THE GEOCHRONOLOGY OF THE IGNEOUS ROCKS OF EASTERN QUEENSLAND

A STUDY OF THE RELATIONSHIP IN TIME BETWEEN
IGNEOUS ACTIVITY, OROGENIC PROCESSES
AND MINERALISATION

A thesis submitted for the degree of

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by

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STATEMENT

The work described in this thesis was carried out in the Department of Geophysics and Geochemistry, Australian National University between 1964 and 1967. The analytical work and interpretation of results are my own, although assistance in various phases of the investigation was provided by the following people. W. Pascoe, H. Berry and R. Rudowski carried out the mineral concentrations on all samples except those described in Appendices B and C. The Potassium analyses on samples earlier than GA 800 were done by J.A. Cooper. Preliminary X-ray fluorescence spectrographic analyses of the samples for Rb-Sr dating were made by J.M. Rhodes, C.D. Branch and P. Palmer. Dr W. Compston made the Rb and Sr analyses on GA 472 biotite.

In the course of this project, several batches of $^{38}$Ar tracer were prepared and calibrated. This was a cooperative effort involving Drs J.R. Richards, and I. McDougall and the author. The preparation and calibration of the Rb and Sr tracers used in this project were mainly the work of M.J. Vernon and P.A. Arriens. The computer programs for the reduction of the Rb and Sr mass spectrometer data were written by Drs A. Turek and P.A. Arriens.

Appendices B and C, and the data contained in Chapter 3 have been published under co-authorship. However, the analytical work and the interpretation of the results are the work of the present writer.

A. W. Webb
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With 29 Tables, 20 Figures and 2 Plates
GENERAL INTRODUCTION

The Australian continent (Figure 1) is composed of two major units; the Precambrian Shield and the Tasman Ortho-geosyncline of Palaeozoic to Mesozoic age. The Shield occupies the western two-thirds of the continent, and throughout the Phanerozoic has had several intracratonal geosynclines (using the terminology of Kay, 1951) developed upon it. The Tasman Geosyncline occupies the eastern third of the continent and has been an area of active sedimentation, volcanism, plutonism and tectonism from the Cambrian to the Cainozoic. The demarcation between the shield and the ortho-geosyncline is largely obscured by the Mesozoic strata of the Great Artesian Basin (Autogeosyncline), but no authenticated Precambrian strata are known on the mainland to the east of the heavy line in Figure 1. The focus of activity in the ortho-geosyncline moved slowly eastward during the Palaeozoic, with successive phases of orogenic activity stabilising the area to the west (David, 1950). Many of the earth movements were accompanied by the intrusion of granitic batholiths. The Lower Palaeozoic strata are best exposed in Victoria and southern New South Wales, while the Upper Palaeozoic and Mesozoic are most extensively developed in northern New South Wales and Queensland.

Systematic mapping of the sedimentary basins in Queensland was commenced in the late 1950s as the basis for future petroleum exploration, and since 1960 the work has been carried out jointly by the Commonwealth Bureau of Mineral Resources and the Geological
Major structural units of the Australian continent

Based on Hills (1965) and Voisey (1959)
Survey of Queensland. The author participated in this mapping during the winter of 1963. Concurrently with the mapping program, the Department of Geophysics and Geochemistry, Australian National University and the B.M.R. established a laboratory with facilities for isotopic dating, and one of the major projects undertaken by the B.M.R. was the dating of the igneous rocks in the Queensland section of the Tasman Geosyncline.

The field mapping has been directed mainly toward the sedimentary sequences, and in the regions of plutonic rocks, geological interpretations have depended greatly on the isotopic dating. Many conclusions reached in B.M.R. Reports on the geology of the region, which may appear incontrovertible to the reader, are tenuous observations strengthened by the results of isotopic dating. In other cases, they may be due entirely to the isotopic evidence. Thus, there are instances where this thesis conflicts with the published geological information as to the degree of certainty of many geological relationships.

The aims of the present study were:

1. To make a regional investigation of the isotopic ages of igneous rocks in eastern Queensland. In most cases, only very wide limits can be placed on their ages by stratigraphic methods.
2. To date stratigraphically controlled rocks to obtain more precise ages of the subdivisions of the Upper Palaeozoic, and to provide a scale against which the granite ages could be compared.
(3) To examine the relationship in time between igneous activity and tectonic events, and the distribution of ore mineralisation with time.

(4) To investigate the genesis of igneous rocks (particularly granites) using the $^{87}\text{Sr}$ abundance as an indication of source area.

Related to this aim was the question of continental growth: whether eastern Australia represents freshly derived sialic material that has been welded on to the Precambrian shield over the past 600 million years, or whether it consists of material derived mainly from the shield area and deposited on a depressed section of the continental crust.

Chapter 1 describes the techniques used for the age measurements. The Potassium-Argon method and precision are described in greater detail because the author was more closely involved in the development of the method in this laboratory, and because it has not yet been described fully in the literature.

Chapter 2 contains a brief and generalised description of the regional geology in eastern Queensland and the difficulties involved in dating the igneous rocks by conventional geological means.

Chapters 3 and 4 contain the results obtained and the interpretation of them, and give a somewhat better definition of the age of the Permo-Triassic boundary than was previously available. Dates measured by both the K-Ar and Rb-Sr method are compared to determine the half-life of $^{87}\text{Rb}$ which gives closest agreement between K-Ar and Rb-Sr ages.
Chapter 5 examines the implications of the dating on the broader problems of continental evolution and the relationship between igneous activity and orogeny.

Chapter 6 is a revision of an earlier correlation of igneous activity with mineralisation.

Appendix A lists the rock type and locality of the samples used in this study. Appendices B and C are drafts of publications on K-Ar dating of Tertiary volcanics. Appendix B is a comparison of whole rock and mineral ages of related rocks, and a study of the relationship between alteration and argon loss. On the basis of this study, the samples described in Appendix C were selected.

The tables of analytical data were compiled by putting the information on punch cards and listing them on an IBM computer. A disadvantage of this method is that superscripting and lower case lettering is not possible; thus $^{40}$Ar* appears as 40AR*.

My supervisor during the course of this investigation was Dr Ian McDougall, to whom I am grateful for advice and criticism. Numerous geologists of the B.M.R. and Geological Survey of Queensland have assisted in the collection of samples and have provided geological information which was unavailable in printed form at the time. In particular, discussions with E.J. Malone and A.G.L. Paine have helped greatly in the understanding of the geology of the region.
CHAPTER 1

METHODS

1. a Introduction

Isotopic ages were measured by both the K-Ar and Rb-Sr methods. The K-Ar determinations form the bulk of the work, and the intrusive rocks were collected with a view to suitability for K-Ar analysis. Consequently most of the samples contain biotite and/or hornblende. Because of the relatively low percentage of outcrop in the granitic areas, it is difficult to know whether the samples collected are truly representative of the intrusive rocks; but although the sampling may be random, it is sufficiently closely spaced that it is unlikely that any major age units have gone undetected. Only fresh, unweathered samples were collected, and most were obtained by drilling and blasting large tors.

Potassium was determined as total K by flame photometry, and the percentage of $^{40}K$ calculated from the measured atomic abundance of this isotope in natural K. $^{40}Ar$, $^{87}Rb$ and $^{86}Sr$ were measured by isotope dilution and the present day $^{87}Sr/^{86}Sr$ value by direct mass spectrometry on unspiked Sr separations, and also calculated in the process of measurement of $^{86}Sr$ concentration. The decay constants and natural isotopic abundances used in the calculation of ages are as follows:

$$^{40}K \lambda_e = 0.584 \times 10^{-10} \text{yr}^{-1} \} \quad \lambda_{\beta} = 4.72 \times 10^{-10} \text{yr}^{-1} \}$$

Aldrich and Wetherill (1958)
$^{40}\text{K} = 1.19 \times 10^{-2}$ atom. percent of total K

$^{40}\text{Ar} = 99.60$ " " " atmospheric Ar \hspace{1cm} \text{(Nier, 1950)}$

$^{38}\text{Ar} = 0.063$ " " " "

$^{36}\text{Ar} = 0.337$ " " " " \hspace{1cm} \text{(Nier, 1938)}

$^{87}\text{Rb} \lambda_\beta = 1.47 \times 10^{-11} \text{yr}^{-1}$ \hspace{1cm} \text{Flynn and Glendenin, 1959)}

$^{88}\text{Sr}/^{86}\text{Sr} = 8.3752$ \hspace{1cm} \text{Nier, 1938)}

$^{85}\text{Rb}/^{87}\text{Rb} = 2.5995$ \hspace{1cm} \text{Shields and Garner, 1963)}

1. b \hspace{0.5cm} \text{Sample Preparation}

The rock samples ($\sim 1.5$ kg) were crushed to pass 36 B.S. mesh and from this, an aliquot was split and ground to pass 100 B.S. mesh. This total rock sample was used for Rb-Sr analyses. The remainder of the sample was screened and the required size fraction separated for mineral concentration. A compromise must be reached between the conflicting needs of a coarse grain size, for easier handling under vacuum, and a fine grain size, to avoid composite grains and to obtain a more homogeneous sample. Most concentrates were in the range 60-100 B.S. for biotites and 85-120 B.S. for hornblendes. The mineral separation was done by flotation in high density liquids, and by dry electromagnetic and electrostatic processes. The concentrate was cleaned in acetone in an ultrasonic washer to remove adhering dust and to shake free chlorite which may have been attached to the edges of biotite flakes.

The purity of the final concentrate usually exceeded 98\% (based on a grain count), and with these samples, the normal Ar and K
reproducibility was achieved. A correlation was noted between increasing amounts of impurity (above 2%) and decreasing precision in the measurement of duplicates. The chief contamination normally encountered was chlorite in biotite, and this had the effect, not only of decreasing the precision of the analyses, but in extreme cases, of reducing the measured K-Ar "age". An example of the latter is set out in Table 1. Both samples were collected from the same road cutting, and biotite concentrates were prepared and dated by Shell Development Company's laboratory (Sample A) and by the author (Sample B). The biotite in the rock was moderately chloritised, but a concentrate of acceptable purity was obtained (Sample B). The reduced K and Ar content of Sample A was probably due to the presence of excessive amounts of chlorite in the sample, and the poor argon retentivity of the chlorite is reflected in the lowered "age".

**TABLE 1**

Comparison of ages determined on different concentrates from the same rock mass.

<table>
<thead>
<tr>
<th></th>
<th>Sample A</th>
<th>Sample B (GA 5318)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^39$K</td>
<td>3.70</td>
<td>5.81</td>
</tr>
<tr>
<td>$^{40}$Ar* (moles/gm)</td>
<td>$1.19 \times 10^{-9}$</td>
<td>$2.38 \times 10^{-9}$</td>
</tr>
<tr>
<td>Age (m.y.)</td>
<td>178</td>
<td>218</td>
</tr>
</tbody>
</table>

Kulp and Engels (1963) in laboratory experiments examined the effects of base ion exchange with Mg and Ca chloride solutions on Rb-Sr and K-Ar mica ages, and concluded that the Rb-Sr age was most
susceptible to lowering by such a process. They found that biotite may lose up to 80% of its K with a corresponding decrease of only 10% in the measured age. Similar conclusions were reached by Goldich and Gast (1966) from a study of biotite in weathered and unweathered rocks from the one formation. However, this gives no information on the argon retentivity of chlorite during geological time. Chloritisation is presumed, normally, to be a deuteric process associated with late stage alteration during the cooling of an igneous rock and is not directly comparable to groundwater leaching. Kulp and Bassett (1961) reported lowered K-Ar "ages" for chloritised samples.

1. c The Potassium–Argon Method

$^{40}\text{K}$ decays to $^{40}\text{Ca}$ by the emission of $\beta$ particles, and to $^{40}\text{Ar}$ by the capture of an electron and the emission of $\gamma$ radiation. It is the latter decay scheme upon which the K–Ar age calculations are based. The decay constants for the production of $^{40}\text{Ca}$ ($\lambda_\beta$) and $^{40}\text{Ar}$ ($\lambda_e$) and the atomic abundance of $^{40}\text{K}$ in natural potassium must be known. The age is calculated from the equation:

$$t = \frac{1}{\lambda_e + \lambda_\beta} \ln \left[ 1 + \frac{\lambda_e + \lambda_\beta}{\lambda_e} \cdot \frac{^{40}\text{Ar}}{^{40}\text{K}} \right]$$

where $t$ is the age and $^{40}\text{Ar}$ and $^{40}\text{K}$ are the present day abundances in the sample.

A.G. Smith (1964) reviewed the various determinations of these parameters which had been made up to that time, and calculated "best
values" by averaging those determinations with least uncertainty (∼ 4%). He showed that the K-Ar ages of Palaeozoic and younger rocks calculated from these "best values" would not be significantly different from those calculated using the values given in Chapter 1a.

The major source of uncertainty in a K-Ar age, assuming no loss or gain of K or Ar, is that incurred in the measurement of K and Ar.

1. c (i) Potassium Analysis

The method of potassium analysis was that described by Cooper (1963) and Cooper, Martin and Vernon (1966). The weight of sample used is regulated by the potassium content of the mineral. For high K minerals such as micas, 0.15 g of sample is sufficient, while for low K minerals, 0.75 – 1.0 g may be necessary.

Two aliquots of the sample were split from the bulk concentrate with a microsplitter and weighed into platinum dishes. The mineral was dissolved in 10 – 20 ml HF with 6 ml 50% H₂SO₄ added. The samples were left in the cold acid overnight and then warmed on a water bath to evaporate the HF. A further 10 ml HF was added, and the solution evaporated again. The dish was transferred to a hot plate and heated gently until the H₂SO₄ began to fume. The dish was cooled, 30 ml H₂O added, and the solution warmed on the water bath. When all the solids had dissolved, the solution was transferred to a 250 ml volumetric flask. 100 ml of a solution containing 1250 ppm Na and 500 ppm Li were added and the solution made up to volume with H₂O. The sample was stored in a polythene bottle with a screw cap.
Over short periods, there was no evaporative loss from these bottles.

The K concentration of the solution was measured on a Perkin Elmer Model 146 flame photometer by comparison with two standard K solutions (one of higher and the other of lower concentration) which contained $\text{H}_2\text{SO}_4$, Na and Li in equivalent concentrations to that in the sample. Six or seven readings of both the unknown and standard solutions were made, and it was assumed that the intensity of the emission from the flame varied linearly between the concentrations of the two standards used.

A filter was used routinely to cut out the Rb emission at 7800 $\AA$ which would otherwise enhance the K emission doublet at 7665 and 7699 $\AA$ on this particular apparatus.

A correction was also made for the enhancing effect of the broad band interference on the intensity of the K peak in samples rich in Fe and low in K, e.g. pyroxenes and many hornblendes. This effect normally increased the measured K content of the hornblendes by 1%.

The accuracy of the method may be determined by measurements on standard materials which have been analysed in other laboratories, and by other methods. Cooper (1963) gave a comparison of flame photometric analyses made in this laboratory with isotope dilution analyses (also done at A.N.U.) and other methods in several laboratories, and in most cases, found agreement to within 1% with the average or "best" values determined elsewhere.

Since 1963 a large number of samples with potassium contents ranging from 0.03 to 10% were analysed by X-ray fluorescence spectro-
graphy (Chappell pers. comm.) and by flame photometry using the technique described above (Cooper pers. comm.). The difference between analyses by the two methods never exceeded 5% and for samples with greater than 1.5% K the difference was less than 1% (standard deviation).

In addition, several analyses of standard muscovites, Bern 4-M and U.S.G.S.-P207 were made by the author (Table 2). These agree closely with those reported by Lanphere and Dalrymple (1965), and with analyses made in this laboratory two years ago (Cooper, pers. comm.). This indicates not only the good agreement that can be achieved with other laboratories, but also that there has been no detectable drift in the accuracy in this laboratory (due to changes in the concentration of the standards, etc) over the past two years.

1. c (ii) Argon extraction

The technique used for argon extraction has been described by McDougall (1964, 1966) and was based upon that developed at the University of California, Berkeley (Evernden and Curtis, 1965). The extraction line shown in Figure 2 is made of pyrex and silica and is comprised of the following units: -
(A) sample bottle with inner silica liner
(B) stainless steel furnace containing CuO, heated externally
(C) molecular sieve (Linde 5A artificial zeolite) 1/8 inch pellets
(D) break-seal tube containing \( {^{38}} \text{Ar} \) tracer
(E) silica furnace containing titanium sponge, heated externally
Figure 2

Argon extraction and purification line
(F) ion gauge
(G) sample take-off with granular activated charcoal side arm
(H) activated charcoal fingers for gas transfer.

The system was evacuated through a bakeable, Alpert-type metal valve by a mercury diffusion pump backed by a rotary forepump. After baking the line at 250°C for 4 to 8 hours, a pressure of $1 \times 10^{-7}$ torr or lower was attained. During this bakeout, most of the air adsorbed on the glassware and the materials in the line was removed, and the molecular sieve was re-activated.

The $^{38}$Ar tracers were prepared in batches of 400–450, and were approximately equal in volume. Consequently, the weight of sample used was dependent upon the age and the potassium content of the mineral, the aim being to keep the measured $^{40}$Ar/$^{38}$Ar ratio in the range 1.0 to 4.0. In this study, the average sample weight was 0.25 g for micas and 0.75 g for hornblends. No flux was used.

The sample was suspended in a molybdenum bucket in the pyrex bottle, and heated externally by a radiofrequency induction furnace. The temperature was raised slowly (over a period of 20 minutes) to about 1300°C. If the temperature increase is too rapid, the mineral grains tend to blow out of the bucket – this happens with micas as the bucket begins to show signs of redness, and at a considerably higher temperature with hornblends. When the maximum temperature was reached, the calibrated volume of $^{38}$Ar tracer was released into the system by breaking the glass bubble with the iron slug. The sample was heated above its fusion temperature for 15 minutes, and the evolved gases
held on activated charcoal cooled with liquid nitrogen.

While the sample was being fused, the CuO and Ti furnaces were warmed up to their operating temperatures and the clean-up side of the line was open to the pumps. The Ti furnace was outgassed at 950°C.

After fusion of the sample, the mixed gases were allowed to circulate over the hot (600°C) CuO, and the water produced by oxidation of H₂ absorbed in the molecular sieve. The reaction was monitored using a high frequency spark discharge coil and observing the colour of the discharge produced in the line. This colour changes from bluish to pink as the water is removed.

The gas was then transferred to the clean-up side of the line, and allowed to react with the titanium sponge, which had been cooled to 800°C. Oxygen and nitrogen were removed by the gettering action of hot titanium. The standard time allowed for this step was 45 to 50 minutes, although the clean-up was probably completed in a shorter time. The Ti furnace was cooled to room temperature, and liquid N₂ placed around a cold trap to remove any condensible gases which remained. The purified argon was adsorbed on activated charcoal cooled with liquid N₂, and the sample sealed off with a flame at the constriction.

The extraction and purification process takes about four hours.

1. c (iii) Preparation of Ar tracer

  38Ar tracers were prepared in batches of 400 to 450 by the system
described by Reynolds and Spira (1966). The volume of each pyrex tube, with glass break-seal, was calculated from the weight of Hg needed to fill the tube, with a correction made for the temperature at the time of weighing. The tracer ampoules had an approximate volume of 1 cc, which was calibrated to within ± 0.1 percent.

The break-seal tubes were joined vertically to a pyrex manifold by means of capillary tube. The tracer preparation line consisted of the manifold, a McLeod gauge, and a Hg reservoir which was filled by distillation of mercury under vacuum. The system was evacuated and the manifold baked to obtain a pressure of $1 \times 10^{-5}$ torr or lower. The line was isolated from the pumps by raising a Hg cut-off and the tracer released into the system and allowed to reach equilibrium. A magnetically operated valve on the mercury reservoir (modified after Richards, 1962) was opened to introduce Hg into the manifold. The gas displaced by the Hg filled the emptying mercury reservoir, and there was no change in the pressure of the gas during the operation. Consequently, it was not important if the ends of the capillaries of the break-seal tubes were not sealed simultaneously by the Hg. The mercury was introduced until it rose in the capillaries about 1 inch above the manifold. The tubes containing the tracer were cut off at the mercury-gas interface with a hot flame. Each ampoule contained approximately $5 \times 10^{-6}$ cc of $^{38}$Ar at NTP.

The relative concentrations of $^{36}$Ar, $^{38}$Ar and $^{40}$Ar in the tracer were measured directly by mass spectrometry. Using tracer prepared
by the University of Zurich, the measured $^{38}\text{Ar}/^{40}\text{Ar} \simeq 5000$ and the $^{38}\text{Ar}/^{36}\text{Ar} \simeq 17,500$. This was in agreement with the manufacturer's stated purity of $>99.9\%$ $^{38}\text{Ar}$ in the tracer, and indicated that no obvious contamination by air argon had occurred during the preparation of the batch of tracers in this laboratory.

The concentration of the tracer was measured by calibration against a primary standard (air argon) and a secondary standard (GA 49, biotite) whose argon content had been measured by isotope dilution using tracer calibrated against air argon.

Air samples were collected in ampoules similar to those used for the tracer, but with a volume of 0.1 to 0.2 cc. Several of these were attached to a manifold, which was evacuated and sealed. Liquid $N_2$ traps were used to prevent oil vapour entering the system from the rotary pump. The seal was broken and the ampoules filled with air drawn through a trap cooled with frozen $CO_2$. The volume of air was measured in a McLeod gauge and one of the prepared tracers mixed with it. The mixed gas was cleaned in an argon extraction line, and the isotope ratios measured with the mass spectrometer. There appears to have been no significantly improved measurements of the concentration of argon in air published since Kellas and Ramsay's (1895) determination of 0.937% (by volume). This agrees closely with the value determined by isotope dilution by Aldrich and Wetherill (J.R. Richards, pers. comm.) of 0.935%, and that published in the Handbook of Chemistry and Physics (43rd edition p. 3429) of 0.934%. The value of 0.94% was used in the subsequent calculations.
One ampoule of tracer from each row of the manifold was run with a split from GA 49 biotite. This secondary standard was initially calibrated against air argon and M.I.T. standard biotite B-3203.

1. c (iv) Mass spectrometry

The argon isotope ratios were measured in a glass, 60° sector, 4.5 inch radius of curvature mass spectrometer (Reynolds, 1956). An accelerating voltage of 2 kV and a magnetic field of approximately 3340 gauss was used to scan the mass range from 36 to 40. A source magnet was not used. The pressure before admitting the gas sample was $1 \times 10^{-8}$ torr or lower, and the background was free from mass 36. The ion current at the collector was measured with a vibrating reed electrometer and was recorded graphically on a chart recorder. The peak height was proportional to the ion current and to the abundance of the mass being measured.

The static method (Reynolds, 1956) was used to measure the isotope ratios. The mass spectrometer was isolated from its vacuum pump, and the sample leaked in through a small orifice. A correction was applied to allow for the effect of mass fractionation through the orifice. The accelerating voltage and magnet field were set for mass 40 and the sample admitted into the spectrometer until the mass 40 beam produced full scale deflection with the electrometer set on the 10 volt range. Using a $5 \times 10^{10}$ ohm resistor in the vibrating reed, this deflection was equal to an
ion current of $2 \times 10^{-10}$ amps, and the efficiency of the ionisation and collection system (ions/atom Ar) was about $0.05 \times 10^{-3}$. For most samples, the 38 mass was then recorded either on the 3 volt or 10 volt scale, while the 36 mass was registered on the 10 millivolt scale. The spectrum from mass 40 to mass 36 was scanned by holding the accelerating voltage constant and varying the strength of the magnetic field. The sweep from mass 40 to 36 and back to 40 was done 5 times, giving 10 sets of comparisons of the 40/38 and 38/36 peak heights.

The peak heights, and the ratio of the heights of different masses changed during a run. This variation was normally linear, and the isotope ratios of the sample at the time of admittance to the spectrometer were derived by plotting the 40/38 and 38/36 ratios against time during the run, and extrapolating the plot back to zero time. A "memory" of previous samples run in the mass spectrometer (a disadvantage of the static method of analysis) was observed if consecutive runs had markedly different 40/38 and 38/36 ratios. The variation of the isotope ratios with time was then strongly non-linear, especially in the early stages of the analysis, where the extrapolation must be made. This effect greatly increased the uncertainty in the extrapolated value of the isotope ratios, but was normally avoided by running consecutively, samples which had similar isotopic ratios, and by regulating the weight of sample used for the argon extraction so that the 40/38 ratios fell within fairly close limits. When the plots were strongly curved, the analysis was
repeated.

Corrections were applied for the orifice fractionation, and for mass discrimination in the spectrometer. The latter was determined by the dynamic measurement of the 40/38 and 38/36 ratios of air argon. The percentage departure of these ratios from Nier's (1950) values for the isotopic abundance of argon in air was calculated. The average discrimination over 2 mass units favoured the heavier isotope by approximately 1%.

Argon measurements on U.S.G.S. standard muscovite P-207 made in this laboratory by McDougall (in Lanphere and Dalrymple, 1965) were as much as 3 percent lower than those made by other laboratories. More recent measurements, using tracer from other spike sets, have not varied significantly from the original determinations.

1. c (v) Precision of K-Ar measurements

A random sample of size $N$, drawn from a normal population with mean $\mu_x$, will have a mean $\bar{x}$. The Standard Deviation (SD) of each determination of $x$ in the sample $N$ is given by

$$SD = \sqrt{\frac{\sum |x_i - \bar{x}|^2}{N - 1}}$$

The SD of $\bar{x}$ for several samples of size $N$

$$= \sqrt{\frac{\sum |x_i - \bar{x}|^2}{N(N - 1)}}$$
To enable a direct comparison of the variation in analyses on samples whose Ar or K may differ by an order of magnitude, the precision of the measurements is expressed as the Coefficient of Variation (CV).

\[
CV = \frac{SD \times 100}{\text{Mean}}
\]

and for duplicates (1 degree of freedom),

\[
CV = \frac{|\text{Dup.}_1 - \text{Dup.}_2| \times 100}{\sqrt{2} \times \text{Mean}}
\]

The Variance (Var) \( = SD^2 \)

The precision of the K analyses may be calculated from the internal variation of six or seven sets of flame photometer readings for each sample, or from the variation between duplicate dissolutions. For biotites, the average CV for the flame photometer readings was 0.22, and the CV of 115 duplicate analyses was 0.24. For hornblendes, the values were respectively 0.30 and 0.33. Thus the precision appears to be controlled by the instrumental variation. Intuitively, this conclusion is optimistic because it rejects the possibility of any sampling errors. All the flame photometer measurements were included in the calculation of instrumental CV. If those readings which were greater than 3 SD from the mean were rejected, the instrumental CV would be reduced and a more realistic estimate of the sampling error would be achieved. At the 95% confidence level, the overall precision would be approximately \( \pm 0.5 - 0.6\% \) (SD \( \times 1.96 \)).
The precision of the argon determinations is dependent on the following factors.

