (King and Thomson, 1953). As is indicated in the appendix, the bulk sample consists of both gneissic and pegmatitic phases, which appear to be very similar in composition. After the first results were obtained, a second mineral separation was carried out on carefully selected pieces of the gneissic phase. Both sets of measurements agree in showing that the biotite reflects the Palaeozoic event, whereas the muscovite shows an older K-Ar age of 1360 m.y., which is at the same time considerably younger than the conformable lead model age of about 1600 m.y. (Kanasewich,

1962, pers. comm.; Russell, Farquhar *et al.*, 1957; Russell and Farquhar, 1960). Although this is one case where approximate agreement with the Cambridge results (Binns, 1962, pers. comm.) has been obtained, comparison with Rb-Sr results is the minimum needed to assess the significance of this muscovite result.

CONCLUSION

The data indicate a metamorphic event of low intensity at some time in the interval 450-550 m.y. The metamorphism appears to have covered most of the Broken Hill region and to have been of sufficient intensity to control the Rb-Sr ages and most K-Ar ages on biotites. This event may be correlated, as a first hypothesis, with the emplacement of the Thackaringa leads.

This study stresses the caution which must be practised in the interpretation of one or two results from a complex metamorphic area, especially on the basis of one geochronological method since, even with a statistically significant number of samples and two techniques, the interpretation cannot be regarded as final.

ACKNOWLEDGMENTS

We are indebted to Mr. H. F. King for his interest and encouragement, and to Mr. D. S. Carruthers, of the Zinc Corporation Ltd., who was responsible for the supply of the greater part of these samples. Samples GA106 to GA111 inclusive were biotite concentrates obtained from the collection of the Commonwealth of Australia Bureau of Mineral Resources, Geology and Geophysics, Canberra. We are grateful to Dr. G. A. Joplin for her advice and assistance with the petrographic descriptions of most of these samples, and have leaned heavily on the technical skill of Mr. J. A. Cooper for the K analyses, Mr. A. W. Webb for the Ar extraction runs, and Mr. R. Rudowski, advised by Mr. H. Berry, for the mineral separations. The Rb-Sr work was carried out under the tutelage of Dr. W. Compston, who has kindly read the manuscript. Prof. J. C. Jaeger has contributed materially to our understanding of the problems involved in argon-loss processes. One of us (RTP) acknowledges his gratitude to the Australian National University for a Commonwealth Postgraduate Award during the tenure of which this work was performed.

APPENDIX

SAMPLE DETAILS

Petrography by G. A. Joplin and R. T. Pidgeon

GA106 Granodiorite gneiss. Biotite. K-Ar and Rb-Sr.

Locality: Outcrop 5 miles north of Stevens Creek Reservoir. Zinc Corporation (Z.C.) co-ordinates (see Fig. 1), 68,000'N.; 47,000'E. Collected by Commonwealth Bureau of Mineral Resources (B.M.R.), reference No. H54/15/1.

Geology: Equivalent to lower granitic gneiss, formation No. 1 of the Broken Hill mine sequence.

Petrography: The rock is grey, with fine foliations, and contains quartz, K-feldspar, plagioclase, biotite, a little muscovite and accessory iron ore, apatite and a trace of zircon; average grain size about 1 mm. The plagioclase is almost entirely replaced by sericite and the whole rock appears to have suffered a mechanical crushing at low temperature, there being little recrystallisation, but much cracking and fracturing. The biotite is greenish-brown and shows a parallel arrangement of flakes. It is slightly bleached with separation of minute grains of iron ore along cleavages and cracks. The K-feldspar shows some sericitisation, but is relatively fresh, though much cracked. It is perthitic and contains rounded inclusions of quartz. GAJ.

Weathering: There is no iron-staining in hand specimen, and the sample appears fresh in thin section.

GA107 Alma Augen Gneiss.

Biotite.

K-Ar and Rb-Sr.

Locality: Outcrop half mile north-east of aerodrome, two miles south-east of main shaft of Z.C. Ltd. Z.C. co-ordinates, 4,000'S.; 10,300'E. Collected by B.M.R., reference No. H54/15/2.

Geology: Probably lies stratigraphically below the lower granitic gneiss of the Broken Hill mine sequence.

Petrography: The rock is grey, with well-marked gneissic banding and has the appearance of having been a recrystallized sediment, the large K-feldspar porphyroblasts being in fact a later growth of feldspar caused by feldspathization. The K-feldspar augen range in size from 1-2 mm. and smaller grains in the body of the rock average about 0.25 mm. Plagioclase forms small, sericitized grains interlocking with quartz and K-feldspar, but a number of such grains tend to group in elongated lenses parallel to the general gneissic banding. Biotite occurs in elongated flakes about 0.3 mm. in length, in lenticular aggregates measuring about 2 mm. and appears to be fresh. GAJ.

Weathering: Fresh rock.

GA108 Granite gneiss.

Biotite.

K-Ar and Rb-Sr.

Locality: Outcrop nine miles north along Wilcannia Road just north of Flying Doctor Base Station. Z.C. co-ordinates, 24,800'N.; 31,900'E. Collected by B.M.R., reference No. H54/15/3.

Geology: See GA106.

Petrography: Coarse-grained granitic rock consisting of quartz, microcline, plagioclase (oligoclase), and biotite, with much secondary white mica. A rude gneissic banding is present. Average grain size is 2-3 mm., but with large irregular grains of microcline, up to 6 mm., which encloses most of the other minerals. It appears to be relatively fresh, except where cracks are infilled with sericite, and in some places oligoclase inclusions are surrounded by fringes of encroaching myrmekite. In certain zones, however, the plagioclase is completely sericitized with the other material granulated. These would appear to be lines of shear. Quartz is much cracked. Thus the rock would appear to have been affected by severe crushing at a relatively low temperature. Biotite forms flakes about 1 mm. in length and is very fresh. A few inclusions of zircon are present. GAJ.

Weathering: Mostly fresh, slight iron staining in cracks.

GA109. Alma Augen Gneiss.

Biotite.

K-Ar and Rb-Sr.

Locality: Outcrop one mile south-east of Broken Hill, one mile east of main shaft of Z.C. Ltd. Z.C. co-ordinates, 4,300'S.; 6,000'E. Collected by B.M.R., reference No. H54/15/4.

Geology: See GA107.

Petrography: The rock consists of quartz, K-feldspar, oligoclase, biotite and garnet (probably almandine) with accessory iron ore, rutile and zircon. Coarse, gneissic in texture, consisting of roughly alternating bands of quartz-feldspar and biotite. Some biotite, however, occurs in smaller flakes, surrounding the larger aggregates and grains of quartz and feldspar. Oligoclase occurs in large, fresh, irregular grains, many of which are slightly rounded and surrounded by small interlocking grains of quartz and orthoclase. These last two minerals form also very large grains (up to 7 mm.) enveloping the other minerals. The larger grains of K-feldspar show slight micropertthitic intergrowth, and quartz is very much cracked. Biotite is fresh, about 0.25 mm., and tends to form lenticular aggregates measuring about 2 mm. These are commonly associated with grains of iron ore, and small zircons and needles of rutile occur as inclusions. A few large irregular garnets are intimately intergrown with quartz and biotite and show micaceous alteration along cracks. The rock appears to have been subjected to some crushing but a less severe one than that which affected GA107. This may be due to the physical nature of the rock itself. GAJ.

Weathering: Essentially fresh rock.

GA110 Granite (Mundi Mundi type)

Biotite.

K-Ar and Rb-Sr.

Locality: Outcrop one mile north of Hen and Chicken Smelters and Day Dream Mine, 14 miles north-west of Broken Hill. Z.C. co-ordinates, 63,000'N.; 33,000'W. Collected by B.M.R., reference No. H54/15/5.

Geology: "Younger" granite which intrudes Willyama rocks. The intrusion of the Mundi Mundi Granite is believed to have preceded the deposition of Torrowangee sediments.

Petrography: The rock is coarse-grained and consists of K-feldspar, quartz, biotite, muscovite, plagioclase, accessory iron ore and zircon. The K-feldspar is microcline and this forms the bulk of the rock. It occurs in large (5 mm.) irregular grains and is in places slightly micropertitic. It is fresh and contains inclusions of quartz and of completely altered plagioclase. Biotite forms small greenish-brown flakes and shows marginal and inter-cleavage separation of fine iron ores, but is not chloritized. In places it is intergrown with muscovite. Plagioclase is rare and almost completely saussuritized, but may have a clear sodic border. GAJ.