1. Mass spectrometer effects, which include
   a. variations in mass discrimination,
   b. non-uniform behaviour when the gas is fractionated through the valve,
   c. electronic stability, which affects
      (i) the degree of scatter of isotope ratio measurements about a straight line, and
      (ii) the accuracy of measurement of the small mass 36 peak height.
   The percentage error in determination of $^{36}\text{Ar}/^{40}\text{Ar}$ (e) in a sample with a percentage air contamination (f) will produce a percentage error in radiogenic argon given by the equation
   \[
   E = \frac{e \times f}{100 - f}
   \] (Lipson, 1958). An increase in either e or f will cause an increase in E.

d. memory from previously run samples causing rapid changes in isotope ratio with time and a non-linear extrapolation of these ratios back to zero time.

2. Argon extraction and purification procedures. Poor techniques cause
   a. higher than necessary air contamination (see 1 c (ii)).
   b. incompletely cleaned samples, producing gas pressure scattering of the ion beam and large tails under the 36 peak (see 1 c (ii)).

3. Tracer purity and calibration.
   a. the accuracy of measurement of the proportions of argon 36, 38 and 40 in the tracer
b. uniformity of tracer concentration between ampoules prepared in each batch

c. the accuracy of measurement of tracer concentration

d. calibration of the volume of each break-seal tube.

4. Sample (mineral) purity, which affects the homogeneity of the sample.

The effects of 1 d, 2 a and b, 3 d and 4 can be reduced to an insignificant level by taking suitable precautions. 3 a is negligible with the high purity Zurich tracer. 1 a and b are assumed to be constant and can be allowed for, but fluctuations from sample to sample can not be monitored. 1 c will vary from day to day despite regular attention to the electronics. The final sources of error are 3 b and c. The proportion which each factor contributes to the overall error is difficult to assess, but the uncertainty in 3 b is believed to be the most important.

The tracers used in this study were calibrated against air argon, and against a secondary standard, GA 49 biotite. The tracers have also been run with U.S.G.S. standard muscovite P-207 (Lanphere and Dalrymple, 1965). Over a period of several years, during which 8 or more sets of tracer were prepared, the CV of the calibrations against GA 49 biotite varied between 0.75 and 1.5. (This is based on calibrations of at least one tracer from each row of the spike manifold in each set.) This variation was a combination of real fluctuations in tracer concentration between ampoules, the errors in the mass spectrometer measurements of the isotope ratios and sample inhomogeneities.
Calibration of tracer with atmospheric argon eliminates the problem of inhomogeneities in the standard mineral but introduces an error associated with the McLeod gauge readings. These measurements of the volume of the air samples involved at least 40 readings for each sample. The best precision attained was 0.3 (CV), but at times was as high as 2 (CV). This was due to sticking of Hg in the capillaries. Despite the use of double distilled Hg, which had previously been cleaned in columns of HNO₃, NaOH and trichloroethane, it was found necessary to dismantle the capillaries and clean them at frequent intervals. Thus the variation of the McLeod gauge measurements alone may be equivalent to the total variation encountered in calibration against a standard mineral, and the tracer calibration by this method often shows a larger uncertainty than that against the standard mineral. This had been noted by Reynolds and Spira (1966), who reported an overall mean deviation (± standard deviation) of 1.7% for the calibration of ³⁸Ar tracers.

The CV for duplicate determinations on biotites in this thesis was 0.9, while McDougall (1964) quoted a somewhat higher figure for whole rock determinations on basalts. The latter can be related to the greater percentage error in correcting for the relatively high air contamination in these young samples. The small difference between the CV for GA 49 calibrations and for the biotite determinations quoted in this thesis was probably due to the greater sample purity of GA 49 and to smaller memory effects when these calibrations were run.
It would appear that \( CV = 0.75 \) is close to the limit of precision attainable under present conditions, and a value of 0.9 is more appropriate for normal samples.

**Variance in the \( ^{40}Ar^*/^{40}K \) ratio**

An approximation of the precision of the K-Ar measurements can be calculated from the following equation.

\[
\text{Var} \left( \frac{^{40}Ar^*}{^{40}K} \right) = \frac{^{40}Ar^{*2} \cdot \text{Var} \, K + ^{40}K^2 \cdot \text{Var} \, ^{40}Ar^*}{^{40}K^4}
\]

This approximation is valid where errors are less than \( \sqrt{5}\% \).

\[
\text{SD} = \frac{CV \times \text{mean}}{100}
\]

and \( \text{Var} = \text{SD}^2 \)

therefore \( \text{Var} \, K = \left[ \frac{0.24 \times \text{mean} \, K}{100} \right]^2 \)

and \( \text{Var} \, Ar = \left[ \frac{0.90 \times \text{mean} \, Ar}{100} \right]^2 \) for biotite.

If duplicates are available, the variance is halved.

\[
\text{The Standard Error (SD)} = \sqrt{\text{Var} \left( \frac{^{40}Ar^*}{^{40}K} \right)}
\]

and the \% Error \( (E) = \frac{\text{SD}}{^{40}Ar^*} \times 100 \)

At the 95 percent confidence limits the percent error \( = 1.96 \times E \).

The uncertainties in the age thus calculated are exclusive of any error in the decay constants used. The limits of error in a
single K-Ar age are found to be approximately equal to the SD of individual ages measured on a number of samples from the one intrusion. Such agreement is presumed to be confirmation that the samples dated were taken from a single population, and that the mean age is geologically meaningful. Where the SD of the measured ages of a group of related rocks is significantly greater than the expected error, it would be interpreted as a smearing of the true ages by some geological effect.

The limits quoted for potassium – argon ages in this thesis are the SD of \( \bar{x} \) (see beginning of this section).

1. d The Rubidium – Strontium Method

Naturally occurring rubidium has two isotopes; mass 85 and 87 in the approximate proportion of 2.6:1. Strontium contains four stable isotopes; mass 84, 86, 87 and 88 with approximate abundances: <1%, 10%, 7% and 83% respectively.

The radioactive decay of \(^{87}\text{Rb}\) to \(^{87}\text{Sr}\) is given by the equation:

\[
N \left( ^{87}\text{Sr}^* \right) = N \left( ^{87}\text{Rb} \right) \cdot (e^{\lambda t} - 1) \tag{1}
\]

where \( N \) is the number of atoms of daughter and parent found at the present time, \( t \) is the age and \( \lambda \) is the decay constant of \(^{87}\text{Rb}\).

This equation may be written:

\[
\lambda t = \ln \left( 1 + \frac{^{87}\text{Sr}^*}{^{87}\text{Rb}} \right) \tag{2}
\]

In addition to the radiogenic \(^{87}\text{Sr}\) produced in a mineral, the sample will invariably contain natural (common) strontium with
approximately 7% of the mass 87 isotope. Thus

$$^{87}\text{Sr}^* = ^{87}\text{Sr}_{\text{total}} - ^{87}\text{Sr}_{\text{initial}}$$

In the determination of a Rb-Sr age, the amount of $^{87}\text{Sr}_{\text{initial}}$ must either be estimated or calculated. In samples with high Rb/Sr ratios, e.g. micas, the percentage of radiogenic strontium is so great that an assumption of the amount of common $^{87}\text{Sr}$ can be made with no great loss in the accuracy of the calculated age. For samples with a high percentage of common $^{87}\text{Sr}$, it is necessary to determine accurately the initial $^{87}\text{Sr}$ by analysing a number of mineral components or several cogenetic total rock samples with different Rb/Sr ratios.

Equation (3) can be restated as:

$$^{87}\text{Sr}^*/^{86}\text{Sr} = R_p - R_i$$

where $R = ^{87}\text{Sr}/^{86}\text{Sr}$, $p =$ present day and $i =$ initial.

The experimental data from total rock analyses of several samples from each rock unit are presented by the isochron method of Nicolaysen (1961). Measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ for a suite of cogenetic rock samples are plotted against measurements of their $^{87}\text{Rb}/^{86}\text{Sr}$. Assuming that the samples had a common initial value for $^{87}\text{Sr}/^{86}\text{Sr}$ at their time of formation and that there has been no loss or gain of Rb or Sr since that time, all points will fit a straight line (isochron) to within experimental error. From equations (1) and (4), the equation for the isochron can be expressed:
\[
\frac{R_p - R_i}{87\text{Rb}} = \frac{87\text{Sr}}{86\text{Sr}} (e^{\lambda t} - 1) \quad (5)
\]

or

\[
\frac{(87\text{Sr}/86\text{Sr})_p}{87\text{Sr}/86\text{Sr}} = (87\text{Sr}/86\text{Sr})_i + \frac{87\text{Rb}}{86\text{Sr}} (e^{\lambda t} - 1) \quad (6)
\]

This is a first order equation in which the slope of the isochron \((e^{\lambda t} - 1 \text{ or } 87\text{Sr}/87\text{Rb})\) is proportional to the age, and the intercept on the \(87\text{Sr}/86\text{Sr}\) axis is the initial \(87\text{Sr}/86\text{Sr}\) common to cogenetic samples.

The parameters which must be measured are \(87\text{Rb}, 86\text{Sr}\) and \((87\text{Sr}/86\text{Sr})_p\). The value for the decay constant \((\lambda)\) of \(87\text{Rb}\) used in this thesis is \(1.47 \times 10^{-11}\) yr\(^{-1}\) and is equivalent to a half life of \(4.7 \times 10^{10}\) years. The uncertainty in the value of this parameter and the reasons for the choice of the \(4.7 \times 10^{10}\) years half life in preference to \(5.0 \times 10^{10}\) years will be discussed in a later section.

In this study, total rock samples ground to -100 B.S. mesh were used in over 90% of the Rb/Sr analyses. Biotite, K-feldspar, plagioclase and hornblende were the only minerals analysed. All samples were analysed by X-ray fluorescence to determine the approximate concentration of Rb and Sr, from which estimates of the Rb/Sr ratio were made. On the basis of these preliminary data, samples for total rock analysis were selected which offered the widest variation in Rb/Sr ratio. At least 5 samples were chosen from each group of rocks.

1. d (i) Chemistry

The analytical procedures followed those described by
Compston et al., (1965). Approximately 0.5 g of sample was weighed into a platinum dish, moistened with demineralised water, and 5 ml HF added. The sample was left cold for several hours (or overnight) and then warmed on a waterbath to evaporate the HF. 5 ml water was added, and the dish warmed to dissolve the fluorides present. Another 5 ml HF was added to break down any unattacked sample remaining, the dish heated on the waterbath, and 5 ml 70% perchloric acid added. When most of the HF had evaporated, the dish was transferred to a hot plate and baked to dryness at a low heat. 5 ml 2.5 N HCl was added and the sample dried again. It was then dissolved in 30 ml 2.5 N HCl and transferred without loss to a weighed pyrex beaker with a Parafilm cover. When cool, the solution was weighed, and aliquots weighed into 30 ml beakers. The weight of the aliquot to be taken was calculated from the X-ray fluorescence values for Rb and Sr, so that the Rb aliquot contained ~15 µg Rb and that for Sr determination contained ~8 µg Sr. When unspiked Sr measurements were made, the aliquot contained ~20 µg Sr. The tracer was added in drops from a polythene bottle. Two different Sr tracers were used in this study; a double spike (86/84) and a single enriched 84 spike.

The spiked aliquots were dried, redissolved in a few ml HCl (2.5 N for Sr and 1.0 N for Rb) and transferred to cation exchange columns. The columns were eluted with 1.0 N HCl for Rb (the Rb cut was made from 155 to 185 ml) and 2.5 N HCl for Sr (collected from 80 to 110 ml). The cation exchange resin was Dowex 50W-X8, 200-400
mesh. The columns were pyrex, 30 cm by 1.2 cm i.d. and contained 8 g of dry resin. The flow rate was approximately 1 ml per minute. The Rb and Sr cuts were evaporated to dryness in pyrex beakers and the samples transferred in one drop of demineralised water to the mass spectrometer source filaments using a pyrex pipette.

The ion exchange columns were cleaned with 100 ml 6 N HCl, washed with 20 ml demineralised H₂O and then 50 ml of the appropriate strength HCl. Separate columns were kept for Rb, spiked Sr and unspiked Sr samples. Glassware that had been in contact with tracer was not used again. The contamination levels of Rb and Sr in all reagents and apparatus were reported by Compston et al. (1965). All glassware was either English pyrex or French pyrex, which had a similar level of Sr to the English product.

1. d (ii) Mass Spectrometry

Rubidium

All Rb runs were made with a Metropolitan Vickers MS2-SG, 6 inch radius of curvature, 90° sector mass spectrometer. The source was operated at 2 kV and the magnet field varied by push-button selection of pre-set values of the magnet power supply. This enabled rapid switching from mass 85 to mass 87 beam. The ion current at the collector was measured with a vibrating reed electrometer and output was digitised with a voltage-to-frequency converter, counter and digital recorder, and was also monitored with a chart recorder. The beam voltage for 85 mass was counted for 1 second, immediately
switched, and the mass 87 beam counted for the same time after a fixed delay of 5 seconds to allow for complete response of the amplifier and magnetic field.

A rhenium ribbon, triple filament source was used, and the sample loaded on to both side filaments. Each side filament was heated separately, and at least 10 comparisons of the 85 and 87 peak heights were made for each filament. Zero counts were made before and after the run.

**Strontium**

Strontium (spiked and unspiked) runs were made with a N.A.A. Nuclide 12 inch radius of curvature, 60° sector mass spectrometer. A triple filament source similar to that used for the Rb runs was used, with the exception that the side filaments were heated simultaneously. Peak switching was again employed, but in this case the high voltage was switched while the magnet field was steady (Arriens and Compston, in prep.).

For spiked samples, sets of 10 or more comparisons were made of the isotope pairs 88/86, 86/84, 86/87 and 88/86. This procedure was later changed and an extra set of 88/86 measurements was made between the 86/84 and 86/87 sets.

With unspiked samples, the 88/86, 86/87 and 88/86 sets were usually measured, but with some samples, e.g. the basalts listed in Table 26, the sequence was 88/86, 86/87, 88/86, 86/87 and 88/86. This gave duplicate measurements of 86/87 for each Sr separation.

The first and last 88/86 sets were a check on the mass fractionation during the run. The extra set of 88/86 introduced recently
allows a more precise interpolation of the mass fractionation to be made. Mass 85 (rubidium) was monitored before and after the set of 86/87 ratios to enable a correction to be made for the 87Rb contribution to the mass 87 beam. The Rb was burnt off before the run until the mass 85 beam was less than 3% of the 87 beam. This reduced the 87Rb contribution to the mass 87 beam to less than 1%. The error introduced by correcting for this Rb contamination increased significantly as the percentage of 87Rb rose above 1% of the total 87 mass. When the Rb contamination was below this limit, the measured (unspiked) and the calculated (single spiked) 87Sr/ 86Sr ratios usually agreed to within ± 0.0003 (standard deviation). Tail corrections in the strontium runs were made from the mass spectrum drawn at the end of each run.

Sr isotope ratios were normalised to 88/86 = 8.3752, and 87Sr/86Sr measurements on Eimer and Amend SrCO3 with the N.A.A. machine were 0.70813 ± 0.00015 (P.A. Arriens, pers. comm.).

1. d (iii) Precision of Rb-Sr measurements

The uncertainties in the slope and intercept of the total rock isochrons in this thesis are given at the 95% confidence level. The precision of measurement of the parameters 87Rb/86Sr and (87Sr/86Sr)p have been discussed by McIntyre et al. (1966), who also described the regression of the data based upon errors in both parameters. These authors quoted a variance of 0.22 x 10^-6 for the measurement of 87Sr/86Sr on unspiked samples, and 1.73 x 10^-6 for determinations on mixtures of sample and tracer. These estimates were based on
analyses made with the MS2 mass spectrometer, and, in the case of sample-tracer mixtures, a double tracer was used.

Analyses of unspiked and sample-single tracer mixtures with the N.A.A. machine suggest that a more realistic estimate of the variance of $^{87}\text{Sr}/^{86}\text{Sr}$ is $0.10 \times 10^{-6}$ for both types of analyses. The only restrictions on this estimate of variance are that the $^{87}\text{Rb}$ contribution to the total mass 87 beam is less than 1%, and that the drift in isotope ratios (mass fractionation), between the $^{88}/^{86}$ sets, is low (<0.1%). The errors introduced in correcting for $^{87}\text{Rb}$, and the interpolation between $^{88}/^{86}$ from beginning to end of the run are then minimised.

A variance of $0.22 \times 10^{-6}$ was used for the Maryborough Basin and Gayndah - Proston granites as most of the Sr analyses were made with double Sr spike. Also, these were the first measurements made by the writer and inexperienced operation of the mass spectrometer probably added, to some degree, to the uncertainties in the analyses. All other calculations of errors were made using $0.10 \times 10^{-6}$ for the variance in $^{87}\text{Sr}/^{86}\text{Sr}$. The variance of $^{87}\text{Rb}/^{86}\text{Sr}$ assumed by McIntyre et al. (1966), $25.51 \times 10^{-6}$, has been used in the present study.

The computer programme for the regression of the data (McIntyre et al., 1966), in the first stage, fits the best line and calculates the age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. If all variance is within experimental error, the mean square of weighted deviates (MSWD) is <$1$. When the MSWD > 1, a geological effect is presumed to be present and the calculation is repeated up to three times to allow
for variations in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and open system behaviour of samples. However, when MSWD > 1 it may be tested as a variance ratio for $(N - 2)$ and 34 degrees of freedom; $(N - 2)$ being the d.f. of the isochron and 34 the d.f. of the poorest estimate of variance (for $^{87}\text{Rb}/^{86}\text{Sr}$). If MSWD is less than "F" at the 5% level, then the model 1 calculation is accepted.

The data for most groups of rocks analysed in this project fit their respective isochrons to within experimental error. This not only supports the assumption that the samples had a common initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and that they have remained closed chemical systems with respect to Rb and Sr, but also justifies the lower variance placed on the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements.

The slopes and intercepts of two isochrons (A and B) are tested for statistical differences as follows:

\[ t(\text{calc.}) = \frac{|\text{grad. } A - \text{grad. } B|}{\sqrt{\left( \frac{\text{Std. } \text{grad. } A}{\text{Std. } \text{grad. } B} \right)^2 + \left( \frac{\text{Std. } \text{grad. } A}{\text{Std. } \text{grad. } B} \right)^2}} \]

The degrees of freedom, $K$, is given by the equation

\[ K = \frac{\left( \frac{\text{Std. } \text{grad. } A}{\text{Std. } \text{grad. } B} \right)^2}{N_A - 2} + \frac{\left( \frac{\text{Std. } \text{grad. } A}{\text{Std. } \text{grad. } B} \right)^2}{N_B - 2} \]

where $N$ is the number of samples.

If it is found that the slopes and intercepts of two isochrons are not significantly different then the data may be pooled to determine a common age and initial ratio for the two groups of samples.
1. e The Significance of Mineral Ages

When interpreting or comparing ages measured by different methods, or by the one method on different minerals, it is necessary to know what these "ages" represent. For the simplest model, that of a lava or a small pluton that has not been reheated, the age of a mineral will indicate the time at which the radiogenic daughter product began to be retained in the mineral. Experimental and field studies made on the conditions under which argon will diffuse from minerals (Evernden et al., 1960; Hart, 1964) have indicated that above about 300°C argon will be lost from mica as rapidly as it is generated. At 200°C, the diffusion rate is sufficiently low that no argon is lost during the relatively short time in which the extrusive and high level intrusive rocks cool from 200°C to surface temperature. The K-Ar mica age is therefore the time that has elapsed since the mineral cooled below about 200°C, and for rocks of pre-Tertiary age, this time is experimentally indistinguishable from that since extrusion or emplacement occurred. These values of temperature were derived by interpolation between temperatures used in short term laboratory studies, and the extrapolation of these data to deduce diffusion behaviour over long intervals of geological time may introduce a large uncertainty.

It is also assumed that the different activation energies and diffusion rates for argon in different minerals will lead to some minerals becoming closed systems, with respect to argon, at higher temperatures than for others. Thus, where cooling is slow, it
might be expected that cogenetic minerals will have distinctly different "ages". Conversely, when cooling is rapid, no such differences are expected and agreement in age between cogenetic minerals (most commonly biotite and hornblende) is usually accepted as an indication of rapid cooling and no subsequent thermal history.

Outgassing of radiogenic argon from minerals may occur by heating during regional or contact metamorphism. The effects of contact metamorphism are usually restricted to within a region of width equal to the diameter of the younger intrusion (Hart, 1964), where zones analogous to metamorphic isograds can be drawn showing the distances at which different minerals are completely outgassed of argon. Hart (1964) reported that under conditions of thermal metamorphism, hornblende retained significantly greater amounts of radiogenic argon than did biotite in the same rock. Aldrich et al. (1965) commented on the ability of hornblende to retain radiogenic argon under metamorphic conditions, and believed the age measured on this mineral to be equal to that measured by the Rb-Sr method on muscovite and K-feldspar. These authors concluded that in rocks that had undergone metamorphism, the normal order of increasing mineral age is (1) biotite, K-Ar; (2) biotite, Rb-Sr; (3) muscovite, K-Ar; (4) hornblende, K-Ar, muscovite and K-feldspar, Rb-Sr. Richards and Pidgeon (1963) also showed that muscovite has a higher argon retentivity than has biotite under metamorphic conditions. Thus, when hornblende or muscovite K-Ar dates are significantly higher than those of cogenetic biotite, the first assumption is that the rock has suffered a thermal
metamorphism.

Diffusive loss of radiogenic Sr can also occur, but in this case, the $^{87}$Sr may migrate into another mineral phase of the rock. While the Rb-Sr mineral ages may reflect the cooling or metamorphic history of the rock, the rock as a whole may have remained a closed system and indicate an age greater than that shown by some of its component minerals (Compston and Jeffery, 1959).

Although there appears to be little published information on laboratory investigations of the diffusion rates of $^{87}$Sr in biotite, the frequent correspondence between Rb-Sr and K-Ar ages on this mineral from all environments suggests that Sr diffuses at similar rates and at the same temperature as does Ar. From measurements made on biotites from the Alpine Fault Zone of New Zealand, Hurley, Hughes, Pinson et al. (1962) concluded that the diffusion coefficients for Sr and Ar in biotite are similar at low temperatures.

The ideal total rock age is determined on a suite of rocks with varying Rb/Sr ratios, which differentiated from an isotopically homogeneous parent magma. The age measured is the time of the homogenisation of the parental magma, and may be quite distinct from the time at which certain minerals in the differentiated fraction cooled to near surface temperatures. The difference between the two ages will depend to a large degree on the tectonic environment at the time and place of formation and intrusion of the magma. Volcanic and high level intrusive rocks would not be expected to reveal any significant
age difference between mineral and total rock determinations. However, in high grade metamorphic terranes, the difference may be considerable.

The sequence of increasing retentivity of radiogenic daughter isotope in different minerals proposed by Aldrich et al. (1965) may be taken as an approximation to the normal behaviour of these minerals, although departures from it are not uncommon. Arriens et al. (1966) described examples where the Rb-Sr and K-Ar biotite ages exceeded the Rb-Sr K-feldspar ages, and evidence will be given in a later section to show that under certain metamorphic conditions, the argon retentivities of biotite and hornblende are similar.
2. Regional Geology

After the Middle Devonian, the focus of sedimentation and vulcanicity in the Tasman Geosyncline shifted to northern New South Wales and eastern Queensland. This region remained the site of active deposition throughout the Upper Palaeozoic and into the Mesozoic. The present investigation deals with the area of eastern Queensland east of the Great Artesian Basin, between Townsville and the New South Wales border. In this area, five major depositional basins were formed upon a basement of deformed rocks of the Lower Palaeozoic Brisbane Eugeosyncline and Melbourne Miogeosyncline (Voisey, 1959). A general characteristic of the region is the north to northwesterly trend of many of the major structural components. The basins are shown in Figure 3, and the description of them and of the basement areas which follows is based upon the work of Hill (1960), Malone (1964), Malone et al. (1964, 1966), Maxwell (1960) and Veevers et al. (1964 a and b).

The Anakie High is composed of granites and pre-Devonian metamorphics. The main uplift occurred during the Upper Devonian, and it has probably remained a positive stable block ever since.

The Connors and Auburn Arches occupy similar structural positions, respectively, on the northeastern and southeastern sides of the Bowen Basin. They are both composed mainly of granites, which
Figure 3

STRUCTURAL ELEMENTS OF EASTERN QUEENSLAND

After HILL (1960) and MALONE (1964)
intrude volcanic rocks of unknown age. In the Connors Arch, the granites are known as the Urannah Complex, while in the Auburn Arch they form the Auburn Complex. Very little is known of the pre-Permian palaeogeography of the arches. The Connors Arch may have been in existence as a structural feature in the early Permian, when large thicknesses of andesites were deposited on the western side, and pyroclastics on the east. Only a thin veneer, if any, of the volcanics overlapped the arch except at the southern end. The arch subsided during the Lower Permian and commenced uplift in the Upper Permian. Further rejuvenation associated with faulting occurred more recently, perhaps in the Cretaceous or Tertiary.

Volcanics and sediments probably covered part of the northern Auburn Arch in the Lower Permian, and uplift occurred in the late Permian and early Triassic.

The region between the Connors and Auburn Arches is the **Gogango Overfolded Zone** (Malone, 1964). This contains at least one small area of Silurian-Devonian rocks, but most of the strata are devoid of diagnostic fossils, and may be Carboniferous and Permian. The rocks are isoclinally folded, and the current interpretation is that they are part of the Bowen-Yarrol Basin sequence deformed in the Permian or Mesozoic, and not part of an older basement.