Weathering: There is slight iron staining in the hand specimen. The thin section appears fresh.

GA111 Granitic rock or feldspathized schist. Biotite. K-Ar and Rb-Sr.

Locality: Outcrop 14 miles along old Adelaide Road, approximately two miles west of North Pinnacles shaft. Z.C. co-ordinates, 18,000'S.; 45,000'W. Collected by B.M.R., reference No. I54/3/1.

Geology: Granitic gneiss which is believed to be in approximately the same stratigraphic horizon as the upper granitic gneiss of the Mine Sequence.

Petrography: In places the rock has a granitic texture and consists of large (up to 4 mm.) grains of quartz (some smoky blue), plagioclase and K-feldspar, and slightly smaller flakes of brownish-red biotite, all of which interlock, or which may be separated in places by a fine granular mosaic of the same minerals together with muscovite.

Elsewhere the rock is finer grained, and though it consists of the same minerals, the biotite is a brownish-green variety and occurs commonly in aggregates of criss-cross flakes. Muscovite is much more abundant in the finer part of the rock, and also occurs in criss-cross aggregates. A few grains of andalusite are associated with biotite. Although the micas appear fresh, the feldspars are slightly sericitized and the rock evidences some strain. GAJ.

Weathering: In hand specimen there are slight signs of iron-staining. In thin section the micas appear fresh.

GA113 Granitic gneiss. Biotite.* K-Ar.

Locality: Outcrop, New Broken Hill Consolidated Mine Lease. Z.C. co-ordinates, 2,000'S.; 4,500'W. Collected by the Zinc Corporation Ltd. (N.Z.C. Ltd.).

Geology: The sample was taken from the upper layer of granite gneiss, formation No. 13 of the Broken Hill Mine Sequence, from the Hanging Wall Basin.

Petrography: The rock consists of a granoblastic aggregate of quartz, plagioclase, orthoclase, sericite, and biotite with accessory small amounts of magnetite, apatite and sillimanite. Quartz and plagioclase are the most abundant minerals and occur as large irregular porphyroblasts and as small xenoblasts in a fine mosaic of the other minerals. Orthoclase is commonly altered to sericite, when it occurs in the mosaic, but appears fresh when occurring as minute inclusions in plagioclase. Biotite occurs as small (about 0.25 mm. and less) flakes and is free from inclusions. No chlorite was observed in the single slide examined, but some bleaching has occurred. GAJ.

Weathering: The sample is mostly fresh.

GA114 Sillimanite gneiss. (a) Biotite;* (b) Mostly sericite. K-Ar.

Locality: Z.C. Ltd. Mine, No. 21 level; Z.C. co-ordinates, 1,000'S.; 500'W. Collected by Z.C. Ltd.

Geology: Sample of sillimanite gneiss in the vicinity of the shaft area, No. 21 level. Formation No. 4 of Broken Hill Mine Sequence.

Petrography: The rock is nematoblastic and lepidoblastic and shows a rough gneissic banding with alternating layers consisting of sillimanite, biotite, garnet and magnetite and of quartz, sericitized cordierite, biotite and orthoclase, and a little muscovite. Accessory minerals are zircon and magnetite. Biotite is very abundant and occurs in elongated flakes up to 1.5 mm. in length and about 0.1 mm. in width. It is crowded with inclusions of quartz feldspars, magnetite and zircons. No chlorite has been detected. Orthoclase is not abundant and also contains quartz, mica and minor inclusions. Muscovite occurs in small

* Previously reported, Evernden and Richards, 1961 and 1962.

flakes, and sericite is secondary after cordierite and is possibly admixed with a chloritic material. GAJ.

Weathering: The thin section is fresh.

GA312 Potosi Gneiss.

Biotite.

K-Ar and Rb-Sr.

Locality: At 50 feet depth on quarry face, Australian Blue Metal Quarry, Broken Hill. Z.C. co-ordinates, 5,300'N.; 7,000'E. Collected by Z.C. Ltd.

Geology: This sample is from formation No. 5 in the Broken Hill Mine Sequence.