The **South Coastal High** extends from Broad Sound to northern New South Wales. It is composed mainly of low grade metasedimentary and metavolcanic rocks, thought to be of pre-Devonian age.
Diagrammatic sketch showing relation of major rock units. Approx. 24° S lat.
It is possible that some areas included in this High are younger than Devonian but have been included because of their metamorphic texture. The High is intruded by numerous small granitic plutons, and by a large batholith in the southwestern area. Serpentinite bodies which are elongated in a north-south or N.N.W. - S.S.E. direction often occur in the fault zones along the western margin of the High. South of 26° S. latitude, the High has been divided longitudinally by the down faulting of the Esk Rift Valley in the late Permian or early Mesozoic.

Sedimentation commenced in the Drummond Basin in the Upper Devonian. The western region is now covered by Mesozoic sediments of the Great Artesian Basin, and the eastern margin is formed by the Anakie High. The High is composed of the Anakie Metamorphics which, in the central and southern region, are intruded by the Retreat Granite. Small pockets of fossiliferous Middle Devonian strata rest unconformably on the metamorphics, but the relationship between the Retreat Granite and these sediments is unknown. The sediments, granites and metamorphics are overlain unconformably by the Drummond Basin sequence.

In the southern region (Figure 4) the oldest strata in the Drummond Basin are volcanics. They are followed, possibly unconformably by continental sediments and volcanics which contain fish remains and plant fossils (Woods, Appendix 2 and White, Appendix 4, in Veevers et al., 1964 b). On the basis of this evidence, the age of the succession is Upper Devonian to Lower Carboniferous. The
Diagrammatic sketch showing relation of major rock units. Approx. 21° S lat.
strata were folded, and unconformably overlain by the Permian sediments of the Bowen Basin. The only known granitic intrusion within the Drummond Basin is an adamellite stock to the west of Anakie.

In the north (Figure 5) fossiliferous Upper Devonian marine sediments unconformably overlie Middle Devonian rocks on the eastern side of the Anakie High. Granites intrude the Middle Devonian strata and may also intrude the Upper Devonian. On the western side of the High the Middle Devonian sediments and the granites are overlain by freshwater sediments of the Drummond Group. The age of the Drummond Group, based on plant remains, is Lower Carboniferous. All of the units so far mentioned are overlain by the Upper Carboniferous Bulgonunna Volcanics, which are, in turn, intruded by granites. These granites and the Bulgonunna Volcanics are overlain by the early Permian volcanic rocks of the Bowen Basin.

The Yarrol Basin formed during the Middle Devonian and received marine sediments and volcanics during the Devonian, Carboniferous and Permian. It has a faulted eastern margin against (?) Lower Palaeozoic metamorphics of the South Coastal High. North of Marlborough, the western margin is formed by the Connors Arch, while in the south, the present western boundary is the granitic complex of the Auburn Arch. Between these two regions, the Lower Permian sediments of the Bowen Basin overlap the Yarrol Basin. During the Lower Permian, the two basins were probably joined throughout their length, inundating the Connors Arch, and part of the Auburn Arch.
Except for evidence of a faunal break during the Namurian, Maxwell (1960) believed sedimentation to have been almost continuous throughout the period from Middle Devonian to Lower Permian, although facies changes and shifts in the region of greatest deposition occurred. Unpublished work by geologists of the Bureau of Mineral Resources and the Geological Survey of Queensland suggest that this interpretation oversimplifies the geological history. Small granite plutons were intruded throughout the basin, cutting Devonian, Carboniferous and Permian sediments.

The Bowen Basin today is the area between the Anakie High in the west, the Auburn and Connors Arches in the east, and the Surat Basin in the south. The present western margin is probably close to the depositional margin of the basin, but the eastern margin has been obliterated by post-depositional folding, faulting and erosion. Deposition commenced in the early Permian in four subsiding and probably isolated regions. The Denison Trough, near Springsure (Figure 3), received predominantly terrestrial sediments, and as there was no subsequent igneous activity in the area until the Tertiary, no further reference will be made to this trough. Volcanics were deposited on the northern part of the Auburn Arch (Camboon Andesite) and in two basins on the eastern and western sides of the Connors Arch (Carmila Beds and Lizzie Creek Volcanics). The Lizzie Creek Volcanics were mainly andesitic, although on the more stable shelf area to the north-west, basalts were extruded. The Carmila Beds contain abundant pyroclastics, and interfinger with the Lizzie
Creek Volcanics at the southern end of the Connors Arch. The volcanism may have commenced as early as the Carboniferous, but the only palaeontological control is provided by interbedded marine sediments with an early Permian fauna high in each of the three volcanic units.

Marine sedimentation became more widespread during the remainder of the Lower Permian. The Connors Arch subsided and a large thickness of sediments was deposited in a trough which migrated slightly westward during the Lower Permian and the early Upper Permian. During this time the Bowen and Yarrol Basins were united. Paralic and freshwater sedimentation occurred on the shelf to the west, producing coal measures near Collinsville and Blair Athol. Early in the Upper Permian, subsidence occurred in the north of the Auburn Arch and the area of the Gogango Overfolded Zone. Spilitic lavas and immature sediments were deposited, and ultramafic rocks emplaced. The formations deposited during the late Lower Permian and early Upper Permian comprise the Back Creek Group.

After the early Upper Permian, sedimentation was predominantly non-marine. Uplift along the line of the Connors and Auburn Arches may have isolated much of the Bowen Basin area from the sea. No sediments of this age have been found in the Gogango Overfolded Zone. The depositional trough persisted in the north, while to the west and south, sedimentation occurred in fluviatile and lacustrine environments. The sediments comprise the Blackwater Group, the lower part of which is predominantly clastic and contains widespread beds of volcanic ash. The
upper part of the Blackwater Group contains coal measures, which are widely distributed throughout the basin.

A lithologic and perhaps climatic change occurred at the close of the Permian, and the coal measures pass conformably into the red beds of the Rewan Formation. This unit probably marks the transition from the Permian to the Triassic. At this time uplift of the Auburn Arch continued and a new basin, the **Mimosa Syncline**, was superimposed on the southern end of the Bowen Basin to the west of the Auburn Arch. The syncline contains a Lower to possibly Upper Triassic sequence of freshwater sediments. Similar rocks occur in the central part of the Bowen Basin and may once have been continuous with the sediments of the Mimosa Syncline. Sedimentation ceased in the Middle to Upper Triassic, and the strata of the Bowen Basin were unconformably overlapped in the Lower Jurassic by sandstones of the Great Artesian Basin.

The Permian sequence is rarely complete in any one region, but no major angular unconformities have been recognised within the succession. The main depositional trough, in the east, moved slowly westward throughout the Permian, while in the marginal or platform areas west of the trough, the seas transgressed and retreated at irregular intervals. The movement of the trough westward was probably accompanied by uplift in the Connors Arch, bringing about the change from marine to lacustrine conditions in the Upper Permian. A similar uplift in the Auburn Arch in the late Permian was thought to have initiated the downwarp of the Mimosa Syncline and produced its asymmetrical shape. It has been suggested that granitic intrusion in this area accompanied the uplift.
The strata of the Bowen Basin may have been subjected to more than one period of deformation, e.g. Malone (in prep.) suggests that folding occurred in the Upper Permian and Lower Cretaceous. The most intense deformation occurred in the areas of thickest sedimentation, and involved Permian and older strata. The Triassic sandstones in the central part of the basin are relatively undeformed.

Minor granitic intrusions within the basin invade the folded Permian sequence, and dykes cut the Triassic strata.

The Maryborough Basin occupies an area approximately 120 miles long and exceeding 60 miles in width. The western margin is formed by the Lower Palaeozoic rocks of the South Coastal High, and on this basement the earliest (Lower Permian) sediments were deposited. The strata of the basin become progressively younger eastwards, and the eastern margin of the basin is interpreted from geophysical data to be a shallow platform east of the present coastline (Ellis, 1966). Marine sedimentation in the Lower Triassic was followed by terrestrial deposition that may have continued into the Middle Triassic. Continental sedimentation commenced again at the end of the Triassic, or in the early Jurassic. During this period, coal measures were deposited. Volcanism began at the end of the Jurassic, and continued into the early Cretaceous. In the Aptian, marine conditions returned for a short period and following the withdrawal of the seas, coal measures were formed. This was the final phase of deposition in the Mesozoic.

Major breaks in sedimentation occurred between the Permian and Lower Triassic and during the Middle to Upper Triassic. A disconformity occurs
below the Aptian sequence. Folding movements probably accompanied each of these sedimentary breaks, and strong folding occurred in post-Aptian times. Bryan (1925) suggested that the Cretaceous folding may have been the most intense one, not only in the Maryborough Basin but in the whole of eastern Queensland. The Permian and Triassic rocks have been intruded by granites, and the Jurassic coal measures are cut by hypabyssal intrusions (Bryan and Massey, 1925; Evernden and Richards, 1962).

The Esk Rift Valley formed by foundering of the central part of the South Coastal High. The upthrown blocks on the east and west of the Rift are, respectively, the D'Aguilar and Yarraman Blocks. It has been suggested (Hill, 1960 p.273) that the eastern margin of the Rift may have originated as early as the Devonian. Movement occurred in the late Permian or early Triassic, forming a depositional area which received Triassic volcanics and sediments. The large volume of volcanic boulder beds was probably produced from centres along this zone of faulting. Later movements, perhaps in the Upper Triassic, truncated folds in the Middle Triassic strata, and developed the configuration of the Rift as seen today. Narrow wedges of Permian strata have been downfaulted on each side of the Rift, and on the west are intruded by granites (Campbell, 1951).

**Intrusive rocks**

Rocks of dioritic to granitic composition are abundant throughout eastern Queensland, and although granodiorites predominate, the term "granite" will be used in this thesis to cover plutonic rocks of acid
to intermediate composition. Small intrusions are found in all of the sedimentary basins, but the greatest volume of plutonic rock occurs in large batholiths in the marginal areas of the basins.

The granites of the southern part of the Anakie High received little attention before the work of Veevers et al. (1964 b). These workers showed the granites to be unconformably overlain by Upper Devonian sediments, and preliminary K–Ar dating (Webb et al., 1963) indicated a Middle to Upper Devonian age for the intrusions (on the basis of the Devonian–Carboniferous boundary being 345 m.y. old).

In the north, in the Ukalunda–Mt Wyatt area, two phases of intrusion were recognised; one was early and the other late in the Carboniferous (Malone et al., 1966). Thus, in the western region, the ages of the granites are reasonably well controlled by stratigraphic evidence.

The large batholith in the Connors Arch extends from Bowen almost to St Lawrence. Gradwell (1960) tentatively suggested a Permian or older age for these granites. Later field work (Malone et al., 1966) indicated the existence of pre-Permian intrusions, but the extent of these granites was not known with any degree of certainty. Isotopic dating (Webb and McDougall, 1964) has shown that Lower Cretaceous granites are also present.

Igneous rocks in the Auburn Arch are known to intrude Permian strata, but large areas of granites of unknown age occur.

In southeastern Queensland, numerous granitic intrusions are found cutting the Lower Palaeozoic metamorphics in the South Coastal High, and in some places they invade Permian (Campbell, 1951) and
Triassic rocks (Jones, 1947). In the Maryborough Basin the granites intrude Mesozoic sediments.

2. b Previous attempts to date the granites of coastal Queensland

Gradwell (1960, p. 245) recognised the problem of dating the granites of the coastal belt, from Bowen to Brisbane, and stated that "in summarising the literature on the granitic rocks of Queensland of Permian to Triassic age, one is struck by the fact that so little is known from geological evidence as to the age of emplacement of these rocks". Thus, while acknowledging the lack of direct evidence on the age of the granites, he accepted the popular view that they were Permian or Triassic. The approach to this problem has been largely intuitive. The age of emplacement of the granites has been deduced from scattered field observations coupled with an interpretation of the relationship between plutonism and tectonism in the area.

The contacts between the larger batholiths and the basin sediments and volcanics are frequently obscured by Tertiary volcanics, laterites, or areas of no outcrop. Even within the sedimentary basins, the stratigraphic control on the age of the intrusions is poor. The granites invade rocks of Devonian, Carboniferous, Permian and Triassic age, and frequently there are no overlying strata to provide a younger age limit.

The texture of the intrusive rocks and the fabric of the surrounding country rocks have played an important part in assigning ages to the granites. A few occurrences of gneissic rocks have been
tentatively placed in the Precambrian, e.g. at Normanby (Jones, 1947)
and in the Auburn Complex (Hill, 1960, p. 11), because of indications
of strong metamorphism. However, most of the granites in eastern
Queensland either have only a weak primary lineation or are completely
massive and homogeneous. There is no evidence of any large scale
assimilation of the country rocks, and the contacts where they can be
observed, are sharp. Thermal effects are generally slight; minera-
logical changes do not occur on a macro scale, although the country
rocks may be indurated several thousand feet from the contact. As the
country rocks are frequently folded while the granites are massive,
the intrusions have been termed post-tectonic.

Reid (1930) observed the coincidence of the area of outcrop of
the granites, from Townsville to New South Wales, with the region of
folded Upper Palaeozoic rocks, and noted that the Mesozoic strata
were mainly undisturbed. He suggested, therefore, that the intrusive
activity was related to the cessation of the folding, which he placed
in the late Permian.

Carey and Browne (1938) came to a similar conclusion after
studying the Upper Palaeozoic sequence in northern New South Wales.
They believed the strata to have been folded during the late Permian,
and named this diastrophism the Hunter-Bowen Movement. The granites
were thought to have accompanied this movement. This view has become
generally accepted by Australian geologists although Jones (1947)
extended the period of intrusive activity to the Middle Triassic after
the discovery of a granite intruding Lower Triassic strata at Monsildale.
The granites of the Maryborough Basin had been excluded from this proposed Palaeozoic magmatism because they had been thought to have accompanied a late Cretaceous orogeny (Bryan, 1925). Ridley (1960 a, b) suggested an Upper Jurassic age for the granites, but isotopic dating has shown them to be Middle Triassic (Webb and McDougall, 1967).

Thus, attempts to date many of the intrusions have been subjective, and the conclusions have been dependent upon the individual's view of the connection between tectonism and magmatism, and the assumed age of the tectonism. Widely divergent opinions on this latter problem have been held by Bryan (1925) and by Reid (1930) and Carey and Browne (1938). The application of isotopic dating methods to the granitic rocks has afforded the first opportunity of determining the age of many of the intrusions. This investigation has confirmed some of the deductions of earlier workers, while in other instances it has shown large differences in times of intrusion that had not previously been suspected.
CHAPTER 3

THE TIME SCALE

3. a Introduction

One of the aims of the present study was to determine the ages of emplacement of plutonic rocks which often lacked any form of stratigraphic control. The position of these rocks in the stratigraphic column could then be found by correlation with isotopic ages measured on palaeontologically dated rocks. As an aid to this correlation, numerous attempts have been made to measure the isotopic ages of rocks within the stratigraphic column, but many uncertainties and long intervals with no control still remain. The paucity of data is very evident in the Upper Permian and Triassic, where there are no reliable isotopic dates on any rock in the sedimentary succession between the extrusion of the Gerringong Volcanics (early Upper Permian) in New South Wales 250 million years ago (Evernden and Richards, 1962), and the intrusion of the Palisades diabase with its presumably consanguinous extrusives in the Upper Triassic of North America 195 million years ago (Erickson and Kulp, 1961).

Kulp (1961) by "linear interpolation" from the date of the Upper Triassic Palisades diabase, derived an age of $230 \pm 10$ m.y. for the base of the Triassic. Smith (1964), using dates on intrusive rocks from New South Wales (Evernden and Richards, 1962; Cooper et al., 1963), suggested an age of $225 \pm 5$ m.y. for the Permian - Triassic
boundary. Following David (1950), Smith assumed that the granitic intrusions accompanied, or closely followed phases of a Permian orogeny, and that they preceded the deposition of the Triassic coal measures. The intrusion of the youngest dated granites (220 m.y.) was correlated with a stratigraphic break below the Triassic continental sediments, although the oldest strata known to overlie the granites are of Lower Jurassic age.

Polevaya et al. (1964) recommended considerable changes to the accepted ages for the divisions of the Triassic. They reported K-Ar ages on igneous rocks from Vietnam which indicated an age of $238 \pm 20$ million years for intrusions of pre-Triassic or Lower Triassic age, and $210 \pm 10$ million years for Upper Triassic (pre-Norian) intrusions. (These results have been recalculated using the potassium decay constants quoted in Chapter 1. a). K-Ar and Rb-Sr dating of igneous rocks from the Esk Rift Valley and the Maryborough Basin of southeastern Queensland, and from the southeastern part of the Bowen Basin (Chapters 3. b and c) support the conclusions of these authors.

3. b. Permian

The Upper Permian sequence in the southeastern part of the Bowen Basin is described by Mollan et al. (in prep.). The Blackwater Group conformably overlies a marine sequence (the Back Creek Group) which has faunas which range in age from Artinskian to Kazanian; and is conformably overlain by the Rewan Formation which transgresses the
### Table 3

Stratigraphic correlations in southeastern Queensland

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>IPSWICH BASIN</th>
<th>ESK RIFT</th>
<th>BRISBANE - N.COAST</th>
<th>MARYBOROUGH BASIN</th>
</tr>
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<tbody>
<tr>
<td>L. JURASSIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RHAETIC</td>
<td>Marburg Sst. 4</td>
<td>Wivenhoe Sst. 5</td>
<td>Landsborough Sst. 7</td>
<td></td>
</tr>
<tr>
<td>NORIAN</td>
<td>Bundamba Sst. 2</td>
<td>Somerset Dam Gabbro</td>
<td></td>
<td>Myrtle Creek Sst. 8</td>
</tr>
<tr>
<td>KARNIAN</td>
<td>Ipswich Coal Measures</td>
<td>Brisbane Valley 5</td>
<td></td>
<td>Granites 9</td>
</tr>
<tr>
<td>LADINIAN</td>
<td></td>
<td>Porphyrites</td>
<td></td>
<td>Neurum Tonalite 6</td>
</tr>
<tr>
<td>ANISIAN</td>
<td></td>
<td>Esk Beds 5</td>
<td></td>
<td>Brooweena Fmn. 8</td>
</tr>
<tr>
<td>M. TRIASSIC</td>
<td></td>
<td>Neara Volcanics 5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. TRIASSIC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

References:
1. Tillyard and Dunstan (1923)
2. de Jersey (1964)
3. Jones and de Jersey (1947)
4. de Jersey (1963)
5. Hill (1960)
6. Ridley (1958)
7. de Jersey and Paten (1963)
8. Bryan and Massey (1925)
9. Ellis (1966)
Permian-Triassic boundary. The Group consists of the Gyranda Formation and the overlying Baralaba Coal Measures. A biotite bearing tuff occurs at the top of the Gyranda Formation and K-Ar measurements on the biotite given in Table 4 indicate an age of 240 million years for this mineral. The biotite is fresh and euhedral, and appears not to be detrital. It is fresher than any biotite seen in the Carboniferous granites in this region, and there is no other obvious source of detrital biotite which is older than the tuff. The upper formations of the Back Creek Group can be equated on marine fossil evidence with the Gerringong Volcanics, for which Evernden and Richards (1962) reported an age of 250 m.y. This date is in good agreement with the 240 m.y. age for the top of the Gyranda Formation.

3. c Triassic

A summary of the stratigraphic correlations of the early Mesozoic strata in southeastern Queensland is given in Table 3.

The Esk Rift Valley

The Esk Rift Valley (Hill, 1960) contains a folded conformable sequence of terrestrial rocks - the Narea Volcanics and the overlying Esk Beds - unconformably overlain by the Wivenhoe Sandstone. The Narea Volcanics are intruded by the Somerset Dam Gabbro, and the Esk Beds are intruded by swarms of dykes - the Brisbane Valley Porphyrites (Hill, 1930). Zimmerman (unpublished M.Sc. thesis, University of Queensland, 1956) and in Hill (1960) believed the dykes
## Table 4

K/Ar Ages of Stratigraphically Controlled Rocks

<table>
<thead>
<tr>
<th>GA No.</th>
<th>Mineral</th>
<th>4K</th>
<th>Ave.K</th>
<th>4Ar*4K</th>
<th>4Ar ATM</th>
<th>Age M.Y.</th>
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</thead>
<tbody>
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<td><strong>Gyrranda Formation</strong></td>
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<tr>
<td>5562</td>
<td>Biotite</td>
<td>6.754</td>
<td>6.75</td>
<td>(1)0.01489</td>
<td>2.3</td>
<td>239</td>
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<tr>
<td></td>
<td></td>
<td>6.734</td>
<td></td>
<td>(2)0.01488</td>
<td>2.6</td>
<td>239</td>
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<tr>
<td><strong>Somerset Dam Gabbro</strong></td>
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<tr>
<td>5315</td>
<td>Hornblende</td>
<td>0.5015</td>
<td>0.5023</td>
<td>(1)0.01232</td>
<td>14.0</td>
<td>213</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(2)0.01331</td>
<td>11.6</td>
<td>215</td>
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<tr>
<td>5323</td>
<td>Plagioclase</td>
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<td>(1)0.01276</td>
<td>42.8</td>
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<td></td>
<td></td>
<td>(2)0.01288</td>
<td>69.4</td>
<td>208</td>
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<td><strong>Porphyrite Dykes</strong></td>
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<td>5324</td>
<td>Hornblende</td>
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<td>218</td>
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<td></td>
<td></td>
<td>(2)0.01358</td>
<td>19.5</td>
<td>219</td>
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<tr>
<td><strong>Maryborough Basin Granites</strong></td>
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<td>1217</td>
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<td>7.09</td>
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<td></td>
<td></td>
<td>7.105</td>
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<td>5297</td>
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<td>6.85</td>
<td>0.01346</td>
<td>3.3</td>
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<td></td>
<td>6.856</td>
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<td>6.5794</td>
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<td></td>
<td></td>
<td>6.858</td>
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(Continued)
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE.K</th>
<th>40AR*/40K</th>
<th>VAR ATM.</th>
<th>AGE M.Y.</th>
</tr>
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<tbody>
<tr>
<td>5317</td>
<td>BIOTITE</td>
<td>6.117</td>
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<td>6.153</td>
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<td>BIOTITE</td>
<td>5.804</td>
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<td>5.907</td>
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<td>5321</td>
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<td>9.5</td>
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<td></td>
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<td>7.445</td>
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<td>5325</td>
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<td>6.764</td>
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<td></td>
<td>HORNBLENDE</td>
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<td>0.291</td>
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<td>BIOTITE</td>
<td>7.206</td>
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<td></td>
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<td>7.210</td>
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<td></td>
<td>7.592</td>
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</table>
to have been intruded immediately after the folding of the Esk Beds, but the time relationship between the intrusions and the Wivenhoe Sandstone has never been conclusively determined.

The Esk Beds have been equated with the lower part of the Ipswich Coal Measures on lithological correlations (Hill, 1929), and the approximate equivalence of the two units has been supported by macro-floral evidence (Jones and de Jersey, 1947). Determinations of the age of the Ipswich Coal Measures have been made by three independent palaeontological studies.

(1) Tillyard and Dunstan (1924) described insect species from the top of the Coal Measures, and placed their age as Upper Triassic, and not younger than Rhaetic. (The Rhaetic is taken, in this thesis, to represent the uppermost part of the Triassic, although it is acknowledged that there may be equally strong evidence for placing it in the Jurassic.)

(2) Jones and de Jersey (1947) studied the macro-flora of the Ipswich Coal Measures and the Esk Beds, and compared them with the Hawkesbury and Wianamatta floras of the Sydney Basin, and with those of the Upper Beaufort and Molteno Beds of South Africa. They concluded that the floras most probably indicated a Middle Triassic age.

(3) On the basis of spore and pollen evidence, de Jersey (1964) assigned the Ipswich Coal Measures to the Ladinian - Karnian, i.e. Middle to Upper Triassic.

The Wivenhoe Sandstone has been correlated with both the Bundamba Sandstone and the Marburg Sandstone (Hill, 1960), the ages of these formations being respectively Upper Triassic (Karnian-Norian).
(de Jersey, 1964) and Lower Jurassic (de Jersey, 1963). Thus, the widest probable limits on the age of the porphyrite dykes are Middle Triassic to Lower Jurassic.

K-Ar ages determined on minerals from the Somerset Dam Gabbro and the Brisbane Valley Porphyrites are listed in Table 4 and indicate a minimum age of 215 to 220 million years for the Middle Triassic strata of the Esk Rift.

The Maryborough Basin

The Maryborough Basin contains rocks which range in age from Permian to Cretaceous (Hawthorne, 1960). The Triassic sequence was subdivided by Bryan and Massey (1925) into the Brooweena Formation and the overlying Myrtle Creek Sandstone. The older formation was thought to be entirely terrestrial, and was correlated with the Ipswich Coal Measures on lithological similarities and scant floral evidence. The recent discovery of a marine fauna near the base of the Brooweena Formation (Denmead, 1964) has provided support for a Lower to Middle Triassic age for this unit. The Myrtle Creek Sandstone was equated with the Bundamba Sandstone on lithological grounds, but there is no palaeontological control on its age. Other sandstones in eastern Queensland were once correlated with the Bundamba Sandstone but where spore and pollen evidence has been found, these formations have been shown to be younger than the Bundamba Sandstone in the type locality (de Jersey, 1964). Similarly, the correlation of the Myrtle Creek and Bundamba Sandstones may not be valid.

Bryan and Massey (1925) and Ridley (1960 a) reported that both
the Brooweena Formation and the Myrtle Creek Sandstone are cut by small granitic plutons. Ellis (1966) after a re-examination of the area described by Bryan and Massey, believes that the older unit, only, is intruded by granites, and from regional mapping has shown that an unconformity separates the two units.

Another intrusion in this region, the Neurum Tonalite (GA 1217), is overlain by the Landsborough Sandstone (Ridley, 1958), part of which, at least, is of Lower Jurassic age (de Jersey and Paten, 1963).

If it is assumed that the granites in this region are all of the same age, then they can be placed within the following stratigraphic limits.

(i) They are younger than the Brooweena Formation (Lower to Middle Triassic).

(ii) They are older than the Landsborough Sandstone (Lower Jurassic).

(iii) Their age relative to that of the Myrtle Creek Sandstone is uncertain.

Rb-Sr total rock and K-Ar mineral ages were measured on a number of granites from within the Basin and along the western margin. The analytical data are listed in Tables 4 and 5 and an isochron plot of the Rb-Sr data is shown in Figure 6. All variance in the Rb-Sr data can be attributed to experimental error. The age of $218 \pm 16$ m.y. is identical with the mean K-Ar age of $217 \pm 1.5$ m.y.