Petrography: The rock is medium-grained granoblastic consisting of anhedral quartz, orthoclase, plagioclase, biotite and magnetite, with subhedral to euhedral garnet. The quartz shows undulose extinction. The orthoclase is showing myrmekitic alteration and plagioclase is partially sericitized. Biotite appears to have formed from garnet, clots of biotite crystals representing completely altered garnets. Apatite and a considerable number of rounded zircons are accessories. RTP.

Weathering: This is fresh rock.

GA313 Biotitic lode material.

(a) Biotite; (b) Muscovite.

K-Ar.

Locality: The Z.C. Ltd. Mine, No. 15 level. Z.C. co-ordinates, 700'S.; 500'W. Collected by the Z.C. Ltd.

Geology: The sample is from formation No. 7, the gneiss separating No. 2 and No. 3 lens orebodies, in the Broken Hill Mine Sequence.

Petrography: The rock is granoblastic and porphyroblastic and banded. It consists of quartz, orthoclase, garnet, biotite, muscovite and magnetite. The mineral assemblages of the alternating bands is the same, but there is a difference in the grain size and in relative abundance of the minerals present. The garnet shows slight alteration to epidote clinozoisite, and the biotite, which occurs in equidimensional flakes ranging in size from 0.6-2 mm., is fresh, strongly pleochroic and contains small rutile needles and inclusions of zircon. Some rhodonite also is present. GAJ

Weathering: This is fresh rock.

GA314 Granitic Gneiss.

(a) Biotite; (b) Plagioclase.

K-Rr and Rb-Sr.

Locality: Outcrop just east of the De Bavay Fault. Z.C. co-ordinates, 8,800'N.; 14,000'E. Collected by the Z.C. Ltd.

Geology: The sample is from formation No. 1 in the Broken Hill Mine Sequence.

Petrography: The rock consists of quartz, microcline, plagioclase, biotite, iron ore, apatite and zircon. Most minerals are quite fresh, but the rock has been partly crushed and then recrystallized. Quartz and feldspars are traversed by cracks filled with sericite and a "cement" of small grains of quartz, feldspar and reddish-brown biotite surround larger grains of quartz and feldspar. The biotite would appear to be completely recrystallized. GAJ.

Weathering: There is slight iron-staining in hand specimen. The thin section is fresh.

GA405 Alma Augen Gneiss.

Biotite in two size ranges.

K-Ar.

Locality: From the same outcrop as GA107. Z.C. co-ordinates, 4,000'S.; 10,300'E. Collected by the Z.C. Ltd.

Geology: As for GA107. The Alma Augen Gneiss is a granitic type gneiss believed to occur stratigraphically below the Broken Hill Mine Sequence.

Petrography: The rock consists of K-feldspar, plagioclase, quartz, and biotite and has been severely crushed. The feldspars have been cracked and sericite has developed along the cracks so that many of them now appear as a mass of sericite with optically continuous cores of feldspar. Quartz is also crushed and broken and in places there is secondary silicification. Some fairly large flakes of biotite occur, but much of it is present as small criss-cross flakes intimately associated with sericite and obviously replacing another mineral, possibly hornblende. It is the reddish-brown variety, common to metamorphic rocks, and has been recrystallized. There is no sign of chloritization, and recrystallization, under moderately high temperature, would appear to have followed crushing. GAJ.

Weathering: There is appreciable iron staining in the hand specimen; the thin section is fresh.

GA406 Augen Gneiss.

Biotite.

K-Ar.

Locality: Euriovie area, 31 miles NNE. of Broken Hill. Z.C. co-ordinates, 75,500'E.; 154,000'N. Collected by the Z.C. Ltd.

Geology: The sample comes from an occurrence of augen gneiss near the eastern edge of the Euriovie Inlier. The rocks are correlated with the Willyama (Lower Proterozoic).

Petrography: The rock consists of grains up to 5 mm. of microcline, quartz, and biotite. Some plagioclase appears to be present in smaller grains, but the feldspars are so much sericitized, it is difficult to identify them. Both feldspars and quartz are cracked, minute flakes of sericite and biotite have recrystallized along these cracks and along cleavage planes in the feldspars. In places micrographic intergrowth occur between quartz and K-feldspar. Biotite is abundant. Larger flakes are chloritized and smaller flakes, along cracks, have been recrystallized and appear fresh. GAJ.

Weathering: The rock is practically fresh in hand specimen, although there is some iron-staining along cracks.

GA407 Mundi Mundi Granite. Biotite and Muscovite (two separations of each). K-Ar.

Locality: Near Mundi Mundi Creek, Broken Hill district. Z.C. co-ordinates, 83,000'N.; 55,000'W. Collected by the Z.C. Ltd.

Geology: One of the southernmost of the Mundi Mundi granite bosses which intrude schists of the Willyama Group.

Petrography: The sample is divisible into a medium-grained gneissic phase and a coarse-grained pegmatitic phase. The medium-grained gneiss consist of microcline, quartz, plagioclase, biotite and muscovite. The quartz shows undulose extinction. The biotite occurs in flakes about 0.72 mm. in length and has a greenish-brown colour. It shows parallel intergrowth with muscovite in some places and occasionally is bent. Muscovite is not so abundant as biotite and is intergrown with biotite and feldspars. The coarse-grained pegmatite has essentially the same mineralogy though the foliation is absent and crystals of feldspar are approximately 2 mm. x 3 mm. and mica books 6 mm. x 4 mm. The contact does not appear to be intrusive. RTP.

Separation A was of material taken at random from the sample.

Separation B was made from hand picked lumps of gneissic material, pegmatitic portions being carefully excluded.

Weathering: The hand specimen is iron stained.

GA437 Augen Gneiss boulder in tillite.

Biotite.

K-Ar.

Locality: Gairdner's Creek area, approximately 32 miles NNE. of Broken Hill (about three miles NNW. of GA406). Z.C. co-ordinates, 170,000'N.; 67,000'E. Collected by the Z.C. Ltd.

Geology: The gneiss occurs as an erratic in Torrowangee tillite (Upper Proterozoic) formed by the erosion of Willyama rocks.

Petrography: The rock consists of quartz, orthoclase, plagioclase, biotite, muscovite and a little accessory zircon and sphene. Both micas occur in bands consisting of aggregates of small flakes and slightly larger flakes of biotite may be moulded around the small flakes of muscovite. In places bands consisting of tiny needles of muscovite occur. Quartz and feldspar occur in interlocking grains and potash feldspars may be surrounded by growths of myrmekite. The quartz shows undulose extinction. GAJ.

Weathering: The rock appears fresh in hand specimen and in thin section.

GA438 Granitic Gneiss.

Biotite.

K-Ar.

Locality: Approximately four miles west of the Pinnacles. Z.C. co-ordinates, 18,000'S.; 59,000'W. Collected by the Z.C. Ltd.

Petrography: This rock shows cataclastic structure and evidences severe crushing. It consists of quartz, plagioclase, microcline-micropertthite, biotite, muscovite and accessory iron ore. Originally the rock had a grainsize of about 3 mm., but though undulose grains of quartz and cracked grains of feldspar of this size may occur, much of it shows granulation and the larger grains are set in a mass of extremely fine material, consisting of quartz, feldspar and sericite. Biotite is bent and breaks along cleavage planes tend to fan out the mica, the cleavage cracks being infilled with quartz?. Some iron has been exsolved by the micas. GAJ.

Weathering: The rock is essentially fresh in hand specimen and fresh in thin section.

GA439 Alma Augen Gneiss.

Biotite.

K-Ar and Rb-Sr.

Locality: From approximately the same point as GA109. Z.C. co-ordinates, 4,300'S.; 6,000'E. Collected by the Z.C. Ltd.

Geology: As for GA109 and GA107.

Petrology: Augen of microcline measure up to 5 mm. and these are surrounded by a fine granoblastic intergrowth of quartz, feldspar, biotite and muscovite. The biotite is fresh and there is a slight tendency for it to occur in parallel bands consisting of an aggregate of tiny flakes. Muscovite is less abundant than biotite and much of it appears to be secondary after feldspar. GAJ.

Weathering: The hand specimen and the thin section are fresh.