The conclusions are dependent upon the accuracy of the palaeontological and stratigraphical determinations, but the data from both the Esk Rift and the Maryborough Basin indicate that at
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>Rb PPM</th>
<th>Sr PPM</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>87Sr/86Sr* AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5314</td>
<td>TOTAL ROCK</td>
<td>170.9</td>
<td>220.8</td>
<td>2.228</td>
<td>0.7110</td>
<td>0.7101</td>
</tr>
<tr>
<td>5318</td>
<td>TOTAL ROCK</td>
<td>120.4</td>
<td>285.6</td>
<td>1.217</td>
<td>0.7076</td>
<td>0.7077</td>
</tr>
<tr>
<td>5320</td>
<td>TOTAL ROCK</td>
<td>141.8</td>
<td>117.4</td>
<td>3.478</td>
<td>0.7160</td>
<td>0.7146</td>
</tr>
<tr>
<td>5321</td>
<td>TOTAL ROCK</td>
<td>131.7</td>
<td>159.2</td>
<td>2.381</td>
<td></td>
<td>0.7115</td>
</tr>
<tr>
<td>5325</td>
<td>TOTAL ROCK</td>
<td>73.1</td>
<td>419.0</td>
<td>0.502</td>
<td></td>
<td>0.7051</td>
</tr>
<tr>
<td>5501</td>
<td>TOTAL ROCK</td>
<td>152.8</td>
<td>54.9</td>
<td>8.026</td>
<td>0.7297</td>
<td>0.7295</td>
</tr>
<tr>
<td>5501</td>
<td>TOTAL ROCK</td>
<td>151.9</td>
<td>54.3</td>
<td>8.075</td>
<td>0.7294</td>
<td></td>
</tr>
</tbody>
</table>

* DENOTES MEASURED RATIO.
least part of the Middle Triassic is older than 220 million years. The narrowest possible limits on this age are Karnian to Norian, and both these and the wider limits of Middle Triassic to Lower Jurassic are in agreement with the conclusions of Polevaya et al. (1964) that the early Upper Triassic is $210 \pm 10$ million years old. The age of the base of the Triassic is considered to be $230 - 235$ million years.

The ages adopted for the sections of the geological time scale referred to in this work are set out in Table 6.

TABLE 6

<table>
<thead>
<tr>
<th>Boundary</th>
<th>Age (in millions of years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oligocene - Miocene boundary</td>
<td>26 m.y. (Funnell, 1964)</td>
</tr>
<tr>
<td>Jurassic - Cretaceous boundary</td>
<td>135 m.y. (Casey, 1964)</td>
</tr>
<tr>
<td>Middle to Upper Triassic</td>
<td>220 m.y. (This thesis, Chapter 3c)</td>
</tr>
<tr>
<td>Permian - Triassic boundary</td>
<td>230-235 m.y. (This thesis, Chapter 3b)</td>
</tr>
<tr>
<td>Carboniferous - Permian boundary</td>
<td>280 m.y. (Francis and Woodland, 1964)</td>
</tr>
<tr>
<td>Devonian - Carboniferous boundary</td>
<td>363 m.y. (McDougall et al., 1966)</td>
</tr>
</tbody>
</table>
CHAPTER 4

INTERPRETATION OF RESULTS

4. a Geological Interpretation

4. a (i) Introduction

K-Ar mineral ages have been measured on granitic rocks throughout eastern Queensland, and a smaller number of Rb-Sr total rock and mineral ages were determined on granites and volcanics from selected regions. The analytical data are presented in Tables 4-22 and 27.

The K-Ar ages indicate two major epochs of granitic emplacement, the older one covering a time interval of 150 million years from the Devonian to the Triassic, and the younger one being of about 15 million years duration in the Lower Cretaceous. Within the older magmatic epoch, a histogram of the K-Ar "ages" would reveal several apparent maxima of intrusive activity, the time interval between many of these maxima being just greater than the expected experimental error of the K-Ar method. The agreement in age between cogenetic minerals increases the credibility that the peaks of K-Ar dates record phases of igneous activity. These apparent episodes occurred at 360, 305, 285, 270, 250, 235, and 220 million years ago, some of the phases occurring in several widely separated areas, and many of them in the one area. In the Lower Cretaceous, the K-Ar dates indicate two phases of granitic intrusion at 125 and 110 - 115 million years ago.

The Rb-Sr data suggest that this interpretation of the geological history may be too complex, and that some of the apparent intrusive
phases recorded by the K-Ar dating are probably the result of loss of radiogenic argon; e.g. in the Connors Arch, where the K-Ar dating indicates episodes of intrusion at 305, 285, and 270 million years, the Rb-Sr analyses show that the 285, and many of the 270 m.y. granites were part of the 305 - 310 m.y. period of intrusion. The wide extent of this phase has become more apparent, while the 270 m.y. phase, which on the K-Ar evidence was extremely widespread, has been reduced considerably.

Nevertheless, there may have been as many as seven periods of intrusion during the older epoch of magmatic activity, the most widespread occurring during the Upper Carboniferous and the Upper Permian. The former may be correlated with granitic intrusions in New South Wales (Evernden and Richards, 1962) and possibly in north Queensland (Richards, et al., 1966), while the latter extended from Marlborough to the New England district of New South Wales, (Evernden and Richards, 1962; Cooper et al., 1963; Binns and Richards, 1964). These intrusive events were probably related to the two major tectonic phases of the Upper Palaeozoic: the Kanimbla and the Hunter - Bowen Orogenies.

The intrusions become younger from west to east. Some overlapping is known to occur, but there is a general progression from Devonian granites in the Anakie High through Carboniferous and Permian to Triassic intrusions in the east. The Cretaceous granites transgress the older intrusions and are the most marked departure from the northeasterly trend of igneous activity with time noted e.g. by David (1950) and Evernden and Richards (1962).
The western boundaries of the regions of Upper Permian and Middle Triassic intrusions appear to be remarkably sharp (Figure 15), although older intrusions are known to occur to the east of these boundaries, e.g. the Devonian granites at Mount Morgan within the Upper Permian limits, and the pre-Triassic granite at Kilkivan (Denmead, 1945) east of the Middle Triassic limit. The Triassic boundary coincides with a marked structural feature. West of Brisbane, the Esk Rift separates the Triassic granites on the east from the Palaeozoic granites to the west. The eastern margin fault system of the Esk Rift is collinear with the Perry Fault to the north west, and this lineament forms the western boundary of the area of Triassic intrusions between Biggenden and Mount Perry. The structural control appears to end here, because although this trend, if continued, would link up with the fault system of the eastern margin of the Yarrol Basin, Triassic granites have been found in the basin to the west of this fault.

This work has also indicated or confirmed the close association between granitic intrusion and acid to intermediate volcanism in the Upper Carboniferous, Lower Permian and Lower Cretaceous. This is well illustrated by the Bulgonumma Volcanics and the granites that intrude them. The Rb-Sr ages of these two units, and their initial Sr isotopic composition, are identical to within experimental error, suggesting a common source for these rocks.

The granites and volcanics throughout the area had a low and reasonably consistent $^{87}\text{Sr}/^{86}\text{Sr}$ value at the time of their formation. This value, 0.7035 - 0.7055, is comparable with that measured on many
present day basalts, and indicates a possible sub-crustal origin for the igneous rocks.

These results will be considered in more detail in the following sections.

4. a (ii) Devonian

Granites were emplaced during the Upper Devonian in the Anakie High and at Mt Morgan. In the Anakie High, the Retreat Granite intrudes the Anakie Metamorphics, and a single K-Ar date on a muscovite from the metamorphics (GA 1040, Table 7) indicates a minimum age of 450 m.y. for the final phase of metamorphism of this sample. Fourteen measurements on the Retreat Granite (Table 7) have a mean of 359 ± 2 m.y. Included in Table 7 are published data (Webb et al., 1963) and remeasurements on GA 399. The granite is unconformably overlain by volcanics and sediments of the Drummond Basin, the oldest units being probably of Upper Devonian age (Veevers et al., 1964 b). This suggests that the K-Ar ages may be too young, if 363 m.y. is taken as the age of the Devonian – Carboniferous boundary.

Mount Morgan lies within the Yarrol Basin, and is included in the area of folded Upper Palaeozoic rocks defined by Reid (1930). The oldest fossiliferous strata in the Mt Morgan district, the Dee Volcanics of Middle Devonian (Givetian) age (Maxwell, 1953, 1960), are reported to be intruded by the Mt Morgan Granite. Five K-Ar ages measured on hornblende from the Mt Morgan and Town Granites (Table 7) have an average age of 362 m.y., and are therefore late Devonian (McDougall,
TABLE 7

K/Ar Ages of Pre-Devonian and Devonian Rocks

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE. K</th>
<th>40Ar*/40K</th>
<th>% AR ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>399</td>
<td>BIOTITE</td>
<td>7.104</td>
<td>7.09</td>
<td>(1) 0.02265</td>
<td>7.5</td>
<td>353</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.074</td>
<td>400</td>
<td>BIOTITE</td>
<td>7.118</td>
<td>7.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.098</td>
<td>0.7266</td>
<td>0.726</td>
<td>0.02304</td>
<td>10.8</td>
</tr>
<tr>
<td>401</td>
<td>BIOTITE</td>
<td>7.269</td>
<td>7.28</td>
<td>0.02357</td>
<td>3.6</td>
<td>366</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.285</td>
<td>0.7348</td>
<td>0.734</td>
<td>0.02366</td>
<td>11.5</td>
</tr>
<tr>
<td></td>
<td>HORNBLENDE</td>
<td>0.7251</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>402</td>
<td>BIOTITE</td>
<td>6.708</td>
<td>6.72</td>
<td>0.02238</td>
<td>5.5</td>
<td>349</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.731</td>
<td>0.5735</td>
<td>0.576</td>
<td>0.02290</td>
<td>14.9</td>
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<td>HORNBLENDE</td>
<td>0.5777</td>
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</tr>
<tr>
<td>1024</td>
<td>BIOTITE</td>
<td>7.169</td>
<td>7.16</td>
<td>0.02339</td>
<td>2.4</td>
<td>363</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.152</td>
<td>402</td>
<td>BIOTITE</td>
<td>6.284</td>
<td>6.29</td>
</tr>
<tr>
<td></td>
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<td>6.305</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>1025</td>
<td>BIOTITE</td>
<td>7.279</td>
<td>7.25</td>
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</tr>
<tr>
<td></td>
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<td>7.227</td>
<td>402</td>
<td>BIOTITE</td>
<td>6.331</td>
<td>6.34</td>
</tr>
<tr>
<td></td>
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<td>6.339</td>
<td></td>
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</tr>
<tr>
<td>1026</td>
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<tr>
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<td>HORNBLENDE</td>
<td>0.6358</td>
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(CONTINUED)
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>$^8$K</th>
<th>AVE.$^8$K</th>
<th>$^{40}$Ar/$^{39}$Ar</th>
<th>$^{39}$Ar ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
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<td>1028</td>
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<td></td>
<td></td>
<td>6.743</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MT MORGAN GRANITE</td>
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<tr>
<td>5339</td>
<td>HORNBLende</td>
<td>0.2920</td>
<td>0.291</td>
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<td>23.9</td>
<td>360</td>
</tr>
<tr>
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<td></td>
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<tr>
<td>5360</td>
<td>HORNBLende</td>
<td>0.3896</td>
<td>0.389</td>
<td>0.02295</td>
<td>21.7</td>
<td>357</td>
</tr>
<tr>
<td></td>
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<tr>
<td>5370</td>
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<td>0.02351</td>
<td>31.1</td>
<td>365</td>
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<td>0.3608</td>
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<tr>
<td>5371</td>
<td>HORNBLende</td>
<td>0.4146</td>
<td>0.415</td>
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<td>5372</td>
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<td>0.0966</td>
<td>0.02306</td>
<td>60.5</td>
<td>358</td>
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<td>0.0964</td>
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<td>ANAKIE METAMORPHICS</td>
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</tr>
<tr>
<td>1040</td>
<td>MUSCOVITE</td>
<td>7.835</td>
<td>7.83</td>
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<td>458</td>
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<td></td>
<td>7.822</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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</table>
et al., 1966). This agrees with the published information on the geology of the area. However, Kirkegaard et al. (in prep.) believe the Mt Morgan Granite to be overlain by Upper Devonian (Frasnian) sediments, thereby placing extremely narrow limits on the age of the granite. I.M. Paltridge (pers. comm.) has found granite pebbles similar to the Mt Morgan Granite in rocks which have been mapped as Dee Volcanics. It appears therefore that there are divergent views on the relationship of the granite to the surrounding strata, and an evaluation of the K-Ar ages is difficult. If the age of the Devonian-Carboniferous boundary is 363 m.y., and if no argon loss has occurred from the samples analysed, then the granite can not be overlain by Frasnian sediments; similarly, it can not be old enough to have provided the pebbles in the Dee Volcanics.

Plutonic rocks of Devonian age, in the zone of folded Upper Palaeozoic strata, appear to be restricted to the area about Mt Morgan. Granitic rocks within 25 miles to the north and south of the town are of Upper Permian age (Chapter 4. a (v)). In spite of the folding that has occurred in the region since the Devonian, the granite at Mt Morgan shows no signs of having lost radiogenic argon from this cause.

4. a (iii) Carboniferous Western region (Anakie High)

Granitic rocks of Devonian to Carboniferous age have been mapped in the Mt Wyatt area in the north of the Anakie High (Malone et al., 1966, and Figures 3, 5). They are known to intrude the Middle Devonian,
### Table 8

**K/Ar Ages of Northern Anakie High Granites**

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>40Ar/K</th>
<th>40Ar/39Ar</th>
<th>39Ar ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>4Ar/39Ar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>4Ar/39Ar</td>
<td></td>
<td>4Ar/40Ar</td>
<td>39Ar ATM.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>39Ar ATM.</td>
<td>AGE M.Y.</td>
<td></td>
<td></td>
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</tbody>
</table>

#### Devonian / Carboniferous Granites

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>4Ar/39Ar</th>
<th>39Ar ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1160</td>
<td>BIOTITE</td>
<td>7.481</td>
<td>0.01859</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>7.401</td>
<td></td>
<td>0.01859</td>
</tr>
<tr>
<td></td>
<td>HORNBLENDE</td>
<td>0.3882</td>
<td>0.387</td>
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<tr>
<td></td>
<td></td>
<td>0.3856</td>
<td></td>
<td>0.01859</td>
</tr>
<tr>
<td>1161</td>
<td>BIOTITE</td>
<td>7.545</td>
<td>0.01834</td>
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</tr>
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<td>7.566</td>
<td></td>
<td>0.01834</td>
</tr>
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</tr>
<tr>
<td></td>
<td></td>
<td>0.4102</td>
<td></td>
<td>(2) 0.02116</td>
</tr>
</tbody>
</table>

#### Granites Intruding Bulgonunna Volcanics

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>4Ar/39Ar</th>
<th>39Ar ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
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<tr>
<td></td>
<td></td>
<td>5.797</td>
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<td>0.01786</td>
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<tr>
<td>831</td>
<td>BIOTITE</td>
<td>6.252</td>
<td>0.01737</td>
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and possibly the Upper Devonian strata, and are reported to be overlain by the Lower Carboniferous Drummond Group near Ukalunda. Three samples (GA 1160, 1161, 5288) of these granites were dated by the K-Ar method (Table 8). A date of 330 m.y. was measured on one of the samples, and the other two gave ages of 295 m.y. If the field observations are correct, then all of the samples must have lost radiogenic argon, possibly during the volcanic-granitic phase that occurred in the same area in the Upper Carboniferous, 290 m.y. ago. Alternatively, the samples with the younger K-Ar age may have been part of the Upper Carboniferous phase of granitic intrusion, and have not been distinguished from the older granites during the field mapping. A Rb-Sr total rock analysis of GA 1160 (Table 10) indicates that, within the limits of experimental error, the data for this sample lie on the isochron fitted to the Upper Carboniferous granite data. However, the enrichment of radiogenic strontium in GA 1160 is small, and only a slight lowering of the assumed initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio would be needed to calculate an age of 360 m.y. for this sample.

During the Upper Carboniferous, the northwestern area was the site of acid volcanism and granite emplacement. The Bulgonunna Volcanics overlie Lower Carboniferous sediments, and are intruded by granites. These granites and the Bulgonunna Volcanics are overlain by the Bowen Basin sequence. In the field, the close association between the intrusives and the extrusives suggests that they may be related in age and origin. The Rb-Sr age of the Bulgonunna Volcanics (Figure 7, Table 9) is $287 \pm 12$ m.y., and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is $0.7049 \pm 0.0005$. All
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<th>87Sr/86Sr</th>
<th>87Sr/86Sr*</th>
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* Denotes measured ratio
### Table 10

**Sr/Sr Data for Northern Anakie High Granites**

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<th>Sr PPM</th>
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<th>87Sr/86Sr</th>
<th>87Sr/86Sr*</th>
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* Denotes measured ratio
variance in fitting the isochron can be attributed to experimental error. The Rb-Sr analyses of the total rock samples of the granites which intrude the Bulgonunna Volcanics (Table 10, Figure 8) define an isochron of 298 ± 25 m.y. with no variance in excess of that due to experimental error. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is 0.7045 ± 0.0008.

Two biotites from the granites have Rb-Sr ages of 286 m.y. (Table 10). The regression of the combined total rock and biotite data also defines a Model 1 isochron with an age of 286 ± 3 m.y. It may be assumed, from this, that there has been no loss of radiogenic Sr from the biotites and the age of 286 ± 3 m.y. is the preferred one for the granites. The initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7049 ± 0.0003$.

The apparent reversal in the total rock ages of the volcanics and granites, when compared with the field observations, is due to the relatively poor precision of the age calculated for the granites. Student's t-test shows that the ages and initial Sr isotopic composition of the two rock units are not significantly different at the 75 percent confidence level. When the total rock data of the granites and volcanics are pooled (this is justified if the samples are comagmatic and coeval) they define a Model 1 isochron of 289 ± 9 m.y.

The Rb-Sr age is close to the average K-Ar mineral age of 283 m.y. for the granites (Table 8). This agreement in age lends support to the field observations that this region has remained stable since the Carboniferous.

A small granitic body (GA 1029, 1030) that intrudes the folded strata of the Drummond Basin to the west of Anakie has K-Ar mineral ages (Table 8) which spread between 285 and 300 m.y. Both on field
and isotopic evidence, this granite may be correlated with the 285 m.y. old granites to the north.

Eastern (coastal) region

1. Connors Arch

Bounding the eastern margin of the Bowen Basin for a distance of over 200 miles, from Bowen in the north to 50 miles south of Mackay, is a continuous belt of granitic rocks. Isolated granitic intrusions occur for another 50 miles to the south. These igneous rocks were called the Urannah Complex by Malone et al. (1966). Evidence that some of these intrusions are of pre-Permian age was noted in the area to the south-east of Collinsville, where granite boulder conglomerates are interbedded with Lower Permian Lizzie Creek Volcanics (Malone et al., 1966). Although phases of apparently different ages were mapped by these authors, the extent of the pre-Permian granite was not known. More detailed mapping of the igneous rocks to the north of the Normanby goldfield (Figure 13) by Paine et al. (in prep.) has distinguished two dominant lithological and textural types. These units can also be distinguished clearly on aerial photographs. The most widespread type is sometimes foliated and may be sheared and recrystallised. It is of dioritic or tonalitic composition, and is intruded by swarms of dykes which impart the distinctive air photo pattern. The other type is a massive adamellite with fewer dykes. There are two large (several hundred square miles in area) intrusions and several smaller bodies of this more felsic type which is presumed to be younger than the tonalite.
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<th>Age M.Y.</th>
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<td>0.007959</td>
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<td></td>
<td>7.651</td>
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The isolated intrusions in the south of the Urannah Complex are massive and granodioritic.

The K-Ar mineral ages measured on samples from the foliated tonalitic types, and the massive intrusions in the south of the Complex are listed in Table 11. Three apparent phases of emplacement occurred at 305, 290, and 270 m.y. ago (Figure 12), the oldest in the south and the youngest in the north. Agreement in age between cogenetic biotite and hornblende is almost universal, and from the discussion in Chapter 1, one would expect these ages to have geological significance.

Rb-Sr analyses were made on total rock and mineral concentrates from members of each of the three K-Ar age groups. The total rock data (Table 12) define an isochron of 288 ± 31 m.y. and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7047 ± 0.0009 (Figure 9). All points fit the isochron to within experimental error, and the large uncertainty is due to the extremely low enrichment of $^{87}\text{Sr}$. The regression of the combined total rock and mineral data shows a large residual variance which is not due to experimental error, and an age of 299 ± 8 m.y. and suggests that redistribution of Rb and/or Sr within the mineral phases has occurred. Four biotite determinations, which are independent of slight differences in the choice of initial strontium isotopic composition, indicate ages of 314, 309, 290 and 284 m.y. A comparison of the Rb-Sr and K-Ar ages of these samples is given in Table 13.

Two interpretations of these data are possible.

(1) Because of the low $^{87}\text{Sr}$ enrichment in the total rock samples, the uncertainty in the total rock isochron covers the range of K-Ar ages.
### Table 12

**Rb/Sr Data for Carboniferous Granites from Urannah and Auburn Complexes**

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>Rb PPM</th>
<th>Sr PPM</th>
<th>Rb/Sr/86Sr</th>
<th>87Sr/86Sr</th>
<th>87Sr/86Sr* Age M.Y.</th>
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<td>1067</td>
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<tr>
<td>1190</td>
<td>TOTAL ROCK</td>
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<td>3.450</td>
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<td>0.530</td>
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<tr>
<td>5555</td>
<td>TOTAL ROCK</td>
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<td><strong>URANNAH COMPLEX</strong></td>
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<td>BIOTITE</td>
<td>251.8</td>
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<td>69.507</td>
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<td>812</td>
<td>TOTAL ROCK</td>
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<td>5269</td>
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<td>5270</td>
<td>TOTAL ROCK</td>
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<td>TOTAL ROCK</td>
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<th>SR PPM</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>87Sr/86Sr* AGE M.Y.</th>
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<td>809.290</td>
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<tr>
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<td>242.060</td>
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<td>6.9</td>
<td>439.825</td>
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* DENOTES MEASURED RATIO
Consequently the Model 1 regression of the total rock data may be fortuitous and the points may actually lie on two or more slightly divergent isochrons. The different ages suggested by the K-Ar measurements could therefore be correct, in general if not in detail. (2) If the Model 1 regression of the total rock analyses is not due to chance, it must indicate that the samples are cogenetic and coeval. The spread in both Rb-Sr and K-Ar mineral ages must then be due to variable leakage of radiogenic strontium and argon during a later thermal event. The general lack of agreement between the mineral ages measured by both methods suggests a smearing effect rather than several distinct phases of intrusion, and this interpretation is considered to be the most likely explanation of the data. Further arguments in support of this conclusion will be presented later. Since the large uncertainty in the total rock age can not be reduced, the most realistic minimum estimate of the age would be the oldest mineral ages measured by one or both methods, i.e. 305-310 m.y.

The K-Ar ages of minerals in the Urannah Complex show a general decrease from 305 m.y. in the south to 270 m.y. in the north (Figure 12). This probably reflects a greater intensity of tectonic activity in the northern region during the Lower Permian. At this time, over 10,000 feet of volcanics were deposited on the Connors Arch, and many of the dykes cutting the granites are thought to have been feeders for the extrusives. Granites intruded the older plutonic rocks, and the region subsided while marine sediments were deposited. At this depth, mineralogical changes which are attributed to a zeolite facies meta-
**TABLE 13**

K-Ar and Rb-Sr mineral ages of samples which fit the total rock isochron in Figure 9.

<table>
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<th>GA No.</th>
<th>Mineral</th>
<th>K-Ar Age</th>
<th>Rb-Sr Age</th>
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<td>Biotite</td>
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<td>Muscovite</td>
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<td>Biotite</td>
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<td>(5290)</td>
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<tr>
<td>5289</td>
<td>Hornblende</td>
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* Not on total rock isochron (Figure 9)
morphism took place in the volcanics. As the granites were buried to an even greater depth than the volcanics, the temperatures reached may have been sufficient to cause outgassing of argon and redistribution of radiogenic strontium.

The depth of burial of the granites in the northern region is difficult to estimate. The overburden may have amounted to 15,000 - 20,000 feet, but the granite exposed now at the surface was possibly brought into juxtaposition with the volcanics by upfaulting, and may have been buried at a depth greatly exceeding 20,000 feet during the Lower Permian.

By contrast, the granites at the southern end of the Connors Arch were emplaced at a higher level and may represent cupolas of the batholith. Differential uplift of the batholith, with accompanying cooling to below the temperature threshold of argon diffusion, could produce the spread in K-Ar ages, but is considered unlikely to have been the cause in this case. The geological evidence suggests that the uplift of the northern area must have occurred subsequent to 270 m.y. ago, and not between 310 and 270 m.y.

The Carboniferous granites intrude volcanics of unknown age which were first mapped as Lizzie Creek Volcanics (Lower Permian), although they did not fit well with the regional structure of this unit. Isotopic dating of the granites confirms the pre-Permian age of the volcanics.

2. Auburn Arch

A similar relationship occurs to the south in the Auburn Arch
where granites of the Auburn Complex are in contact with volcanics. K-Ar mineral ages on granites in the western part of the Complex (Table 11) average 300 m.y. The Rb-Sr total rock data define a Model 1 isochron of $311 \pm 29$ m.y. and an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of $0.7040 \pm 0.0007$ (Figure 10, Table 12). The reasonable agreement between the K-Ar and Rb-Sr ages suggests that the rocks of the western part of the Complex were not affected by the widespread magmatic activity that took place during the Upper Permian a few miles to the east. The known Carboniferous granites are found only in a narrow strip along the western part of the Complex. They may also occur further to the east, but so far, K-Ar dating has not given any indication of their presence.

The occurrence of Upper Carboniferous granites in the west of the Auburn Complex has introduced a problem for the field geologist. Formerly, the granites were believed to be of Permian age. They lie within the area of folded Upper Palaeozoic strata and granite intrusions (Reid, 1930), and intrude volcanics which were equated with the Lizzie Creek Volcanics (Denmead, 1931, 1946). If it is accepted that the granites intrude the volcanics, then the latter cannot be as young as Lower Permian. Alternatively, there may be two volcanic units present; an older, pre-310 m.y. formation, and a younger, Lower Permian unit. The problem lies in distinguishing between two massive, unfossiliferous and lithologically similar volcanic sequences. Dear (in prep.) has now mapped two volcanic formations - the Torsdale Beds (Carboniferous) and the Camboon Andesite (Lower Permian) in the area to
Figure 11

$\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ and $\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$

Carboniferous Granites

Urannah Complex and Auburn Complex

Initial $\frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.7043 \pm 0.0004$
FIGURE 1

POTASSIUM-ARGON AGES
NORTHEASTERN BOWEN BASIN

K-Ar ages, Urannah Complex

- 110-125 Cretaceous
- 265 Permian (Thunderbolt Granite)
- 305
- 290 Carboniferous (Urannah Complex)
- 270
the north of Cracow.

The similarity of the geological setting of the granites in the Connors and western part of the Auburn Arch suggests that they could be of the same age. Student's t-test shows that the Rb-Sr total rock ages of both groups of granites are not different at the 90 percent level, and the combined data give an age of $305 \pm 15$ m.y. (Figure 11). All variance can be attributed to experimental error. This age is considered to be the most reliable estimate of the Rb-Sr age of these granites, and will only be improved upon, with present techniques, if rocks with higher Rb/Sr ratios can be found.

These granites are of the same age as intrusions in New South Wales which are related to the Kanimbla Orogeny (David, 1950; Evernden and Richards, 1962). The relationship between the Carboniferous granites of the Urannah and Auburn Complexes and the Kanimbla Orogeny will be discussed in Chapter 5. a.

4. a (iv) Lower Permian

(1) Extrusives

The oldest formation in the northern Bowen Basin is the Lizzie Creek Volcanics; at least 10,000 feet of these volcanics underlie the earliest marine fauna which is probably of late Sakmarian age (Dickins et al., 1964; Malone et al., 1966). Hill (1960, p. 183) suggested that these volcanics may be, in part, of Carboniferous age. The eastern contact with the Urannah Complex is faulted throughout much of its length, but the volcanics contain interbedded granite boulder
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>K/AR *</th>
<th>K/AR **</th>
<th>K/AR ATM</th>
<th>AGE M.Y.</th>
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</tbody>
</table>
conglomerates indicating that they are at least younger than the oldest granites of the Complex (305 m.y.). In the west, the Lizzie Creek Volcanics overlie 285 m.y. old granites and the Bulgonunna Volcanics. On the time scale of Francis and Woodland (1964) the Lizzie Creek Volcanics are therefore post-Carboniferous, so a Lower Permian (Sakmarian) age seems likely.

Three K-Ar measurements made on plagioclases from basalts mapped as Lizzie Creek Volcanics are listed in Table 14. Two of these determinations indicate an approximate age of 270 m.y. for this unit, while the third (GA 5374, 229 m.y.) is obviously too young. Either the third sample has lost radiogenic argon, or it does not belong to the Lizzie Creek Volcanics. It will be shown in Chapter 4. a (vi) that acid volcanics of this age (230 m.y.) occur in the same area, to the north west of Collinsville, so GA 5374 may be part of the younger unit. The age of 270 m.y. determined on the other plagioclases lies within the Sakmarian (Smith, 1964). These samples were from the northwestern shelf region and were not subjected to the burial metamorphism suffered by the Lizzie Creek Volcanics in the eastern trough. The K-Ar ages are therefore regarded as being a reasonable estimate of the age of extrusion of the volcanics.

(2) **Intrusives**

A sample from one of the batholiths of massive adamellite in the Urannah Complex was reported by Webb *et al.* (1963) to have a minimum K-Ar age of 270 m.y. This intrusion was named the Thunderbolt Granite by Paine *et al.* (in prep.). Several samples from this batholith and
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE.K</th>
<th>40AR*/40K</th>
<th>TAR ATM.</th>
<th>AGE M.Y.</th>
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<td>5.0</td>
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<td></td>
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</table>
### TABLE 15 B

<table>
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<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>RR PPM</th>
<th>SR PPM</th>
<th>87RB/86SR</th>
<th>87SR/86SR</th>
<th>87SR/86SR*</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5252</td>
<td>BIOTITE</td>
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<td>7.8</td>
<td>285.525</td>
<td>1.7988</td>
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<td>260</td>
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<td>BIOTITE</td>
<td>603.5</td>
<td>5.8</td>
<td>302.016</td>
<td>1.9120</td>
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<td>271</td>
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</tbody>
</table>

* DENOTES MEASURED RATIO
similar smaller bodies have now been dated by the K-Ar and Rb-Sr methods.

The total rock samples have uniform and low Rb/Sr ratios, usually less than 0.25. Thus, at the present level of analytical precision it is not possible to obtain a precise total rock age for the intrusion. It becomes necessary, then, to rely on mineral ages. The only stratigraphic control on the age is that the Thunderbolt Granite appears to be younger than the granites which were shown in Chapter 4 (iii) to be of Upper Carboniferous age.

The mineral ages are shown in Tables 15A and B. The mean K-Ar age is 265 ± 1.3 m.y. and is supported by the two Rb-Sr measurements. Despite this apparent agreement, it is possible that these dates are younger than the true age, and reflect Ar and Sr loss similar to that observed in the Carboniferous granites. However, the absence of a significant spread in measured ages, and the field evidence that this granite is younger than the Carboniferous granites suggests that the age of 265 m.y. may be meaningful. Also, except in a few special cases which will be examined later, 260 - 270 m.y. is the youngest date measured for either intrusive unit, recording the end of igneous or thermal activity in the region. It is concluded that the age of the Thunderbolt Granite is 265 m.y.

A Cretaceous intrusion of greater areal extent than the Thunderbolt Granite also intruded the Carboniferous granites, (Figure 13), and had a limited thermal effect on their K-Ar mineral ages. Near Normanby, a sequence of K-Ar biotite ages - 270 m.y. (GA 5335), 187 m.y. (GA 5347),
**Northern Urannah Complex**


Faults.

Scale:

- 5 Miles
- 5 Kilometers

Collinsville. Edgecumbe Bay.
132 m.y. (GA 5560), 123 m.y. (GA 5331), has been measured along a line normal to the contact between the two granites. The oldest date, 270 m.y. although being too young, has not been affected by the Cretaceous intrusion. The two samples with intermediate ages are within a mile of the inferred contact, and exhibit marked argon loss. A similar example is found in the Cathu State Forest, where the sequence of ages is 283 m.y. (GA 5346), 235 (biotite and hornblende) (GA 1135), 117 m.y. (GA 1170). The cases where ages between 260 and 125 m.y. have been found are restricted to the narrow zone surrounding the Cretaceous intrusions. Thus, it is unlikely that the intrusion of this granite could have been responsible for the general lowering of the mineral ages in the Carboniferous granites.

Granites were emplaced in southeastern Queensland in the Lower Permian, but will be discussed in Chapter 4. a (v) because they were affected by slight metamorphism during the Upper Permian.

(3) Dykes

The Urannah Complex is intruded by swarms of dykes which appear to be most abundant in the Carboniferous granites, thereby implying an age between 305 and 265 m.y. for most of the dykes. Only a few measurements have been made on these dykes. They are listed in Tables 16 A and B, and an isochron plot of the Rb–Sr data is shown in Figure 14. The Rb–Sr analyses were made on a group of quartz–feldspar porphyries that intrudes the older granites in Massey Gorge, and the K–Ar age was measured on hornblende from a porphyritic micro–diorite
### TABLE 16 A

**Rb/Sr Data for Urannah Complex Dykes**

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<thead>
<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>Rb PPM</th>
<th>Sr PPM</th>
<th>87Rb/86Sr</th>
<th>87Sr/86Sr</th>
<th>87Sr/86Sr* AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5502</td>
<td>TOTAL ROCK</td>
<td>142.0</td>
<td>65.6</td>
<td>6.267</td>
<td>0.7284</td>
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<tr>
<td>5503</td>
<td>TOTAL ROCK</td>
<td>130.4</td>
<td>54.7</td>
<td>6.899</td>
<td>0.7307</td>
<td>0.7318</td>
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<tr>
<td>5504</td>
<td>TOTAL ROCK</td>
<td>136.5</td>
<td>35.9</td>
<td>11.031</td>
<td>0.7447</td>
<td>0.7463</td>
</tr>
<tr>
<td>5505</td>
<td>TOTAL ROCK</td>
<td>117.2</td>
<td>98.3</td>
<td>3.445</td>
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<td>0.7185</td>
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<tr>
<td>5506</td>
<td>TOTAL ROCK</td>
<td>129.0</td>
<td>55.9</td>
<td>6.662</td>
<td>0.7295</td>
<td></td>
</tr>
</tbody>
</table>

* Denotes Measured Ratio

### TABLE 16 B

**K/Ar Ages of Urannah Complex Dykes**

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE. K</th>
<th>40Ar*/40K</th>
<th>SAR ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
<tr>
<td>5329</td>
<td>HORNBLende</td>
<td>0.4243</td>
<td>0.425</td>
<td>0.01593</td>
<td>15.6</td>
<td>255</td>
</tr>
</tbody>
</table>
\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure14.png}
\caption{DYKES URANNAH COMPLEX}
\end{figure}

Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7058 \pm 0.0015$

$^{87}\text{Sr}/^{86}\text{Sr}$

$249 \pm 15$ m.y.
that cuts the Carboniferous granite near Normanby. The ages of both
the microdiorite and the suite of quartz-feldspar porphyries are
indistinguishable (250-255 m.y.) and are younger than the Thunderbolt
Granite. This suggests that there were several phases of dyke intrusion.
At least some of the older dykes may have been feeders for the extrusive
centres of the Lizzie Creek Volcanics, while other dykes are almost
certainly of Cretaceous age (e.g. those surrounding the 115 m.y. old
intrusion of Mt Abbot).

4. a (v) Upper Permian

(1) Extrusives

Volcanic rocks are common in the Upper Permian strata of the
Bowen Basin, and a tuff band occurs near the top of the Gyranda
Formation. K-Ar measurements on biotite from this tuff were discussed
in Chapter 3. b. The age of this tuff is 240 m.y. The age of the top
of the underlying Back Creek Group, by correlation with the Gerringong
Volcanics, is 250 m.y. (Evernden and Richards, 1962).

(2) Intrusives

Reid (1930) and Carey and Browne (1938) suggested that the
granites of the coastal belt from Townsville to Newcastle were mainly
of late Permian age. It has been shown subsequently that many of
these granites, especially in the northern part of the belt, are
early Permian or older. However, extensive plutonic activity occurred
from the late Permian to early Triassic over a wide area of southern
Queensland and New England (Figure 15). The K-Ar results presented
Distribution of U. Permian, Triassic and L. Cretaceous granites, coastal Queensland
Histograms of K-Ar ages of Permian and Triassic granites
here (Table 17), and data published by Evernden and Richards (1962), Cooper et al. (1963) and Binns and Richards (1964) suggest that granite emplacement may have occurred continuously over a period of 20 million years, between 250 and 230 m.y. ago. The spread in ages is much greater than the expected experimental error (± 6 m.y.) and must be explained by a geological effect.

The area of outcrop of the Upper Permian granites shown in Figure 15 is divided into three arbitrarily chosen regions for the purpose of examining the spread in ages. The results from each region and New England are represented in the histograms in Figure 16. The total spread in ages in each group is almost identical, and no significant differences can be found between the groups.

The recognition of statistically valid differences in the ages within any one group is difficult, due partly to the paucity of data, but mainly to the problem of defining subgroups within each group which are acceptable on geological grounds. It has been possible to do this in the Marlborough area where there is a general trend in the sequence of intrusion from gabbro (earliest) to adamellite (latest) which can be demonstrated in the field (Malone et al., 1967). When the K-Ar ages determined on these rocks are divided into two groups according to rock type (gabbro-diorite and granodiorite-adamellite) it is found that these groups have mean ages of 244 ± 1 m.y. and 236 ± 1 m.y. respectively. Application of student's t-test to these data shows that there is a greater than 99.9 percent probability that the means are significantly different. These two groups are
**TABLE 17**

**K/Ar AGES OF UPPER PERMIAN GRANITES**

<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE.K</th>
<th>4CAR/40K</th>
<th>PAR ATM.</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>1163</td>
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<td>0.897</td>
<td>0.01528</td>
<td>4.8</td>
<td>245</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.8988</td>
<td>0.897</td>
<td>0.01528</td>
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</tr>
<tr>
<td>1164</td>
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<td>6.79</td>
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<tr>
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<th>%AR ATM.</th>
<th>AGE M.Y.</th>
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ROCKHAMPTON / AUBURN COMPLEX

|       |           | 0.3188| 0.317 | 0.01555   | 28.3     | 249      |
|       |           | 0.3151|       |           |          |          |
| 1168  | BIOTITE   | 7.520| 7.54  | 0.01489   | 2.6      | 239      |
|       |           | 7.568|       |           |          |          |
|       | HORNBLende| 0.5858| 0.585 | 0.01511   | 14.7     | 242      |

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**ROCKSBERG GREENSTONES**

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differentiated in the histogram in Figure 16, the shaded areas representing the ages determined on the more basic rocks.

In other areas a distinction of this type can not be made on the evidence at present available. In both the Rockhampton–Auburn Complex area and in southeastern Queensland, a distinct peak occurs at 235 m.y., identical with the younger group at Marlborough, while a smaller number of determinations spread down to 250 m.y.

In New England, although the ages spread between 253 m.y. and 234 m.y., most of the determinations group in the lower (older) limit of the range. Binns and Richards (1964) reported ages of 250 m.y. for Lower Permian strata that had been regionally metamorphosed, and it is probable that this age records the end of the metamorphic episode. This date could not be much older without seriously conflicting with the field evidence.

In Queensland, the rocks giving the 250 m.y. K–Ar ages include the porphyritic and rapakivi granites of the Gayndah–Proston area (southeastern Queensland), and some strongly banded and recrystallised rocks (GA 1370, 5343) in the Auburn Complex. It is possible therefore, that these are the Queensland equivalents of the 250 m.y. old metamorphism in New England. Other metamorphic rocks in the Auburn Complex (GA 5342, 5344, 5357) have K–Ar mineral ages of 235 m.y., which probably reflect the age of the granites which intrude them e.g., GA 5345. Thus, the 250 m.y. dates measured on GA 1370 and GA 5343 may not be a metamorphic age, but be the result of incomplete outgassing of argon during the 235 m.y. old intrusive event. It was shown in
Chapter 4. a (iii) that granites of Carboniferous age occur in the west of the Auburn Complex and give no indications of having suffered any subsequent dynamic or thermal metamorphism. The metamorphic rocks may therefore be even older than Carboniferous, and the coincidence of 250 m.y. dates in Queensland and New England may have no geological significance.

Rb-Sr analyses were made on the granites from the Gayndah-Proston area which gave 250 m.y. K-Ar ages (Table 18). The regression of the five total rock analyses indicate a residual variance which can not be attributed to experimental error. This is due entirely to one sample (GA 5382), and the remaining four samples define a Model 1 isochron of 272 $\pm$ 20 m.y. The inclusion of GA 5382 in the calculation makes very little difference to the age (274 m.y.) but increases the uncertainty to $\pm$ 28 m.y. (Figure 17). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio indicated by the five samples is 0.7041 $\pm$ 0.0028, and when GA 5382 is omitted, it is 0.7046 $\pm$ 0.0020. The granites occur in the Lower Palaeozoic basement area, and any contamination of them by older rocks might be expected to produce a significantly higher value for the initial ratio (Pidgeon and Compston, 1965). Thus, despite the suggested replacement or contamination origin for granites with rapakivi textures, it is doubtful whether such a mechanism occurred to more than a minor degree with these particular granites.

Biotite from one of these granites (GA 5387) has a Rb-Sr age of 253 m.y. in agreement with the K-Ar age. Thus it appears that the 250 m.y. mineral dates in the Gayndah-Proston area are the result of
<table>
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<th>Sr PPM</th>
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<th>87Sr/86Sr</th>
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* Denotes measured ratio
\[ \frac{^{87}\text{Sr}}{^{86}\text{Sr}} \]

Initial \( \frac{^{87}\text{Sr}}{^{86}\text{Sr}} = 0.7041 \pm 0.0028 \)

\[ \frac{^{87}\text{Rb}}{^{86}\text{Sr}} \]

GRANITES

GAYNDAH–PROSTON AREA

274 ± 28 m.y.
partial argon and strontium loss, possibly during the intrusion of the 235 m.y. old granites. A similar explanation can be applied in the case of the metamorphic rocks in the Auburn Complex, but no estimate of their initial age can yet be made.

The event at 235 m.y. is interpreted as being one of widespread granitic intrusion. Almost certainly, some of the rocks included in this group on the basis of K-Ar mineral age are older granites or metamorphics which have been thermally metamorphosed by the younger intrusions, but the latter group predominates.

Only two Rb-Sr analyses (GA 5326, total rock and biotite, Table 18) have been made on the younger group of rocks. The biotite age is 240 m.y. and is virtually independent of the value of the initial \(^{87}\text{Sr}/^{86}\text{Sr}\) chosen; while the total rock age lies between 230 and 240 m.y., depending on whether a value of 0.7035 or 0.7050 is taken as the initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio.

Two distinct plutonic episodes can therefore be recognised in the Upper Permian on the basis of the isotopic ages. A third phase, the emplacement of the serpentinite near Marlborough, possibly occurred at the beginning of the Upper Permian. Gabbroic and dioritic bodies were intruded, also near Marlborough, 245 m.y. ago, following the cessation of sedimentation in the Gogango Overfolded Zone (Plate 1). Widespread granitic activity from Marlborough to New England followed the deposition of the Upper Permian coal measures (230 – 235 m.y.). This age corresponds to the late Permian or early Triassic (Chapter 3. b, c). There is no definite evidence, in Queensland, of a phase of regional metamorphism 250 m.y. ago corresponding to that recognised
in New England. If regional metamorphism occurred, it could not
have been on a large scale, as the older granites of Mt Morgan and
the western Auburn Complex have retained their initial K-Ar ages.

The plutonic rocks throughout the region have been loosely
related to phases of the Hunter-Bowen Orogeny (David, 1950). A
closer examination of this relationship will be made in Chapter 5. a.

(3) Metamorphics

The Rocksberg Greenstones in the D'Aguilar Block are the oldest
exposed rocks in the Brisbane Metamorphics (Bryan et al., 1960), and are
the product of low grade regional metamorphism of basic volcanics.
In some rocks, relict phenocrysts of augite remain, while other rocks
have a completely new mineral assemblage. One such group is the
glaucophane schist, which is composed of albite, epidote, muscovite,
chlorite, and glaucophane. The greenstones are intruded by the Neurum
Tonalite (GA 1217; K-Ar biotite age, 223 m.y.).

A sample of the glaucophane schist (GA 5192) collected a few
miles from the contact with the Neurum Tonalite yielded mineral ages
of 245 to 250 m.y. for both muscovite and glaucophane (Table 17).

Glaucophane schists are usually regarded either as a product of
metasomatism related to the intrusion of serpentinites, or of regional
metamorphism. Serpentinites occur along the faulted margin of the Esk
Rift and the D'Aguilar Block, and also within the D'Aguilar Block.
They have traditionally been believed to be of Middle Devonian age
(Wilkinson, 1960) although there is no definite proof that they must
be as old as this. In New South Wales the serpentinites are generally
regarded as Upper Palaeozoic (Carey and Browne, 1938). However, serpentinites have not been found close to the greenstones, and a metasomatic origin related to the intrusion of the serpentinites, for the glaucophane schist assemblage, is unlikely.

Turner and Verhoogen (1960) described the metamorphic conditions which they believed to be necessary to bring about the formation of the glaucophane schists. While they noted the frequent association of serpentinites and glaucophane schists in the field, they did not believe this to be a genetic association. They cited the Rocksberg Greenstones as an example of a transitional stage between normal greenschist facies and true glaucophane schist facies metamorphism. The question of whether such a metamorphism occurred in the D'Aguilar Block at 250 m.y. will now be considered.

There is no evidence in the surrounding rocks for regional metamorphism at this time. The blocks of Lower Permian sediments and volcanics in the Esk Rift are unmetamorphosed. However, the D'Aguilar Block was uplifted many thousands of feet during the Upper Permian and Triassic, and possibly a metamorphism at this depth could have occurred before the uplift, producing the glaucophane schist assemblage, while leaving no manifestation of its presence in the overlying rocks.

An alternative, and preferable explanation, is that while the greenstones were buried at great depths, the crustal temperature was sufficiently high to cause continuous and complete outgassing of argon from the constituent minerals. The age of 245 m.y. then, is
the time when the D'Aguilar Block was raised to a cooler level in the crust, and radiogenic argon began to accumulate. Heating due to the intrusion of the Neurum Tonalite is unlikely to have had any effect on the argon content of these minerals.

The probability that K-Ar dates from metamorphic rocks may indicate the time of uplift and bear no relationship to the time of metamorphism has been noted by Hurley, Hughes, Pinson et al. (1962) and Armstrong (1966). The dates on the Rockberg Greenstones are believed to indicate that movement along the marginal faults of the Esk Rift occurred early in the Upper Permian, although the most apparent movement occurred in the Middle Triassic.

4. a (vi) Triassic

(1) Volcanics

To the north west of Collinsville, the Lower Permian Lizzie Creek Volcanics occupy a large area north of the nose of the syncline. In this region, the volcanics are predominantly basaltic, but are intruded and overlain by rhyolites. The whole sequence has been mapped as Lizzie Creek Volcanics. The K-Ar dating of three plagioclase concentrates from these volcanics was discussed in Chapter 4. a (iv). Two of these samples had Lower Permian ages, but the third was 230 m.y. old. Rb-Sr analyses on several of the acid volcanics (Table 19) have indicated an age of \(230 \pm 15\) m.y. for these samples, and an initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratio of \(0.7055 \pm 0.0007\). All analyses fit the isochron in Figure 18 to within experimental error. The mean value of the age lies close to that
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>87RB/86SR</th>
<th>87SR/86SR</th>
<th>87SR/86SR*</th>
<th>AGE M.Y.</th>
</tr>
</thead>
<tbody>
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<td>5522</td>
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<tr>
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<td>5532</td>
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<td>0.7229</td>
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</tbody>
</table>

* DENOTES MEASURED RATIO
FIGURE 18

$^{87}\text{Sr}/^{86}\text{Sr}$

Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7055 \pm 0.0007$

$^{87}\text{Rb}/^{86}\text{Sr}$

ACID VOLCANICS
BURDEKIN – BOGIE –
BOWEN RIVERS AREA

230 ± 15 m.y.
suggested earlier for the Permian - Triassic boundary. GA 5519 and 5532 are intrusions in the 285 m.y. old granites to the west. The data were not included in the regression of the volcanic analyses, but plot on the isochron (Figure 18).

(2) Intrusives

In Chapter 3. c it was shown that a number of granites in the Maryborough Basin and the South Coastal High have K-Ar and Rb-Sr ages of 220 m.y., and from the field evidence, it was deduced that this age could not be older than Middle Triassic.

Other granitic rocks of this age (Table 20) occur to the south in the New England Batholith, and to the northwest in the Yarrol Basin. North of Rockhampton, a dyke (near Marlborough) and two gabbro stocks (in the Connors Arch) also have ages of 220 m.y., but there is no evidence of widespread plutonism in this (northern) area during the Triassic.

There are no obvious features of the granites which would either distinguish them from many of the Upper Permian granites, or lead to a natural grouping of these younger intrusions. They intrude Lower and Upper Palaeozoic and Mesozoic strata. In the Yarrol Basin area, Gradwell (1960) placed the Mt Perry granites in the group of Permian to Triassic age, and Reid (1930) included the Glassford Creek intrusion in the late Permian period of granitic emplacement. Maxwell (1960) believed the granite masses within the Yarrol Basin to have been intruded during the late Permian.

In the South Coastal High (D'Aguilar Block), the granites intrude
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE.K</th>
<th>40Ar*/40K</th>
<th>%AR ATM.</th>
<th>AGE M.Y.</th>
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<td>HORNBLende</td>
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<td>5.95</td>
<td>0.01397</td>
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<td>225</td>
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low grade metamorphic rocks of Lower Palaeozoic age. Bryan and Jones (1945) placed these in the late Palaeozoic, or at least no later than the earliest Triassic sedimentation in the Ipswich Basin. The only granite, outside the Maryborough Basin, that has been identified as being younger than Lower Triassic is at Monsildale (Jones, 1947).

The prolongation of plutonic activity on any significant scale after the early Triassic had not, therefore, been predicted. The extent of the Middle Triassic granitic intrusions in southern Queensland is shown in Figure 15. In addition, granites of this age have been recognised in the New England batholith in widely separated localities (Evernden and Richards, 1962; Binns and Richards, 1964).

The western limit of the Middle Triassic plutonism appears to be a sharp one, and coincides for part of its length with important structural features. West of Brisbane it is marked by the eastern margin of the Esk Rift Valley. The plutons of the D'Aguilar Block are 220 m.y. old, while those of the Yarraman Block to the west of the Rift are Permian or older. North of the Esk Rift, the eastern boundary fault is collinear with the Perry Fault and forms the western limit to the Triassic granites between Biggenden and Mt Perry. The structural control appears to end north of Mt Perry, and the boundary swings westward to include the Triassic granites at Glassford Creek and Diglum in the Yarrol Basin.

The importance of this lineament, which separates the Lower Palaeozoic from the Upper Palaeozoic and Mesozoic strata, was recognised by Bryan (1925) and earlier workers, and it was suggested by Bryan that it extended from Beaudesert (south of Brisbane) to Broad Sound (north of
Marlborough). The sharp boundary between the Lower Palaeozoic and younger rocks extends into New South Wales, where the Mt Warning shield volcano was built astride this junction (Solomon, 1964) during the Miocene (Webb et al., 1967).

South of Brisbane, the structural control on the region of granite emplacement ends, and the western limit swings westward to include the Stanthorpe district, and then south again close to the eastern side of the New England Batholith, at least as far as Armidale (Binns and Richards, 1964).

Strong movements occurred along the Esk Rift during the Middle or Upper Triassic, and the granite emplacement seems to be related in time to these movements, and to the uplift of the D'Aguilar Block. In the Warwick - Stanthorpe area, the block faulting of the Permian strata was related to the intrusion of the Stanthorpe Granite (Richards and Bryan, 1924). It seems therefore, that the intrusion of the 220 m.y. old granites occurred during a period of tensional movements.