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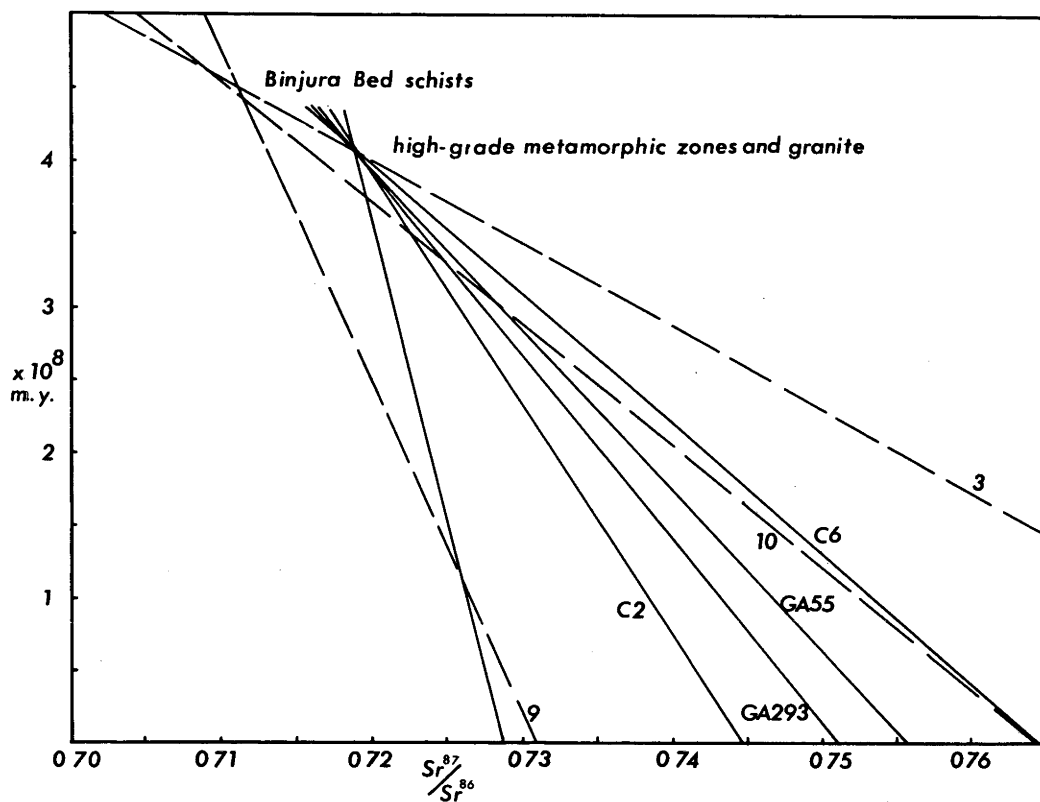
CHAPTER X. THE DISTRIBUTION OF STRONTIUM ISOTOPES.

This chapter presents a brief discussion of the rubidium and strontium isotopic distribution observed in the two areas studied.

A. THE COOMA GRANITE AND ITS ASSOCIATED METAMORPHIC ZONES.

It has been shown in Part I that the Cooma granite has the same age as the surrounding migmatite zone and cordierite-orthoclase zone. It is shown also in Part I that the biotite zone metasediments have a significantly older age than the granite and high grade zones. The evidence suggests that the granite age is the age of formation and sillimanite-andalusite type metamorphism. It also appears likely that the older sediments formed the source material for the granite. Fig.29 shows the possible history of these rocks. In Fig. 29 the total-rock age of the biotite zone metasediments is interpreted as the age of deposition though it is also possible that this is the age of the metamorphism to greenschist facies.

In Part I the movement of strontium isotopes necessary to produce the observed distribution in the granite and high grade zones is considered in detail. It is concluded that complete mixing of strontium isotopes is necessary during recrystallization to



(Fig. 29) Time - R_1 plot of the evolution of the Cooma rocks.

produce the nearly identical initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratio observed in the granite and high grade zones. There are small variations in the indicated initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios but I interpret these as small departures from the overall equilibrium of strontium isotopes.

Biotite from the granite and high grade zones has a similar age to that of the total-rocks indicating that the biotite has remained a closed system to strontium isotopes for the same time as the total-rocks.

It is seen therefore that strontium isotopes reached or approached equilibrium in all phases in a closed system (to strontium) embracing the granite and the high grade metamorphic zones.

B. THE BROKEN HILL GNEISSES.

It has been shown in Part II that the age of the gneisses at Broken Hill most probably represents the time of metamorphism to granulite facies. This interpretation is similar to that for the Cooma granite and high grade metamorphics. Granite has not been formed at Broken Hill, possibly because of a greater load pressure.