4. a (vii) Cretaceous

Granitic rocks of Cretaceous age, outside the Maryborough Basin, were first reported by Webb and McDougall (1964). Since then, many other granites and volcanics of a similar age have been identified by isotopic dating. These determinations are listed in Tables 21 and 22 and the areal extent of the igneous activity of this age is shown in Figure 15. Many of the intrusions in the Mackay district may also be Cretaceous, but since they have not been dated, they are not
included in the area of Lower Cretaceous intrusions in Figure 15.

The Lower Cretaceous intrusions are found in three regions: within the Bowen Basin to the east of the central axis of the basin, in the Urannah Complex to the north east of the basin, and in the coastal strip and off-shore islands in the Proserpine area, where Cretaceous volcanic rocks also occur.

Within the Bowen Basin, the intrusions are usually small and hypabyssal, with a porphyritic texture. They are often gabbroic, but granodiorites also occur. In the Urannah Complex to the northeast of the basin, the intrusions (the Hecate Granite, Paine et al., in prep.) reach batholithic proportions at least 500 square miles in area. Here, the dominant rock type is adamellite/granodiorite which is similar to the 265 m.y. old Thunderbolt Granite a few miles to the west.

In the coastal strip and off-shore islands the granites are usually massive, leucocratic, high level intrusions, and tend to be more alkaline than the other Cretaceous granites. There is frequently a close association between these granites and acid volcanic rocks, and both the intrusives and extrusives in this area are younger (110 - 115 m.y.) than the other granites (125 m.y.). A representative of these younger epizonal granites occurs at Mt Abbot to the north of the Urannah Complex, and the dyke swarm surrounding the intrusion is probably also of this age. The close association between the volcanics and granites in the Cumberland Islands was noted by White and Brown (1963), who suggested a Tertiary age for these rocks.
### Table 21

**K/Ar Ages of Cretaceous Granites and Volcanics**

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<th>GA No.</th>
<th>Mineral</th>
<th>% K</th>
<th>Ave. K</th>
<th>40Ar*/40K</th>
<th>3Ar Atm.</th>
<th>Age M.Y.</th>
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<th>AVE.K</th>
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<th>%AR ATM.</th>
<th>AGE M.Y.</th>
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**YOUNGER INTRUSIONS AND VOLCANICS**

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<th>%AR ATM.</th>
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<td>0.790</td>
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<td>0.9956</td>
<td>0.994</td>
<td>0.007012</td>
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<td></td>
<td>0.9915</td>
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<tr>
<td>5394</td>
<td>WHOLE ROCK</td>
<td>1.717</td>
<td>1.714</td>
<td>(1)0.006370</td>
<td>15.0</td>
<td>106</td>
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<td></td>
<td></td>
<td>1.711</td>
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<td>(2)0.005749</td>
<td>23.7</td>
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<td>5553</td>
<td>HORNBLende</td>
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**TRACHYTES**

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<tr>
<th>GA NO.</th>
<th>MINERAL</th>
<th>% K</th>
<th>AVE.K</th>
<th>40Ar*/40K</th>
<th>%AR ATM.</th>
<th>AGE M.Y.</th>
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<tr>
<td>1037</td>
<td>WHOLE ROCK</td>
<td>3.976</td>
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<td></td>
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<td>(2)0.004150</td>
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<td>0.004108</td>
<td>10.5</td>
<td>69.0</td>
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</table>
The K-Ar ages measured on minerals from these granites and volcanics are given in Table 21. The intrusions within the Bowen Basin and in the Urannah Complex have an average age of 125 m.y. This is significantly older than the few ages measured on the more alkaline high level granites of the coastal area, and the single determination on hornblende from a dacite on Carlisle Island.

Rb–Sr total rock analyses on acid volcanics from the Conway Range area, northeast of Proserpine, are listed in Table 22. The data fit an isochron of $111 \pm 5$ m.y. to within experimental error (Figure 19). The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio is $0.7037 \pm 0.0004$. This total rock age is in close agreement with the K-Ar age on the dacite and on the coastal granites, and supports the field observations of White and Brown that the intrusives and extrusives are closely related in age.

Another indication of the Cretaceous age of the volcanics is given by K-Ar total rock dating of a sample from Pentecost Island (GA 5394). This rock is composed essentially of alunite ($\text{KAl}_3(\text{OH})_6(\text{SO}_4)_2$) and quartz, the alunite forming by reaction between feldspars and sulphur-bearing vapours or solutions given off during the volcanism. Duplicate determinations of 106 and 96 m.y. indicate a minimum age of late Lower Cretaceous for the volcanism. The spread in the age may be due either to variable argon leakage, or to an inhomogeneous sample. The potassium was measured on finely ground rock, so would be expected to give reproducible results. The argon was extracted from 1 cm$^3$ pieces of rock, and any variations in the extent of the alteration to alunite may cause localised variations in the
<table>
<thead>
<tr>
<th>GA NO.</th>
<th>SAMPLE</th>
<th>RB PPM</th>
<th>SR PPM</th>
<th>87RR/86SR</th>
<th>87SR/86SR</th>
<th>87SR/86SR*</th>
<th>AGE M.Y.</th>
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<td>5508</td>
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<td>5511</td>
<td>TOTAL ROCK</td>
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<tr>
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<td>5547</td>
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<td>0.656</td>
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</table>

* DENOTES MEASURED RATIO
$^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$

ACID VOLCANICS
CONWAY RANGE

Initial $^{87}\text{Sr}/^{86}\text{Sr} = 0.7037 \pm 0.0004$

$111 \pm 5$ m.y.
K content, and therefore in the argon content. The first run (106 m.y.) was pre-baked at 250°C, and the second run (96 m.y.) at 110°C. Alunite breaks down at relatively low temperatures so there is little chance that incomplete argon extraction occurred in either run.

Two features of these granites may be noted. Firstly, they were intruded in an area in which there is no proof of either sedimentation or folding movements for at least 90 million years. The existence of Cretaceous granites in this area is perhaps the most unexpected result of this work. Secondly, numerous occurrences of small scale ore mineralisation have been noted associated with many of the intrusions. The mineralised areas include Mount Flora, Eungella-Mt Barker, and the contact between the Hecate Granite and the Permian volcanics west of Proserpine, an area which includes the Dittmar mine (Figure 13). Another area of mineralisation which is possibly of this age is the Normanby goldfield. This lies within the older intrusions, but close to the contact with the Cretaceous granites.

A brief comment on the K-Ar age of the Watalgan granite (Evernden and Richards, 1962) is necessary in any discussion on Cretaceous granites and the Maryborough Basin, since this intrusion appears to be the exception to the conclusions reached earlier (Chapter 4. a (vii) that the granites in the Maryborough Basin are of Middle Triassic age. Evernden and Richards (1962) reported a K-Ar age of 110 m.y. for biotite from this intrusion, and the present writer has confirmed this result by analysing a fresh separation of biotite from the same sample. The analysis, then, appears technically reliable, and the K-Ar date is
early Aptian (Casey, 1964). The field relations were reported by Ridley (1960 a), who stated that the granite is overlain unconformably by the Grahams Creek Formation. This formation is predominantly volcanic, and pebbles derived from it are found in the basal beds of the overlying Maryborough Formation. Ammonites from near the top of the Maryborough Formation indicate an Aptian age for this part of the unit (Fleming, 1966; Hawthorne et al., 1960). Therefore, the K-Ar age of the Watalgan granite is at variance with its stratigraphic position. Since Ridley's (1960 a ) field evidence and deductions have never been challenged, it must be accepted that the biotite from the Watalgan granite has lost radiogenic argon, and a pre-Cretaceous age is likely for this intrusion.

In the late Cretaceous, alkaline trachyte plugs were intruded in Central Queensland, north and southwest of Rockhampton. These plugs are apparently unrelated to any extrusive activity, and geomorphologically and petrologically are similar to the Miocene trachytic plugs of the Moreton District, north and southwest of Brisbane (Appendix 3). Whole rock K-Ar analyses on the Central Queensland trachytes shows them to be at least 70 million years old (Table 21).

4. a (viii) Tertiary

Widespread, predominantly basaltic, volcanism occurred in many regions of eastern Queensland during the Tertiary. Most of this activity took place on the site of the old Tasman Orthogeosyncline, although in north Queensland it overlapped the contact between the
Precambrian Shield and the geosyncline. The study of the K-Ar age of the volcanism in two of these areas has been the subject of two publications which are included as Appendices B and C. Two problems were examined, in addition to the determination of the age of the volcanism. Firstly, the question of suitability of altered material for whole rock K-Ar dating was investigated. This involved a comparison of the whole rock ages with the ages of sanidines separated from comagmatic rocks. As sanidine is widely regarded as an eminently suitable mineral for K-Ar dating, it was thought that a comparison of the ages of the two different types of sample would give an indication of the argon retentivity of the whole rock sample, which might then be related to the degree of alteration of the material.

This investigation led to the second, when it was found that reproducible results could not be obtained on sanidines. A number of argon extraction runs on fractions crushed to different mesh sizes, and using different fusion techniques indicated that incomplete argon extraction occurs with the coarser grained samples unless the sample is fused at 1650°C or higher, and held at that temperature for longer than 20 minutes.

When these extraction procedures were followed, the sanidine ages compared closely, in most cases, with the whole rock basalt ages, indicating that slight alteration of the plagioclase and clouding of the fine grained or glassy interstitial material had an insignificant effect on the argon retentivity of these phases. However, there appeared to be a positive qualitative correlation between degree of alteration
of the groundmass and argon retentivity. Thus, with this empirical basis for sample selection, the basalts and acid plugs from Springsure (see Figure 3) and three areas of the Moreton district, southwest of Brisbane, were dated.

In the Springsure district, volcanism began at least 33 m.y. ago, and the greatest thickness of lavas were extruded between 27.5 and 26.5 m.y. ago. The lavas were intruded by trachytic and rhyolitic plugs 26.5 m.y. ago.

Southwest of Brisbane, the main period of volcanism was younger than at Springsure. One basalt was found to be at least as old as early Eocene, but the main volume of basalts was extruded from two centres, the Mt Warning Shield volcano and the Main Range, in the Lower Miocene, 24 to 22 m.y. ago. Acid volcanic plugs in this area were also intruded during the Lower Miocene, and showed a trend of age with chemical composition; alkaline trachytes were 24 to 25 m.y. old while the subalkaline rhyolites were 22.5 to 23 m.y. old. Laterites were developed on the basalts of the Main Range and the Mt Warning Shield. Earlier estimates of the age of the laterites placed them in the Miocene, in reasonable agreement with the conclusions from the K-Ar data.

The lavas of both regions have been localised along relatively ancient lineaments. The Mt Warning Shield volcano was built on the junction of the lower Palaeozoic with the younger Upper Palaeozoic to Mesozoic strata - a fundamental line, or zone, that can be traced northwards for 400 miles. The Main Range lavas are believed to have
### TABLE 23

Summary of geological sequence, E. Queensland

<table>
<thead>
<tr>
<th>PERIOD</th>
<th>AGE m.y.</th>
<th>DRUMMOND BASIN ANAKIE HIGH</th>
<th>BOWEN BASIN SURAT BASIN</th>
<th>YARROL BASIN</th>
<th>MARYBOROUGH BASIN</th>
<th>SOUTH COASTAL HIGH</th>
<th>AGE m.y.</th>
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<td>CRETACEOUS</td>
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<td>Acid Volcanics, Granites</td>
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<td>Granites</td>
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<tr>
<td></td>
<td>110</td>
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<td></td>
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</tr>
<tr>
<td></td>
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<tr>
<td>TRIASSIC</td>
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<tr>
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<td>220</td>
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<tr>
<td></td>
<td>230</td>
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<td>Basic Intrusions</td>
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<td>Dykes: Urannah Complex</td>
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<td></td>
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<tr>
<td>CARBONIFEROUS</td>
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<td></td>
<td>365</td>
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<td>Urannah Complex</td>
<td>(? VOLCANICS)</td>
<td>Auburn Complex</td>
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<td>Basement granites, Surat Basin</td>
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<td>DEVONIAN</td>
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<td>Retreat Granite</td>
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<td>ORDOVICIAN</td>
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</tbody>
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**ABBREVIATIONS:** MAR = MARINE; F.W. = FRESH WATER; C.M. = COAL MEASURES.
been produced from fissure eruptions along a flexure in the under­lying strata. The lavas at Springsure have been extruded in a north­south belt which coincides with the western hinge (possibly a fault) of the Denison Trough.

Other structural controls on the location of the Tertiary Volcanics have been noted by Jensen (1909) and Hills (1955).

4. a (ix) Geological Summary

A summary of the geological history of eastern Queensland south of 20°S. latitude is outlined in Table 23. This is a composite section insofar as the sequence is rarely complete in any area, and nonconformities may occur at different stratigraphic levels in the one basin. Also, granite intrusion may have occurred at one place while sedimentation continued elsewhere. The main depositional phases are listed, and the magmatic or metamorphic events determined by isotopic dating are inserted in the appropriate places in heavier type, and underlined. Only major unconformities are shown.

Almost nothing is known of the pre-Devonian history of this section of the Tasman Orthogeosyncline. The northern boundary, the igneous complex of the Ravenswood Granodiorite, will be discussed in Chapter 6, and has been shown by preliminary isotopic dating (Table 27) to be of Silurian or Ordovician age. In the west, the basement area of the Anakie High was metamorphosed 450 m.y. ago or earlier (i.e. during the Ordovician). The basement rocks of the South Coastal High are older than Devonian, but there is no isotopic or palaeontological
evidence for their age. Small inliers of Silurian to Lower Devonian rocks occur between the Yarrol and Bowen Basins.

Marine sedimentation and volcanism commenced in the Middle Devonian in the Yarrol Basin and in small basins on the Anakie Metamorphics, and closely following this initial sedimentation, granite intrusion occurred in both regions (365 m.y.). There is no information on the basement beneath the Bowen Basin between these two localities, as bores have not penetrated the Permian sequence. Further south in the basement of the Surat Sub-Basin, granites and ancient land surfaces encountered in bores have K-Ar biotite ages ranging from 300 to 345 m.y. (Webb et al., 1963); (measurements made by the author and quoted by Houston, 1964; and unpublished data of this laboratory). However, interpretation of K-Ar ages of bore cores is, at best, uncertain, and the only confident conclusion that can be drawn is that the granites are Lower Carboniferous or older. Other granites reported to be of probable Upper Devonian age occur in the north of the Anakie High, although K-Ar analyses do not confirm this determination.

Commencing in the Upper Devonian, and continuing into the Lower Carboniferous, continental sedimentation and volcanism occurred in the Drummond Basin. Contemporaneous with this was the mainly marine sedimentation of the Yarrol Basin. At the end of the Lower Carboniferous, the emplacement of the granitic batholiths of the Urannah Complex and the Auburn Complex began in the coastal region. At this time, sedimentation in the Drummond Basin ceased, and the strata
were folded probably between 310 and 290 m.y. ago.

During the Upper Carboniferous, marine and terrestrial sedimentation continued in the Yarrol Basin. In the north of the Anakie High, terrestrial acid lavas (the Bulgonunna Volcanics) were extruded (285 - 290 m.y.) and were intruded almost simultaneously by granites which may have been co-magmatic with them. A small isolated intrusion was emplaced in the southern part of the Drummond Basin at this time.

The Bulgonunna Volcanics, in the west, and the 310 m.y. old granites of the Connors and Auburn Arches in the east, were unconformably overlain by the basal units of the Bowen Basin - the Lizzie Creek Volcanics and the Camboon Andesite (270 m.y.). Subsidence of the Connors Arch was accompanied by the intrusion of the Thunderbolt Granite (265 m.y.) and marine sediments were deposited on the Lizzie Creek Volcanics. Reheating of the 310 m.y. old granites caused argon diffusion to occur from biotite and hornblende. The early volcanic-granite association in the Bowen Basin in the early Permian is similar to that which occurred in the Yarrol Basin in the late Devonian. In neither case was the plutonic activity very extensive.

Granitic masses were also emplaced during the Lower Permian (270 m.y.) in the South Coastal High at the southern end of the Yarrol Basin.

Marine sedimentation continued into the Upper Permian (~250 m.y. by correlation with the Gerringong Volcanics). Northwest of Rockhampton spilitic lavas were extruded, and ultramafic rocks emplaced. Uplift
of the Connors and Auburn Arches caused the cessation of marine sedimentation. Diorites and gabbros were intruded near Marlborough (245 m.y.), and volcanic activity occurred throughout much of the Bowen Basin (240 m.y.). Coal measures were deposited during most of the remainder of the Permian.

At the close of the Permian (230 - 235 m.y.), granite emplacement occurred from the Marlborough - Rockhampton area to northern New South Wales. Uplift continued in the Auburn Arch during this magmatic phase and sedimentation began to the west of the arch in the Mimosa Syncline.

A phase of uplift may also have occurred in the South Coastal High to the west of Brisbane in the Upper Permian, raising the glaucophane schists of the Rocksberg Greenstones above the level where continuous outgassing of radiogenic argon occurs. This area was also affected by vertical movements of some magnitude later in the Permian and in the Triassic.

The granite intrusion, and the uplift that accompanied it in the Auburn Arch and the southern part of the South Coastal High, may account for the absence of early Triassic strata in the Ipswich (Clarence - Moreton) Basin during the period of deposition to the west in the Surat Basin and Mimosa Syncline.

Terrestrial sedimentation occurred throughout the Lower and Middle Triassic in the Bowen Basin and Mimosa Syncline. Volcanism occurred to the northwest of Collinsville in the Lower Triassic or late Permian (230 m.y.); and in the Esk Rift and on the eastern side of the D'Aguilar Block in the Lower to Middle Triassic. Coal measures formed
in the Ipswich Basin in the Middle Triassic, and probably equivalent strata, without coal measures, were deposited in the Esk Rift and Maryborough Basin. Granites were emplaced in the Yarrol and Maryborough Basins, and in the South Coastal High and New England during the Middle to Upper Triassic (220 m.y.). A strong regional unconformity separates the terrestrial sandstones of the Lower Jurassic from all older rock units.

Igneous activity occurred in the northeast of the Bowen Basin early in the Cretaceous; granitic intrusions being emplaced 125 m.y. ago, and acid volcanism with associated high level granites occurring 110 m.y. ago.

Alkaline trachyte plugs were intruded in Central Queensland at the end of the Cretaceous (70 m.y.). During the Oligocene and Miocene, basaltic flows were extruded and related near-surface acid intrusives emplaced in the Springsure district and in southeastern Queensland. The volcanism produced predominantly alkali olivine basalts, and was localised along ancient structural trends.

4. b A comparison of biotite and hornblende K-Ar ages

In Chapter 1. e it was stated that the difference in argon retentivity between biotite and hornblende under metamorphic conditions suggested by Hart (1964) and Aldrich et al. (1965) was not always observed. In the present work, K-Ar ages have been measured on 51 pairs of cogenetic biotite and hornblende, and a histogram of the ratio of biotite/hornblende age is given in Figure 20. Figure 20 A contains
FIGURE 20

NUMBER OF MEASUREMENTS

Biotite / Hornblende Age

A

B

0.94 0.96 0.98 1.00 1.02 1.04 1.06

12

10

8

6

4

2

2
samples from the Urannah Complex, which were shown in Chapter 4. a (iii) to have lost radiogenic argon during burial and possibly thermal metamorphism. Some samples included in Figure 20 B may also have lost argon, but this can not be substantiated.

If biotite and hornblende are equally retentive of argon, the mean ratio would be 1.00, whereas in cases where hornblende is more retentive, e.g. under conditions of thermal metamorphism, the mean ratio would be less than 1.00. The mean ratios in Figures 20 A and B (0.990 and 0.998) are not significantly different, either from each other or from 1.00.

The samples represented in Figure 20 A were emplaced 305 m.y. ago and were overlain, or partly overlain by the Lizzie Creek Volcanics 270 m.y. ago. Evidence as to the thermal history during this 35 m.y. interval is lacking. The region was depressed during the Lower Permian, when a large thickness of sediments was deposited on the Lizzie Creek Volcanics. It is not known whether the Urannah Complex was buried beneath the deepest part of the basin, or whether it remained partly emergent near the basin margin. The Thunderbolt Granite was emplaced in the Urannah Complex 265 m.y. ago.

Jensen (1964) reported the development of prehnite, pumpellyite and perhaps epidote in the lower sections of the Lizzie Creek Volcanics. These minerals are characteristic of the prehnite – pumpellyite metagreywacke facies (Coombs, 1961), and investigations by Coombs et al. (1959) and Packham and Crook (1960) suggest that temperatures up to 300°C may have been involved. However, this temperature seems excessive, even in a geosynclinal region, for a depth of about 20,000 feet. A
temperature of about 200°C may be a closer estimate of the temperature at the base of the Lizzie Creek Volcanics during the Lower Permian. The absence of any schistosity developed in the volcanics suggests that heat and static load (burial metamorphism, Coombs, 1961) were the main factors operating at this time.

If the granites of the Urannah Complex were overlain by the thickest section of sediments and volcanics, then the temperature in the granites must have been even greater than that in the volcanics. The depth at which the present granite land surface was below the volcanics is not known, but indications of regional faulting between the granites and volcanics suggest uplift of the granites in the northern region. The present outcrop of the Urannah Complex also seems to indicate that the northern region has been tilted or raised relative to the southern end.

The K-Ar mineral ages on the Urannah Complex decrease from 305 m.y. in the south to 270 m.y. in the north and were interpreted in Chapter 4.a (iii) as indicating variable leakage of argon from biotite and hornblende from rocks that were all 305 m.y. old (Figure 12). If the K-Ar ages can be related to depth of burial (and therefore to temperature), then the dating supports the assumption of differential uplift from south to north.

The maximum temperature reached in the granites may have been between 200° and 300°C, and could not have continued for more than about 5 million years (the 265 m.y. age of the Thunderbolt Granite indicates that the temperature had fallen by that time, either due to
lowering of the isotherms or uplift of the granites).

Damon (1967) calculated from the data produced by Evernden et al. (1960) and Hart (1964) that low grade metamorphism (100° to 150°C) for 50 m.y. would cause a loss of between 10% and 90% of argon from biotite, but less than 10% from hornblende. At 230°C, biotite would lose all of its radiogenic argon in less than one million years, but hornblende would lose only about 10% in 50 m.y. A temperature of around 400°C would be needed to outgas hornblende completely in 5 m.y.

The estimated maximum temperature reached in the Urannah Complex (about 300°C) for 5 m.y. could easily account for the 270 m.y. ages of the biotites, but the predicted argon loss from hornblende for this time and temperature appears to be underestimated. Hence, under certain low grade metamorphic conditions, the argon retentivity of hornblende may not be significantly greater than that of biotite. The concordance of biotite and hornblende K-Ar dates could lead to the erroneous conclusion that the date is the time of emplacement or strong metamorphism. In the present case, the K-Ar age of 270 m.y. could be accepted as the age of intrusion, since there is no field evidence to the contrary. It is the Rb-Sr total rock age that indicates the leakage of argon from these rocks.

4. c The $^{87}$Rb Half-Life

One of the greatest problems in geochronology has been the frequent lack of agreement between isotopic ages measured from different radioactive decay schemes. In addition to the uncertainty
in the half-life of some radioactive isotopes, there are geochemical and geothermal effects e.g. cation exchange and ionic diffusion, about which, in Nature, very little is known. These effects are variable, so the lack of agreement between two dating methods is perhaps not so unexpected.

Since 1956, the more refined techniques which have been applied to the physical measurement of the $^{87}$Rb half-life might be expected to have given increasingly accurate estimates of this parameter. Flynn and Glendenin (1959) determined the half-life as $4.7 \times 10^{10}$ years ($\lambda = 1.47 \times 10^{-11}$ yr$^{-1}$), but subsequent measurements by other analysts have produced values ranging from $4.7$ to $5.8 \times 10^{10}$ years.

The desire to reach a consensus with different methods has led to the development of the "geological" half-life. The age determined by method A is accepted as being correct, and the half-life value used in method B is adjusted so that the ages calculated from both decay schemes are equal. Aldrich et al. (1956) derived the value of $5.0 \times 10^{10}$ yrs ($\lambda = 1.39 \times 10^{-11}$ yr$^{-1}$) for the $^{87}$Rb half-life from a comparison of Rb-Sr and U-Pb ages. Kulp and Engels (1963) proposed a value of $4.7 \times 10^{10}$ yrs for this parameter from a comparison of K-Ar and Rb-Sr mica ages from rocks in which there was no petrological evidence of any subsequent metamorphism.

Zartman (1964) and McDougall et al. (1966) have suggested that an intermediate value of $4.85 \times 10^{10}$ yrs might give the closest agreement between Rb-Sr and K-Ar ages. Zartman (1964) based his estimate on a comparison of mineral ages, and assumed the samples had
not been subjected to metamorphism since their formation. The evidence of McDougall et al. (1966) is inconclusive because of the obvious spread in both the K-Ar and Rb-Sr biotite ages. A comparison of these dates does not seem justified. On the other hand, a comparison between the oldest K-Ar biotite dates (if they are accepted as reliable) and the Rb-Sr total rock isochrons seems to favour a $^{87}\text{Rb}$ half-life of $4.7 \times 10^{10}$ years.

Goldich et al. (1966) also support a value of $4.7 \times 10^{10}$ years from a comparison of K-Ar and Rb-Sr ages (mineral and total rock) on bore core samples. Using this value of the $^{87}\text{Rb}$ half-life, these authors obtained agreement between muscovite ages from both methods. In general the K-Ar biotite ages were higher than the Rb-Sr biotite ages but lower than the Rb-Sr K-feldspar and total rock ages. However, many of these rocks had been metamorphosed, and the freedom of sample selection was restricted by, and subordinate to more economically important criteria in the choice of bore hole sites. Consequently, these samples may not be ideal ones for a comparison of isotopic ages measured by different methods.

The only cases where the geological determination of the $^{87}\text{Rb}$ half-life from a comparison of K-Ar and Rb-Sr analyses could be valid are where unmetamorphosed volcanic and high level plutonic rocks are used. In the present study, the rock units which fall into the above category, and which have been analysed by both methods, are the Triassic granites of the Maryborough Basin (Chapter 3. c) and the Upper Carboniferous granites of the Brawl Creek area which intrude
**TABLE 24**

Comparison of K-Ar ages with Rb-Sr ages calculated on different values of the $^{87}\text{Rb}$ half-life.