It has been demonstrated that it is not until the gneisses are severely crushed and recrystallized that the total-rock samples of the size used in this study (approx. 5 - 10 lbs. for medium grained rocks) become open systems to rubidium and/or strontium.

Distinct bands or units can still be recognised in the

granulite facies rocks at Broken Hill which probably reflect original chemical differences. This suggests that the movement of major elements between units has been restricted during the granulite facies metamorphism. Within a unit however the mineralogical and chemical composition of phases suggests that equilibrium has been approached.

The analytical results suggest that the strontium isotopes have approached equilibrium within a rock unit though the scatter about the least squares lines (Fig. 17 -20) indicates that deviations from equilibrium still exist. Statistical evidence suggests that complete mixing of strontium isotopes between all rock types did not occur in the region which has undergone granulite facies metamorphism.

Later metamorphisms at Broken Hill.

The ages of the gneiss constituent minerals in general do not coincide with the total-rock age. The biotite age is always low being consistently between 530 ± 70 m.y. regardless of rock-type or degree of retrogressive alteration. In some cases the orthoclase age is similar to that of the total-rocks though frequently it is "older". It has been demonstrated in BH5 sillimanite gneiss that this apparently old orthoclase age can nearly be explained by postulating absorption of radiogenic strontium equal to the amount which must be removed from the biotite to produce its "young" age.

This implies that such a mechanism as the preferential movement of radiogenic strontium, is possible, as has been suggested by a number of authors (Hurley 1961, Hart 1964).

C. MECHANISMS OF Sr ISOTOPIC MOVEMENT.

In this study two mechanisms are proposed to explain the experimental observations.

- (a) The complete mixing of strontium isotopes in a closed system.
- (b) The preferential movement of radiogenic strontium in a closed total-rock system.

These mechanisms are frequently invoked in the literature to explain observed isotopic distributions. Compston and Jeffery (1959) conclude that nearly complete mixing of strontium isotopes in a closed total-rock system is responsible for the mineral ages in the Boya granite. Lamphere et. al. (1964) use this mechanism to explain the Rb-Sr ages from the World-Beater Complex. They find that complete mixing of strontium isotopes has produced "young" ages with anomalously high initial $\text{Sr}^{87}/\text{Sr}^{86}$ ratios. Riley and Compston (1961) have expressed the resultant isotopic distribution of mechanism (a) in graphical form and it is seen that the Cooma granite $\text{e}^{-\lambda t} - R_1$ plot (Fig. 29) has a similar geometry.

It is possible to express the distribution of strontium

isotopes between coexisting phases after complete mixing in terms of a simple thermodynamic model. Consider the distribution of strontium isotopes between biotite and potassium feldspar. If equilibrium is assumed the Riley and Compston (1961) model predicts that

$$\left(\frac{\text{Sr}^{87}}{\text{Sr}^{86}} \right)_B = \left(\frac{\text{Sr}^{87}}{\text{Sr}^{86}} \right)_F = \left(\frac{\text{Sr}^{87}}{\text{Sr}^{86}} \right)_{\text{rock}}$$

immediately after complete mixing. (B - biotite, F - feldspar).

This prediction can be expressed in Thermodynamic terms by considering the chemical potentials, μ , of the individual Sr isotopes in any phase.

$$\begin{aligned} \mu_{\text{Sr}^{87}}^A &= \left(\frac{\partial G_A}{\partial n_{\text{Sr}^{87}}} \right)_{T, P, \text{Sr}^{86}, \text{Sr}^{88}, 1 \dots n_c} \\ &= \mu_{\text{Sr}^{87}}^0 + R T \ln a_{\text{Sr}^{87}} \end{aligned} \quad \text{---- (1)}$$

where G is the Gibb's free energy, T is temperature, P is pressure, 1 - n_c are all components except Sr^{86} , Sr^{88} and Sr^{87} . a , is the activity. A refers to phase A, $\mu_{\text{Sr}^{87}}^0$ is the standard chemical potential of Sr^{87} taken here as the infinitely dilute solution. If we consider the distribution of Sr isotopes between biotite and K-feldspar we note first that Rb and Sr probably form very dilute solutions in K sites (Heir, 1962).

This leads to the assumption -

$$F_{a_{\text{Sr}87}} = F_{x_{\text{Sr}87}}$$

where x is the mole fraction of Sr^{87} in K sites in phase F.