<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>K-Ar Age</th>
<th>Rb-Sr Age</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td><strong>4.7 x 10^{10}</strong> yrs</td>
</tr>
<tr>
<td>Bulgonunna Volcanics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Granites which intrude</td>
<td>$283 \pm 2$ (M)</td>
<td>$287 \pm 12$ (T)</td>
</tr>
<tr>
<td>Bulgonunna Volcanics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maryborough Basin granites</td>
<td>$217 \pm 2.5$ (M)</td>
<td>$218 \pm 16$ (T)</td>
</tr>
</tbody>
</table>

(T) Total Rock                     (M) Mineral

The K-Ar age is quoted with 95% confidence limits of the mean.
the Bulgonunna Volcanics (Chapter 4. a (iii). Table 24 lists the K-Ar and the Rb-Sr ages (based on 4.7 and $5.0 \times 10^{10}$ yrs for the $^{87}$Rb half-life) for these rock units. In both cases, the correspondence in age between the K-Ar mineral age and the Rb-Sr total rock age using the $4.7 \times 10^{10}$ yrs half-life is extremely close.

Other rocks dated by the Rb-Sr method had either been subjected to metamorphism e.g. the Urannah Complex, or contained no minerals suitable for K-Ar dating. However, the Rb-Sr dates on the Auburn and Urannah Complexes could be explained most simply if the $4.7 \times 10^{10}$ yr half-life was used.

The evidence therefore suggests that the $4.7 \times 10^{10}$ yr half-life for $^{87}$Rb is closest to the correct "geological" constant, but because of uncertainties in the $^{40}$K decay constants, and the calibration of $^{38}$Ar tracer, such a conclusion may be premature.
CHAPTER 6

GRANITES, OROGENY
AND CONTINENTAL GROWTH

5. a Tectonic setting of the granites: their relation with orogeny

It was reiterated in a recent paper (Gilluly, 1966) that the original definition of orogeny was "mountain building", and that the term did not encompass the entire cycle of geosynclinal filling and subsequent folding, magmatic intrusion and uplift. However, orogeny is not a single, isolated phase in the evolution of a part of the earth's crust, but may occur semi-continuously during the sedimentary filling of geosynclines and the deformation of the sediments within them. Thus it seems logical to use the adjective orogenic to describe the region or the time in which these processes occurred. Tectonism, the "structural behaviour of an element of the earth's crust during, or between, major cycles of sedimentation" (Krumbein and Sloss, 1956) may be strong (diastrophic) during orogenic periods, or slight during epeirogenic phases.

Although it is widely recognised that granites may occur in both orogenic and non-orogenic settings, most granitic rocks have been considered to be associated in space with geosynclinal sediments, and (approximately) in time with relatively strong tectonism. These granites have been subdivided and classified on the basis of texture, chemical composition, mode of occurrence and depth of emplacement, the different
types covering the spectrum from extensive migmatites and metamorphic granites (or granitic gneiss) to small massive homogeneous epizonal plutons, e.g., Read's Granite Series (1949, 1955). Despite the diversity, the various types are usually regarded as being the products of different stages of the one generative process and to be genetically related to orogenic activity.

Browne (1931) described the different conditions which he believed prevailed during the formation of "synchronous" and "subsequent" granite batholiths in New South Wales. Both groups of granites were related to phases of mountain building movements. The former, which contained both "gneissic (contaminated)" and "foliated" granites concordant with the country rocks, were related to separate episodes of compressive folding; while the "subsequent" granites were the "massive" transgressive granites which accompanied the final uplift of the orogenic zone. Browne's view on the close association between granitic intrusion and folding of the geosynclinal sediments which they intrude was stated thus: "wherever a bathylith outcrops we may infer the former presence, on or over that spot, of a series of geosynclinal sediments, terrestrial or marine, during whose folding and elevation the intrusion of the bathylith took place". Joplin (1962) followed Browne's classification of the New South Wales granite types, but not his correlation of rock type with specific orogenic phases.

Most of the granites in eastern Queensland are typical of high level, post tectonic granites (Read, 1955), and of Browne's (1931) subsequent batholiths. Joplin's (1962) description of massive granites
could be applied to a large percentage of these granites, the only departures from this type being in parts of the Auburn Complex and the Connors Arch (which show signs of cataclasis and recrystallisation) and in the rapakivi granites near Proston. The determination of isotopic dates has made possible a closer examination of the relationship between strong tectonism and granite intrusion in this region.

Three major earth movements that occurred after the Lower Palaeozoic in eastern Australia were the Tabberabberan, Kanimbla and Hunter-Bowen Orogenies (David, 1950).

**The Tabberabberan Orogeny**

This movement occurred between the Middle and Upper Devonian, and its effects can be seen most clearly in Victoria and New South Wales. Massive granites which accompanied this orogeny are not structurally or lithologically distinct from those which were intruded during the Kanimbla Orogeny (David, 1950).

In Queensland, the effects of the Tabberabberan orogeny are not as apparent, although the time was marked by the commencement of sedimentation and volcanism in several new depositional areas. Granites of this age occur in the Anakie High (Retreat Granite) and at Mount Morgan. The Retreat Granite pre-dates the main deposition in the Drummond Basin. The granite intrudes rocks that were metamorphosed at least 90 million years earlier, and thus it is not likely to be genetically associated with this metamorphism. Most probably it accompanied the uplift of the Anakie High to form the eastern margin of the Drummond Basin.
The intrusion of the Upper Devonian granites at Mt Morgan closely followed the early sedimentation and volcanism in the Yarrol Basin. They may be compared with the Thunderbolt Granite in the Connors Arch which intruded the Lizzie Creek Volcanics - the initial phase of volcanism in the Bowen Basin. There has been little or no loss of argon from either the Mt Morgan or Thunderbolt Granites, implying the absence of strong tectonism or thermal effects subsequent to the granite emplacement in these areas.

**The Kanimbla Movement**

The Kanimbla Movement, defined by Carey and Browne (1938), was applied to a tectonic phase that affected Upper Devonian rocks in New South Wales. The term was redefined by Browne (in David, 1950, p. 312) on the basis of the following evidence. Wherever they can be observed together in the field, the Upper Devonian strata are followed conformably by the Lower Carboniferous. There is a similar continuous transition of sedimentation (and vulcanicity) from the Upper Carboniferous to the Lower Permian, but where Lower Permian strata are in contact with Lower Carboniferous or Upper Devonian, there is a strong angular break. The Lower Carboniferous rocks include the Lower Kuttung Group and older formations, while the Upper Carboniferous is represented by the Upper Kuttung Group. Where the Lower and Upper Kuttung Groups occur together there is no apparent unconformity, but conglomerates are common at the base of the younger unit, and were believed to represent a period of tectonic uplift. Intrusive rocks that cut Upper Devonian strata are overlain by Lower Permian. Browne considered that the most likely time for tectonism and granite emplacement to have occurred was between the
deposition of the Lower and Upper Kuttung Groups, and this event he called the Kanimbla Movement or Orogeny. He believed that the movement culminated at the end of the Visean (p. 699).

Stratigraphic investigations since 1950 have shown that earth movements were more frequent than Browne (in David, 1950) assumed; in particular, the transition from Carboniferous to Permian is rarely one of continuous sedimentation (Browne, 1960; Voisey, 1965). However this does not detract from Browne's earlier statement that the major tectonism occurred between the deposition of the Lower and Upper Kuttung Groups.

Browne (1960) reviewed the stratigraphy and palaeontology of the Carboniferous succession. The age of the Lower Kuttung Group appears to be reasonably well defined palaeontologically as Visean, but the evidence on the age of the Upper Kuttung Group is inconclusive. Browne suggested that it may have occupied most of the Upper Carboniferous except for part of the Namurian. The Kanimbla Movement, from this evidence, must have occurred during the Namurian.

Palaeomagnetic measurements by Irving (1966) on rocks from the Lower and Upper Kuttung Groups have indicated that a change in palaeolatitude of 45° (of which no more than half could be attributed to polar wandering; the remainder therefore being due to crustal displacement) occurred between the deposition of the two Groups. Even if one accepts a catastrophic model of tectonic activity, a crustal shift of such magnitude relative to the earth's magnetic poles must have taken a significant interval of time; a period in which a major orogeny could have occurred.
The K-Ar dates of volcanic rocks in the Lower and Upper Kuttung Groups (Evernden and Richards, 1962) had a large scatter and appear generally unreliable. However, the oldest ages (~325 m.y.) measured on samples of the Lower Kuttung lavas may give an approximate age for this Group. This age agrees with the age of 325 m.y. proposed by Francis and Woodland (1964) for the end of the Visean. The Upper Kuttung Group had a minimum age of 298 m.y.

Granites which Browne (David, 1950) believed were emplaced during the Kanimbla Movement have K-Ar ages of 305-310 m.y. (Evernden and Richards, 1962), and Rb-Sr dating (total rock, biotite and K-feldspar) of one of these granites (Bofinger, pers. comm.) supports the K-Ar age. The isotopic ages of the lavas and granites therefore agree in general with Browne's interpretation of the age of the Kanimbla Movement. From this evidence, a period of 10 to 15 million years must have separated the Upper and Lower Kuttung Groups.

The granites of the Connors and western Auburn Arches are the time equivalents of the plutonic rocks of the Kanimbla Movement. In the Auburn Complex and the southern part of the Connors Arch, the granites are massive types. Further to the north in the Connors Arch, they show signs of foliation and in places have been sheared and recrystallised. However, much of this fabric may have been produced in the Permian, long after the intrusion of the granites. Other granites were emplaced in northern Queensland at this time, e.g. the Oweenee Granite (see Chapter 6) in the Burdekin Basin (= Star Basin) and the Elizabeth Creek Granite (Richards et al., 1966). In Queensland, the evidence of an orogeny at
this time is probably not as well documented in any one place, but the accumulated data from many localities lend support to Browne's hypothesis that the Kanimbla Movement affected almost the whole of eastern Australia. In the Drummond Basin, the Drummond Group (Lower Carboniferous) is unconformably overlain by the Upper Carboniferous Bulgonunna Volcanics. In the Burdekin Basin (Wyatt, et al., in prep.), an unconformity separates the Upper Devonian-Lower Carboniferous succession from Upper Carboniferous volcanics and associated sediments, and the emplacement of the Oweenee Granite probably occurred during this break. Maxwell (1960) suggested that a faunal break occurred in the southern part of the Yarrol Basin during the Namurian, and east of the Connors Arch, the Upper Carboniferous sequence is absent, and the Upper Devonian to Lower Carboniferous Campwyn Beds are unconformably overlain by the Lower Permian Carmila Beds.

The Permian Hunter-Bowen Orogeny has usually been accorded the position of major importance in discussions of the Upper Palaeozoic orogenic phases that affected the Queensland section of the Tasman Geosyncline. However, it now seems that the Carboniferous Kanimbla Movement, or at least the magmatic phase of it, was of equal importance.

The Hunter-Bowen Orogeny

The Permian strata of eastern Australia crop out in two areas — one in Queensland and the other in northeastern New South Wales — separated by the Mesozoic sediments of the Surat Basin. The contemporaneity of sedimentation, volcanism and coal measure formation in the two areas has long been recognised (David, 1911; Jensen, 1912), and it has
been suggested that the sedimentation occurred in one basin which extended from Townsville to the south of Sydney. The apparently contemporaneous tectonism in both regions led to the introduction of the term "Hunter–Bowen Movement" by Carey and Browne (1938). The Permian sequence in New South Wales had been more closely studied than the equivalent strata in Queensland, and the timing of the tectonic events of the Hunter–Bowen Orogeny has been based on the evidence from New South Wales.

David (1950) described two phases of this orogeny: the first affected strata as young as early Upper Permian (Upper Marine sequence) and was related to uplift in the east which caused the withdrawal of the marine seas and the formation of coal measure swamps. The second phase occurred at the close of the Permian, producing folding and thrust faulting, and was followed by injection of granitic magma. A more detailed description of the earth movements which affected the Permian strata in New South Wales was given by Voisey (1958).

In the Bowen Basin, the intensity of the folding of the strata in the northern trough decreases up section (westwards). The Rewan Formation (Permian–Triassic) is strongly folded while the overlying Triassic sandstones are less strongly affected. The age of the folding is probably post-Middle Triassic, and Malone (in prep.) suggests that it occurred during the Lower Cretaceous.

In the Gogango Overfolded Zone, the youngest unit (early Upper Permian) is also the most strongly folded, and an Upper Permian age for the folding is possible. This would correlate approximately with
the initial phase in New South Wales (David, 1950).

To the west of the Overfolded Zone is the Folded Zone (see Plate 1), which is bounded on the west by thrust faults. The folding was probably caused by the same event that folded the strata of the Overfolded Zone. The marginal thrusts on the west may have been due to decollement, aided by uplift in the east along the Connors and Auburn Arches, in the late Permian or Mesozoic.

In the Marlborough area (Overfolded Zone) the gabbro-diorite intrusions (245 m.y.) followed the cessation of sedimentation and may have been approximately contemporaneous with the folding in the area. The 230-235 m.y. old granites, in the area from Marlborough to the south, are in the region of late Permian uplift (Gogango Overfolded Zone and Auburn Arch) and their emplacement was most probably associated with this vertical movement. Although the Connors Arch was also probably uplifted during the late Permian, there do not appear to be any granites intruded in that area during the Upper Permian.

The ages of the Permian granitic intrusion in Queensland therefore appear to coincide with the phases of tectonic activity (early Upper Permian and late Permian) proposed by David (1950). The area of Permian granite intrusion, however, was more restricted than had been suggested by Reid (1930) and David (1950), who included the granites of the Connors Arch in the Upper Permian intrusions.

Granites not related to orogenic activity

In addition to the Retreat Granite, other granites, whose relationship with tectonic events is uncertain, occur in eastern Queensland.
In the north of the Anakie High in the Upper Carboniferous, the granites were genetically related to acid extrusives in a typical non-orogenic or post-orogenic setting. The volcanic-granite association is similar to that described in north Queensland (Branch, 1966) although the cauldron and ring structures have not been recognised. Joplin (1964) described this type of association of acid lavas and comagmatic granites and adamellites as a late stage in the stabilisation of a geosyncline.

The Middle Triassic granites in southeastern Queensland can not be distinguished on lithology and texture from the late Permian granites to the west. They may represent a second post-tectonic phase of plutonism associated with the Hunter-Bowen Orogeny, but such a relationship is somewhat forced. The intrusions are all closely related to episodes of tensional faulting. Block faulting of Permian sediments occurred in the Stanthorpe-Warwick area, and has been related to the intrusion of the granites (220 m.y.) of the Stanthorpe district (Richards and Bryan, 1924). Rifting occurred in the Ipswich-Esk region in the Lower Triassic, and normal fault movements in the Maryborough Basin (Ellis, 1966) may have initiated the early Triassic sedimentation in this region. Further tensional movements in the Middle or Upper Triassic occurred along the eastern margin of the Esk Rift and in the Maryborough Basin, and it is in the areas of uplift at this time that the 220 m.y. old granites were emplaced.

The Cretaceous granites appear to be unrelated to either sedimentation or folding movements. They are at least 100 m.y. younger than the youngest strata which they intrude, and are, in the main,
older than the Cretaceous sediments of both the Maryborough and the Styx Basins (and therefore older than the folding of the sediments in these basins).

The younger Cretaceous granites are epizonal types and are possibly related to the acid volcanics (111 m.y.) in the region; a similar association to that in the Anakie High in the Upper Carboniferous. The younger granites and the volcanics occur along the margins of the Tertiary Proserpine Graben, and may be related to the early stages of development of this structure. The general area of Cretaceous intrusion was probably being uplifted during the Lower Cretaceous and was perhaps related to the downwarping and marine transgression in the Great Artesian Basin to the west and southwest.

Many of the granites discussed in this Chapter were intruded in regions of non-deposition and tectonic stability, or during an intermediate period of transition from post-tectonic to epeirogenic conditions. The conclusion that can be drawn is that granite intrusion need have no connection with orogenic activity, and even when it does, the style of tectonism is not necessarily reflected in the texture of the igneous intrusion which accompanies it.

Somewhat similar conclusions were made by Gilluly (1965) who criticised the assumption that geosynclinal sedimentation, tectonism and plutonism were always closely related or synonymous.

5. b Continental evolution: Sr isotope geochemistry

Two dates in the history of the earth, within rather broad limits of uncertainty, have come to be accepted by many scientists. The
primordial earth is believed to have formed some 4,500 million years ago (Patterson, 1956; Gast, 1962; Murthy and Patterson, 1962). The oldest igneous and metamorphic events which have been dated by isotopic investigations are 3,000 to 3,500 million years old, but almost certainly, volcanic and sedimentary and perhaps metamorphic processes occurred before that time (Donn et al., 1965). The sialic crust is therefore at least 3,500 million years old, but the earth's history before that date has been largely obscured by more recent events.

The major components of the outer layers of the earth are the Upper Mantle and the Continental and Oceanic Crusts. The mantle and crust are separated by the Mohorovicic Discontinuity, which, in most regions, is a plane marking a fairly abrupt change in density and seismic velocity. The upper mantle is believed to be the source region of basaltic magmas and a composition intermediate between peridotite and basalt was suggested by Ringwood (1962).

The continental crust is usually between 35 and 40 kilometers thick, and is enriched in alkalis, silica and aluminium relative to the underlying mantle. It is divided into an Upper and Lower Crust. The upper crust, from observation, is considered to approach granodioritic composition and is composed of a Basement of crystalline rocks (granites, recrystallised sediments and volcanics) and an overlying veneer of sedimentary rocks, with a total thickness of about 15 kilometers. The composition of the lower crust must be inferred, but is believed to be of more basic composition than the upper crust. The work of Ringwood and Green (1966) indicates that under the pressure and
temperature conditions in the lower crust, the stable form of basaltic rocks would be eclogite. Both the density and seismic velocity of this material are inconsistent with the observed values for the lower crust. Ringwood and Green (1966) prefer a lower crust composed of rocks of intermediate composition occurring in the eclogite facies. Similar conclusions as to the chemical composition and physical nature of the lower crust were reached by Den Tex (1965) and Heier and Adams (1965). There are divergent opinions as to whether it has been involved in the sedimentary cycles and orogenic processes that have moulded the upper crust.

The term Sial has usually been used to describe the average chemical composition of the continental crust, but was restricted by Hurley, Hughes, Faure et al. (1962) to describe only that part of the crust that is observed, i.e. the basement. This definition is used in the following discussion. The term Primary, as used in this thesis, refers to material which has never before been exposed at the surface of the earth, or resided in the upper crust.

Two broad but opposing views, each with numerous variants, have been proposed to explain the evolution of the continents. The initial separation of the crust and mantle probably occurred between 4,500 and 3,500 million years ago, and during this differentiation, the alkalis and radioactive and other lithophile elements were concentrated in the upper mantle and crust. One hypothesis is that fractionation of the crustal material was virtually completed in this episode and that the continents have remained relatively constant in size ever since. Upon
foundered blocks, or between blocks of this ancient crust, the younger sedimentary basins were formed. These basins were filled by volcanics and detritus derived from the neighbouring blocks, and were eventually rewelded to them by metamorphism and granitisation of the material in the geosynclinal pile. The concentric arrangement of progressively younger orogenic belts around an ancient core has been interpreted as a gradual outward solidification (cratonisation) of an originally mobile continent (Gastil, 1960; Hills, 1965). A variation of this hypothesis is that, in an early stage of the earth's history before the crust formed, the lithophile elements were concentrated in proto-continents. Subsequent differentiation resulted in the separation of crust and mantle without any change in the continental area. The sub-continental mantle would be an ultramafic residuum similar to that proposed by Stueber and Murthy (1966).

The model of Stueber and Murthy (1966), however, is not inconsistent with the opposing hypothesis of continental accretion from the adjacent sub-oceanic mantle. This hypothesis is that separation of the lithophile elements is virtually completed beneath the continents, but that the sub-oceanic mantle is still fractionating. The continents are thus believed to have grown by accretion of volcanic and plutonic rocks and sediments derived from them, to the margins of the ancient sialic blocks (Wilson, 1959; Engel, 1963; Dietz, 1966). Measurements of the geothermal flux and gravity in the oceanic and continental crusts suggest that each region has a different structure to a depth of at least 500 kilometers (MacDonald, 1964; Birch, 1965). The geothermal flux is approximately
equal in the two areas, but as the surface rocks in the continents have a higher radioactivity than the corresponding rocks of the ocean basins, there must be a compensating greater content of radioactive elements in the sub-oceanic mantle than in the sub-continental mantle. The sub-oceanic mantle is therefore more capable of undergoing fractionation to produce sial than is the depleted sub-continental mantle; and the boundary between the two regions, to a depth of several hundred kilometers, is the zone of greatest potential instability where orogenic processes may be triggered. Ringwood (1966) also suggests that there are differences in the upper mantle below continents and ocean basins; that the sub-continental mantle is a residual peridotite while the sub-oceanic mantle is primary pyrolite (basalt/peridotite, Ringwood, 1962).

In support of the first hypothesis, with respect to the Australian continent, Hills (1955) has put forward evidence which appears to indicate that the same pattern of lineaments can be observed throughout the whole continent. This implies a basic or primitive structural pattern within the continent which has been in existence and influencing the crust throughout geological time. On this model, eastern Australia is composed of a veneer of Phanerozoic strata which overlies an older (Precambrian) crust: the structures of this veneer reflect the structure of the crust beneath, which is continuous with the exposed craton to the west. Campana (1955) envisaged the folding of narrow mobile belts, e.g. the Adelaide Geosyncline, as due to compression by jostling of adjacent large cratonic blocks, and implied the permanence
of these blocks on a continental scale.

The alternative hypothesis, growth by accretion of sediments and igneous rocks (Voisey, 1959), is an attractive one because there are no known Precambrian rocks to the east of the heavy line in Figure 1. Neither is there any doubt that there has been a progression of sedimentation and igneous activity eastward ever since the late Proterozoic. The absence of continental crust to the east of Australia (Wilson, 1959) also suggests that the youngest geosynclinal sedimentation occurred at or off the continental margin.

Hurley, Hughes, Faure et al. (1962) examined this problem in relation to the North American continent, using as a guide, the evolution of the isotopic composition of strontium. The concentration of $^{87}\text{Sr}$ in a closed rock system which contains rubidium will increase with time by the addition of the daughter product of the radioactive decay of $^{87}\text{Rb}$. The effect of this increase is conveniently expressed and measured as the ratio $^{87}\text{Sr}/^{86}\text{Sr}$. As $^{86}\text{Sr}$ is a stable, non-radiogenic isotope, the ratio $^{87}\text{Sr}/^{86}\text{Sr}$ will increase with time. The primary $^{87}\text{Sr}/^{86}\text{Sr}$ in the earth has been estimated by the determination of this ratio in chondritic and achondritic materials and ancient basaltic rocks (Gast, 1960, 1962) as 0.6985. Measurements of $^{87}\text{Sr}/^{86}\text{Sr}$ in young basalts from oceanic regions (Faure and Hurley, 1963; Lessing and Catanzaro, 1964; McDougall and Compston, 1965; Tatsumoto et al., 1965; Powell and De Long, 1966; Hedge, 1966) fall within the range 0.702 - 0.705, and suggest small but significant differences in strontium isotopic composition and Rb/Sr in the source regions (Upper
mantle). Despite these variations, the data are consistent with a model of earth formation in which the initial fractionation of the crust and mantle began approximately 4.5 billion years ago. The fractionation of the sialic elements outwards resulted in an effective removal of much of the rubidium from the mantle: a Rb/Sr = 0.04 has been suggested for the upper mantle (Faure and Hurley, 1963). Consequently the $^{87}$Sr/$^{86}$Sr ratio in the upper mantle has grown only very slightly during the past 4.5 billion years, from 0.698 to about 0.702-0.705.

A granitic rock, because of its relative enrichment in Rb, will have a $^{87}$Sr/$^{86}$Sr ratio which grows at a greater rate than that of the basalt source region. Hurley, Hughes, Faure et al. (1962) calculated that in the upper crust, with Rb/Sr = 0.25 (granodiorite) the faster rate of increase of $^{87}$Sr/$^{86}$Sr would produce a difference of about 0.010 in 1,000 m.y. This is 10 or 20 times greater than the uncertainty in the initial $^{87}$Sr/$^{86}$Sr of samples analysed in the present study, and such a difference would be easily detectable by present methods. If, after a period of about 200 to 300 m.y. in the crust, a granite is exposed at the surface and eroded, its detritus which becomes incorporated in sedimentary rocks will have a $^{87}$Sr/$^{86}$Sr ratio somewhat greater than 0.702 - 0.705. The magnitude of this ratio will depend on the time between the intrusion and erosion of the granite, and on the Rb/Sr of the parent rock, e.g. the apparent initial $^{87}$Sr/$^{86}$Sr ratios of shales have been found to be between 0.705 and 0.720 (Compston and Pidgeon, 1962; Whitney and Hurley, 1964; Peterman, 1966; Bofinger, 1967).
These predictions have been used by Gast (1960) and Hurley, Hughes, Faure et al. (1962) as a basis to determine the genesis of igneous rocks. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of a rock at the time of its formation should give an indication of the chemical composition of the environment in which the rock formed. A rock which has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio significantly greater than 0.702 - 0.705 at its time of formation is unlikely to have been derived wholly from the region in which basaltic magmas are generated. Such a rock may be of anatectic origin, derived from the remelting of pre-existing sialic rocks, or be the product of the assimilation of this material in a primary magma. On the other hand, an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.702 - 0.705 may, but does not necessarily, indicate a non-crustal source. It could be produced from a secondary source composed largely of volcanogenic detritus with low Rb/Sr (Peterman et al., 1967), or which has been separated from its primary source for only a very short period of time.

Hurley, Hughes, Faure et al. (1962), and Hurley et al. (1965) showed that upper crustal rocks in North America consistently had initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios that, although low, were significantly higher than that proposed for the source of basalt magma. They concluded that although these granites could not contain significant amounts of material that had been in the crust for more than 1,000 m.y., it was possible that assimilated crustal rocks, which had been separated from their source region of low Rb/Sr for only a few hundred million years, could be present in quantities up to 70 percent. This was believed to indicate that the North American continent had grown by the fairly
constant addition of sial during the past 3,000 m.y. Lead isotope investigations by Doe (1967) on igneous rocks in the western United States can be interpreted as indicating that the granitic rocks are not the product of a simple refusion of existing crust.