If equilibrium is also assumed, as is done in Riley and Compston, and Lamphere et. al., the distribution of Sr^{87} between phases B and F is

$$\frac{F_{x_{\text{Sr}87}}}{B_{x_{\text{Sr}87}}} = e^{-\left(\frac{F^o_{\mu_{\text{Sr}87}} - B^o_{\mu_{\text{Sr}87}}}{R T_1}\right)} = D_1$$

$$\text{as } \mu_{\text{Sr}87}^F = \mu_{\text{Sr}87}^B$$

where T_1 is the temperature at which the distribution occurred.

hence

$$\Delta \mu_{\text{Sr}87}^o = - R T_1 \ln D_1 \quad \text{----(2)}$$

As fractionation of Sr isotopes has not been observed in nature the following assumption appears justified -

$$\mu_{\text{Sr}87}^o(T, P, \text{Sr}^{86}, \text{Sr}^{88}, 1 - n_c) = \mu_{\text{Sr}86}^o(T, P, \text{Sr}^{87}, \text{Sr}^{88}, 1 - n_c)$$

and similarly for phase B.

This leads to the conclusion -

$$(\text{Sr}^{87}/\text{Sr}^{86})_A = (\text{Sr}^{87}/\text{Sr}^{86})_B \quad \text{----(3)}$$

which is the observed distribution in the high grade Cooma rocks after complete mixing.

If we now consider complete mixing of strontium isotopes at a lower temperature T_2 , the distribution of Sr^{87} between F and B becomes -

$$\begin{aligned}
 D_2 &= e^{-\frac{\Delta \mu_{\text{Sr}^{87}}^0}{R T_2}} \\
 &= e^{\frac{+ R T_1 \ln D_1}{R T_2}} \\
 \log D_2 &= \frac{T_1}{T_2} \log D_1 \quad \text{----(4)}
 \end{aligned}$$

This expression is at best an approximation, however, it does relate the expected D_2 to D_1 and the ratio of temperatures.

Estimates of D_1 and T_1 may be made from metamorphic rocks which have suffered no later movement of strontium isotopes. The Cooma granite and gneisses are excellent for this and assuming that most strontium occupies K sites in the biotite and potassium feldspar crystals D_1 is approximately 30 and T_1 approximately 500°F. (Miyashiro, 1961).

Equation 4 can be used to investigate the low biotite ages at Broken Hill. It has been shown that BH5 sillimanite gneiss has no retrogressive metamorphic assemblage and no signs of recrystallization and yet the biotite is distinctly younger, at 500 m.y., than the total-rock. Also the total-rock has remained a closed system since formation.

If Sr isotopes are assumed to have been redistributed, between minerals, under low T, P, conditions D_2 can be calculated from 4 and compared with the observed distribution.

Let T_2 be 200°C and T_1 500°C

$$\text{Log } D_2 = \frac{773}{473} \log 30$$

$$= 2.4138$$

$$D_2 = 259.$$

This model clearly indicates that if strontium isotopes were redistributed at equilibrium and 200°C they would almost entirely be incorporated in the K-feldspar lattice. If the Sr^{86} concentration in biotite from the Cooma granite and high grade zones is compared with that in BH5 biotite, there is no evidence to suggest that the BH5 biotite Sr^{86} concentration is unusually low, nor is there any suggestion that the rubidium concentrations have been noticeably altered. In order to explain the Rb-Sr age results of BH5 minerals therefore, it is necessary to invoke mechanism (b), the preferential movement of radiogenic strontium between minerals at some time after the formation of the two minerals.

Hurley et. al. (1961), Allsopp et. al. (1962) and others have postulated the preferential movement of radiogenic strontium, under low grade metamorphic conditions, while common Sr remains fixed, and Hart (1964) has demonstrated this mechanism in an area of contact

metamorphism.

If this preferential movement of radiogenic strontium, under low grade metamorphic conditions, is assumed, then the theoretical distribution D_2 , between feldspar and biotite of BH5, as found from equation 4, is essentially identical to the distribution of Sr isotopes found by assuming that all radiogenic strontium was lost from biotite and gained by orthoclase at 500 m.y. (Chapter VIII).

This shows that the postulated preferential movement of radiogenic strontium is compatible with the simple thermodynamic model.

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