Objections to the hypothesis that initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the order of 0.704 automatically exclude a predominantly crustal origin have been raised by Heier (1964, 1965), who suggested that $^{87}\text{Sr}$ fractionation could occur during metamorphism. Among the earliest minerals to fuse during anatexis are the potassium minerals, which also contain Rb and $^{87}\text{Sr}$. If this melt is removed, the residue would have a low $^{87}\text{Sr}/^{86}\text{Sr}$ and high common Sr. It was also suggested, and later confirmed by Lambert and Heier (1967), that during metamorphism to granulite facies, many elements including the alkali metals and U and Th could not be accommodated by the higher grade metamorphic minerals that formed. These elements were fractionated upwards through the crust. Thus, a combination of these two processes could form a lower crust with Rb/Sr and Sr isotopic composition similar to that of the mantle, and a granitic magma produced from this recycled material would have similar characteristics to a magma formed in the mantle.

The mobility of radiogenic Sr relative to common Sr under metamorphic conditions is possible because this isotope, when it forms, occupies its parent $^{87}\text{Rb}$ lattice site. Much lower activation energy would be required to trigger diffusion of the radiogenic Sr from the Rb site than to cause diffusion of the common Sr. However, most
available evidence indicates that the magnitude of radiogenic Sr diffusion is small, often occurring only across grain boundaries. Isotopic homogenisation of Sr between different mineral phases of a rock during metamorphism was noted by Compston and Jeffery (1959), and further evidence on this phenomenon was given by Fairbairn et al. (1961) and Lamphere et al. (1964). Arriens et al. (1966) reported that movement of $^{87}$Sr from K-feldspar to plagioclase can occur even before metamorphic changes become apparent. Even if the removal of radiogenic Sr from a rock were possible, it would apply only to the $^{87}$Sr produced by radioactive decay since the time of formation of the rock. Fractionation of $^{87}$Sr of the common Sr seem highly unlikely. Sedimentary rocks, which must be present in large volumes in any orogenic region, have been shown to have initial $^{87}$Sr/$^{86}$Sr as high as 0.720. The fact that it is possible to define isochrons with data from total rock analyses of shales attests to an homogenisation of Sr either immediately prior to, or during deposition and diagenesis. The preferential removal of $^{87}$Sr from such a rock, on a large scale, is considered unlikely.

Continental evolution

Firstly, the hypothesis that the continental crust has maintained essentially the same area throughout geological time (Hills, 1955) will be examined. It has been noted, e.g. Gilluly (1955), that small amounts of the continental crust are being lost continuously by erosion and transportation to the ocean basins, so unless the crust is becoming thinner with time, addition of material to the continents is constantly
required. Large additions will cause the continuous thickening of the crust, but there is no evidence available as to whether or not this has occurred. The hypothesis of a constant continental size requires only small additions of material of non-crustal origin (perhaps basalts) to maintain stability, and the introduction of large volumes of sialic rock is unnecessary. The periods of geosynclinal filling and folding and orogenic uplift of different ages recognised throughout the continent are explained as a continuous cycle of erosion - sedimentation - metamorphism - granite formation and emplacement - uplift - and erosion beginning a new cycle, e.g. Barth (1961).

Hedge and Walthall (1963) also suggested that because the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of continental rocks appeared to follow the trend of sea water Sr isotopic composition with time, the continental rocks represented crustal material that had been homogenised during the sedimentary cycle. This was based on very limited data that had a wide scatter about the sea water $^{87}\text{Sr}$ growth line. The data presented in this thesis, and by Hurley et al. (1965) indicate that the trend for igneous rocks is closer to the growth line of oceanic basalts (i.e. mantle) than of sea water.

The work of Lambert and Heier (1967) suggests that during metamorphism to granulite grade, many elements, including U, Th, K and Rb must be concentrated in the higher levels of the crust, from where they are removed by erosion and deposited in the younger sedimentary basins. They also found that the Th and K abundance in the exposed western
Australian shield was approximately equal to that in the younger rocks of the Tasman Geosynclinal zone, while the U content in the east was 1.5 times greater than that in the shield. In spite of this variation, they claimed that radioactivity in eastern Australia was insufficient to account for the difference in the geothermal heat flow in the two regions, even allowing for many uncertainties in the measurement and averaging of these values (0.9 μcal/cm²/sec in the older parts of the shield and 1.6 μcal/cm²/sec in eastern Australia; Howard and Sass, 1964; Hyndman, 1967). Lambert and Heier (1967) suggested that the data on radioactivity in the shield area was probably representative of only a very thin layer, and that underneath it was a lower crust (granulite or eclogite) extremely depleted in U, Th, K and Rb. This conclusion lends support to Heier's previous views on the behaviour of these elements during metamorphism.

This process is attractive, both as an explanation of metamorphic activity, and as support for the concept of a continent of stable size without addition of freshly derived igneous rocks. However, in practice it may be self depleting. As well as material lost to the ocean basins, much of the eroded Precambrian basement is still within the shield area. Between one third and one half of the shield is covered by up to 5 kilometers of essentially undeformed Proterozoic sediments, which must contain much of the eroded radioactive elements. This is also suggested by heat flow measurements in the Carpentaria region (Hyndman, 1967) where a value of 1.7 μcal/cm²/sec was measured in Proterozoic sediments. The loss of radioactive material to the shield platforms reduces the
amount that can be transferred from the Precambrian basement to the Palaeozoic geosynclines. This loss can most readily be made up by the introduction of new sial from a non-crustal source, but this can only be reconciled with a model of a continent of unchanging area if the crust is continually thickening. Thus one might expect a thicker crust in eastern Australia than in the west, where denudation has been postulated to have removed much of the upper crust (Lambert and Heier, 1967). Seismic evidence on crustal thicknesses in eastern Australia is limited, but Doyle et al. (1966) interpret a marked thinning eastward from the Snowy Mountains to the Sydney Basin, while the crustal thickness in the Snowy Mountains region is essentially the same as that in southwestern Australia.

Table 25 lists the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the volcanic and intrusive rocks which have been dated in this study by the Rb/Sr method. In Table 26 the present day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of several hornblendes and basalts are given. The hornblendes contain over 50 ppm Sr and less than 2.5 ppm Rb, and the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios were not corrected for the increase in $^{87}\text{Sr}$ since the time of formation of the minerals. The basalts are of Middle Tertiary age, or younger (Appendices B and C; Webb and Wyatt, in prep.) and no correction for age was made to the measured Sr isotope ratios. Tables 25 and 26 give an almost complete cover of the plutonic and volcanic rocks of eastern Queensland.

The present day (≈ initial) $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the basalts fall within a particularly narrow range ($0.7044 \pm 0.0004$ SD), and indicate a uniform Sr isotopic composition in the basalt source region below


<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>Age (m.y.)</th>
<th>87Sr/86Sr(initial)</th>
<th>K/Rb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urannah Complex</td>
<td>305</td>
<td>0.7047 ± 0.0009</td>
<td></td>
</tr>
<tr>
<td>Dykes in Urannah Complex</td>
<td>250</td>
<td>0.7058 ± 0.00015</td>
<td></td>
</tr>
<tr>
<td>Auburn Complex</td>
<td>305</td>
<td>0.7040 ± 0.0007</td>
<td>231 ± 37 (5)†</td>
</tr>
<tr>
<td>Bulgonunna Volcanics</td>
<td>290</td>
<td>0.7049 ± 0.0005</td>
<td>217 ± 14 (8)</td>
</tr>
<tr>
<td>Granites intruding</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulgonunna Volcanics</td>
<td>290</td>
<td>0.7049 ± 0.0003</td>
<td>198 ± 30 (7)</td>
</tr>
<tr>
<td>Granites (Gayndah – Proston)</td>
<td>270</td>
<td>0.7041 ± 0.0028</td>
<td>219 ± 41 (5)</td>
</tr>
<tr>
<td>Volcanics (Bogie – Bowen Rivers)</td>
<td>230</td>
<td>0.7055 ± 0.0007</td>
<td>298 ± 32 (6)</td>
</tr>
<tr>
<td>Granites (Maryborough Basin)</td>
<td>220</td>
<td>0.7035 ± 0.0008</td>
<td>238 ± 36 (6)</td>
</tr>
<tr>
<td>Volcanics (Conway Range)</td>
<td>110</td>
<td>0.7037 ± 0.0004</td>
<td>288 ± 46 (8)</td>
</tr>
</tbody>
</table>

† The figures in parentheses refer to the number of samples analysed. The variation quoted is the standard deviation.
<table>
<thead>
<tr>
<th>Sample</th>
<th>Locality or Rock Unit</th>
<th>Age</th>
<th>$^{87}\text{Sr}/^{86}\text{Sr}$(measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>782 (H)</td>
<td>Mount Barker</td>
<td>L. Cretaceous</td>
<td>0.7053</td>
</tr>
<tr>
<td>792 (H)</td>
<td>Eungella</td>
<td>L. Cretaceous</td>
<td>0.7059</td>
</tr>
<tr>
<td>5356 (H)</td>
<td>Hecate Granite</td>
<td>L. Cretaceous</td>
<td>0.7045</td>
</tr>
<tr>
<td>1053 A (H)</td>
<td>Marlborough</td>
<td>U. Permian</td>
<td>0.7046</td>
</tr>
<tr>
<td>1163 (H)</td>
<td>Marlborough</td>
<td>U. Permian</td>
<td>0.7036</td>
</tr>
<tr>
<td>5359 (H)</td>
<td>Princhester</td>
<td>U. Permian</td>
<td>0.7046</td>
</tr>
<tr>
<td>1250 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7048</td>
</tr>
<tr>
<td>1369 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7048</td>
</tr>
<tr>
<td>5350 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7063</td>
</tr>
<tr>
<td>5351 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7035</td>
</tr>
<tr>
<td>5353 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7049</td>
</tr>
<tr>
<td>5364 (H)</td>
<td>Auburn Complex</td>
<td>U. Permian</td>
<td>0.7059</td>
</tr>
<tr>
<td>5567 (WR)</td>
<td>Nulla Basalt</td>
<td>Pleistocene</td>
<td>0.70458)</td>
</tr>
<tr>
<td>5568 (WR)</td>
<td>Nulla Basalt</td>
<td>Pleistocene</td>
<td>0.70443)</td>
</tr>
<tr>
<td>5570 (WR)</td>
<td>Nulla Basalt</td>
<td>Pleistocene</td>
<td>0.70412)</td>
</tr>
<tr>
<td>5577 (WR)</td>
<td>Nulla Basalt</td>
<td>Pleistocene</td>
<td>0.70402)</td>
</tr>
<tr>
<td>5578 (WR)</td>
<td>Nulla Basalt</td>
<td>Pleistocene</td>
<td>0.70427)</td>
</tr>
<tr>
<td>5573 (WR)</td>
<td>Mt Fox</td>
<td>Pleistocene</td>
<td>0.70440)</td>
</tr>
<tr>
<td>5574 (WR)</td>
<td>Toomba Basalt</td>
<td>Recent</td>
<td>0.70444)</td>
</tr>
</tbody>
</table>

CONTINUED........
<table>
<thead>
<tr>
<th>Sample</th>
<th>Locality or Rock Unit</th>
<th>Age</th>
<th>$^{87}\text{Sr} / ^{86}\text{Sr}$ (measured)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5575 (WR)</td>
<td>Sturgeon Basalt</td>
<td>Pleistocene</td>
<td>0.70583, 0.70526, 0.7055, 0.7054</td>
</tr>
<tr>
<td>777 (WR)</td>
<td>Springsure</td>
<td>Oligocene</td>
<td>0.7034</td>
</tr>
<tr>
<td>1032 (WR)</td>
<td>Springsure</td>
<td>Oligocene</td>
<td>0.7044</td>
</tr>
<tr>
<td>1033 (WR)</td>
<td>Springsure</td>
<td>Oligocene</td>
<td>0.7041</td>
</tr>
<tr>
<td>1034 (WR)</td>
<td>Springsure</td>
<td>Oligocene</td>
<td>0.7043</td>
</tr>
<tr>
<td>1148 (WR)</td>
<td>Hoy Basalt</td>
<td>? Oligocene</td>
<td>0.70437, 0.70409, 0.7042</td>
</tr>
<tr>
<td>1401 (WR)</td>
<td>Main Range Volcanics</td>
<td>Miocene</td>
<td>0.7042</td>
</tr>
<tr>
<td>1404 (WR)</td>
<td>Main Range Volcanics</td>
<td>Miocene</td>
<td>0.70499, 0.70424, 0.7046</td>
</tr>
<tr>
<td>5302 (WR)</td>
<td>Main Range Volcanics</td>
<td>Miocene</td>
<td>0.70441, 0.70445, 0.7044</td>
</tr>
<tr>
<td>1963 (WR)</td>
<td>Lamington Group</td>
<td>Miocene</td>
<td>0.7042</td>
</tr>
<tr>
<td>5542 (WR)</td>
<td>Lamington Group</td>
<td>Miocene</td>
<td>0.70477, 0.70488, 0.7048</td>
</tr>
<tr>
<td>5544 (WR)</td>
<td>Lamington Group</td>
<td>Miocene</td>
<td>0.7043</td>
</tr>
</tbody>
</table>

(H) = Hornblende (WR) = Whole Rock
most of eastern Queensland. This value lies at the high end of the range of $^{87}\text{Sr}/^{86}\text{Sr}$ measured in young oceanic basalts (Hedge, 1966), and may therefore indicate the Sr isotopic composition of the subcontinental mantle. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Palaeozoic and Mesozoic igneous rocks vary between 0.7035 and 0.7055, and in general are not significantly different from the values measured on the basalts.

This evidence can be interpreted on the model proposed by Hurley, Hughes, Faure et al. (1962) to indicate that the igneous rocks of eastern Queensland were not derived from an old sialic source. The alternative explanation then, is that the rocks were derived either directly from the mantle (basalt source region) or by a two stage process of assimilation or refusion of very young material. In either of these cases, a continuous addition of new sialic rock has been made to the continental margin throughout the Phanerozoic. While the present evidence does not disprove the hypothesis that a Precambrian basement underlies eastern Australia, it does indicate that such a basement, if present, was not actively involved in the geological events of the Phanerozoic.

Although the evidence appears to favour a model of continental growth, the precise mechanism is by no means clear. The simplest explanation is one of direct derivation of sialic material from the mantle. The idea of producing the calc-alkaline suite by fractional crystallisation from a basalt magma is not a new one (Bowen, 1928), but all hypotheses have foundered upon the problem of producing large
volumes of felsic material from the basaltic parent. Green and
Ringwood (1966) have demonstrated that this problem may be overcome
if the calc-alkaline suite is derived by partial melting of eclogite
of basaltic composition, where up to 50% melting can produce liquids
of andesitic composition. With this possible solution to the volume
problem, one can erect hypotheses of multi-stage production of igneous
rocks compatible with the observed low values of initial $^{87}\text{Sr}/^{86}\text{Sr}$,
and the theory of continental growth.

Wilson (1959) and Taylor and White (1966) suggested that the
most likely source of the new material which is added to the crust
is andesitic volcanism. Andesite is a common and often dominant
component of many eugeosynclinal areas (Kay, 1951), either as lavas,
or contributing to the detritus deposited in the geosyncline. The
origin of orogenic andesites has long been disputed, but the mechanism
proposed by Green and Ringwood (1966) and the Sr isotopic evidence
(Hedge and Walthall, 1963; Faure and Hurley, 1963; Pushkar, 1967;
Ewart and Stipp, in press; Compston, pers. comm.) suggest that a
mantle origin is possible. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of andesites in recent
or present day orogenic areas range from less than 0.704 to 0.706, the
lower values being measured in rocks from areas devoid of a continental
crust. The higher values are found in the New Zealand andesites, where
refusion of Mesozoic sediments has been suggested.

The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of eugeosynclinal greywackes derived
from volcanic terranes in the western U.S.A. have been determined by
Peterman et al. (1967) and fall within the range 0.704 to 0.708. The
fusion of this material at the base of a geosynclinal pile, or the assimilation of it in a primary granitic magma could then produce a rock with an initial $^{87}\text{Sr}/^{86}\text{Sr}$ similar to that observed in many granites. If, however, this geosyncline was floored by a sialic basement, it seems probable that partial melting of the basement would also occur and a higher initial $^{87}\text{Sr}/^{86}\text{Sr}$ would result. This, then, appears to be another argument against the presence of a Precambrian crust beneath the younger rocks of eastern Australia.

The geological development of eastern Queensland may be considered to have occurred in two stages; an early phase in the Lower Palaeozoic and a late phase in the Upper Palaeozoic and Mesozoic. Very little is known about the Lower Palaeozoic phase because of the restricted outcrop of rocks of this age. Voisey (1959) suggested that a miogeosyncline and eugeosyncline existed, but this conclusion is partly an extrapolation of the known palaeogeography of Victoria and New South Wales. However, where they occur, the Lower Palaeozoic rocks are usually of low metamorphic grade.

The marine Upper Palaeozoic rocks overlie the suggested Lower Palaeozoic eugeosynclinal area. The younger sequence, too, had eugeosynclinal characteristics, e.g. active sedimentation and widespread intermediate volcanism, but the tectonic activity was much less intense than that normally postulated in the classical orogenic cycle. Folding, except in restricted areas, was less than moderate; and, in contrast to the Lower Palaeozoic rocks, evidence of metamorphism is rare. Granites emplaced early in the cycle have remained closed systems with respect
to potassium and argon, indicating negligible tectonism subsequent to their emplacement.

If the igneous rocks emplaced in eastern Queensland during the Upper Palaeozoic and Mesozoic were the products of fusion of crustal material, the source must almost certainly have been the basement to the Upper Palaeozoic geosyncline, which may have been 150 to 200 million years old at that time. No estimates of the Rb/Sr ratio of these rocks, or their $^{87}\text{Sr}/^{86}\text{Sr}$ in the Upper Palaeozoic have been made, but if a Rb/Sr of 0.25 is assumed, there would have been an increase of 0.002 in the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the basement during the Lower Palaeozoic. Thus, the basement at the time of formation of the Upper Palaeozoic and Mesozoic granites, must have had $^{87}\text{Sr}/^{86}\text{Sr}$ at least as high as 0.705. The granites, then, are unlikely to have formed by direct fusion of the basement, although assimilation in a primary magma could produce the observed low values of initial $^{87}\text{Sr}/^{86}\text{Sr}$.

An idealised model of granite formation may be summarised as follows, although not all stages are obvious in eastern Queensland.

1. The eugeosyncline forms at the continental margin, and is floored by an oceanic crust. Andesitic volcanics, originating from the mantle (Ringwood and Green, 1966) are extruded along an island arc system on the ocean side of the trough.

2. Lavas and volcanic debris fill the eugeosyncline, and these rocks may be intruded by sub-surface equivalents of the lavas, e.g. the Mt Morgan Granite in the Yarrol Basin and the Thunderbolt Granite in the northern Bowen Basin.
3. Episodes of folding occur and the area is uplifted in the final phase of the orogenic period. Granite emplacement may occur during this phase, e.g. the post-orogenic Upper Permian granites of the Marlborough area and the Auburn Arch.

4. As the focus of activity shifts outwards towards the ocean, the old eugeosynclinal region becomes overlain by a miogeosyncline or an autogeosyncline. However, although all diastrophic movements have ceased at the surface, the temperature at the base of the crust is still high due to the accumulated heat producing radioactive elements, magmatic heat associated with intrusive rocks and the blanketing effect of the large thickness of overlying sediments. During this period, the lower crust is evolving from a heterogeneous mixture of sediments, volcanics and plutonic rocks to an assemblage of high grade metamorphic rocks. The development of the lower crust may continue over a long period of time, during which, processes such as those described by Heier (1965) and Lambert and Heier (1967) occur. Granitic magmas are formed by melting of the more granitic material in the crust, or by mixing of this melt in a primary magma from the mantle. Epeirogenic tensional movements in the upper crust localise or permit the release of these magmas into the higher levels of the crust. Thus the formation of the granite can not be related directly to any tectonic activity observable in the upper crust. Examples of granites of this type are the Retreat Granite, the Middle Triassic granites of southeastern Queensland and the Lower Cretaceous granites of the Mackay-Bowen hinterland.
On this model, the lower crust could be the source of granitic magmas, as suggested by Heier (1965), but with the constraint that this process will probably occur only once in any particular region. The concept that the same material will go through several cycles of intrusion, erosion, sedimentation and metamorphism is not compatible with the proposed model. Also, there is no need to postulate $^{87}\text{Sr}/^{86}\text{Sr}$ fractionation (Heier, 1964), since a low initial $^{87}\text{Sr}/^{86}\text{Sr}$ can be attained with a single cycle mechanism.

It may be inferred that this process of continental growth by the addition of sial, initially derived from the upper mantle below the continent-ocean boundary, has operated since the time the Australian continent was represented by a number of discrete nucleii.
CHAPTER 6

METALLOGENETIC EPOCHS

The association of granite intrusion with ore mineralisation

Jones (1947) made a comprehensive study of the ore deposits of Queensland and the relation between these deposits and igneous rocks, and defined several periods of mineralisation which he believed to be associated with distinct episodes of igneous activity. Within the area of the Tasman Geosyncline he recognised three phases of ore deposition. He named these (1) the Herberton Epoch (Devonian to Lower Carboniferous, related to ultrabasic and granitic intrusion), (2) the Gympie Epoch (late Permian to Middle Triassic, related to granitic intrusion and acid volcanism) and (3) the Maryborough Epoch (Upper Cretaceous, associated with granitic intrusion). The Gympie Epoch was subdivided into three phases based on the association of the ore with a particular type of igneous activity. The most important was the Gympie Phase, in which ores were related to granitic intrusions.

Although there had been previous attempts to group the ore deposits, Jones' classification was the first detailed attempt to correlate the ores with igneous rock type and time. This grouping of the Queensland deposits has been followed with few modifications by Browne (1949), David (1950, vol 2), Jones (1953) and Hills (1953, 1965). It was extensively revised by Jones and Carruthers (1965), who believed that almost all of the mineralisation since the Precambrian occurred between the Upper Carboniferous and the Lower Triassic; while the
granites with which Jones (1947) had associated the mineralisation of the Maryborough Epoch were stated to be of Upper Jurassic age.

Two requirements are necessary for this type of correlation of ore deposits with igneous episodes. Firstly, it must be shown that there is a causal (if not genetic) relationship between the ore deposits and the igneous rocks, and secondly, the age of the igneous rocks must be reasonably well known. The first condition was examined in some detail by Jones (1947), and in most cases there seems to be a close physical association between the igneous rocks and the ores. However, as was noted earlier in this thesis, difficulties arise when one attempts to assign close limits to the age of the intrusive rocks by stratigraphic methods. The data reported here, together with published isotopic ages in North Queensland (Richards et al., 1966), have made possible a re-examination of the earlier correlations between mineralisation, igneous activity and time. This thesis has dealt mainly with the coastal region between Bowen and Stanthorpe, but a few age determinations made on igneous rocks in mineralised areas to the north and west of this belt will be examined to complete the coverage of the ore deposits in eastern Queensland.

**Charters Towers – Ravenswood mineral fields**

The Ravenswood Granodiorite, which forms the host rock for much of the mineralisation, intrudes metamorphic rocks, and is overlain by Middle Devonian sediments. At Charters Towers (see Figure 3), it is intruded by dykes ranging in composition from aplite to diorite—
porphyrite, and the latter are known to intrude both the ore body and the aplite dykes (Jack, 1879; Reid, 1917). K-Ar mineral ages on the intrusions are given in Table 27. From these limited data, one can deduce that the mineralisation at Charters Towers occurred between 440 and 330 million years ago.

Ukalunda - Mt Wyatt (Sellheim River)

The mineralisation is related to granitic rocks which intrude Middle and Upper Devonian sediments. The age of these granites was discussed in Chapter 4. a (iii). The isotopic dating was inconclusive, but gave a minimum age of 295 million years for the intrusions. Since the granites cannot be older than Upper Devonian, the age of the mineralisation is most likely to be Lower Carboniferous.

Star River area

Widespread Sn, Cu, Au and Ag mineralisation in this region appears to be related mainly to the Oweenee Granite and smaller granitic intrusions in the Argentine area (Wyatt et al., in prep.). K-Ar mineral ages (Table 27) on some of these granites spread between 275 and 300 million years. This is similar to the spread in ages reported on the mineralised Elizabeth Creek and Herbert River Granites a little further to the north (Richards et al., 1966).

The Herberton Epoch

Most of the mineralisation in northern Queensland, with the exception of the Argentine and Sellheim fields, was placed by Jones (1947) in the Herberton Epoch. K-Ar dating has shown the granites of the Cooktown area to be Upper Permian (Richards et al., 1966) and has
<table>
<thead>
<tr>
<th>GA NO.</th>
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<th>AVE.K</th>
<th>40Ar*/40K</th>
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<td>6.56</td>
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<tr>
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confirmed the Carboniferous age of the remainder of the mineralising granites. In most cases, the K-Ar dates are not precise enough to distinguish between an Upper or Lower Carboniferous age, but an Upper Carboniferous age is most likely. On present evidence, the Argentine and Sellheim deposits also belong to this Epoch. The Charters Towers mineralisation, however, was probably pre-Carboniferous.

The Gympie Epoch

The ore deposits which Jones (1947) included in the Gympie Epoch occur between Mt Flora and Stanthorpe. The granitic rocks with which most of these ore deposits are associated have been shown to be of Upper Permian or Middle Triassic age. Ores which are not associated with granites of these ages occur at Mt Flora (Cretaceous) and possibly at Mt Morgan (Devonian).

At Mt Morgan, the age of mineralisation is not known with any certainty. If the correlation of the host rocks with the Middle Devonian Dee Volcanics (Maxwell, 1953, 1960) is correct, then the ore must be post-Middle Devonian. The ore body is cut by the Porphyrite Dyke, a large porphyritic microgabbro, (GA 5340, Table 17), which yielded an age of 229 m.y. for the plagioclase phenocrysts. The ore, then, is pre-Triassic. If it is related to the Mt Morgan or Town Granites, it is of Upper Devonian age, while if it is related to the mineralised Moonmera Granite (GA 5341, 235 m.y., Table 17) a few miles to the north, it is of Upper Permian age and therefore part of the Gympie Epoch.

Table 28 lists the areas of mineralisation, the type of mineralisation and the age of the granites with which the deposits of the Gympie
<table>
<thead>
<tr>
<th>Locality</th>
<th>Au</th>
<th>Cu</th>
<th>Ag</th>
<th>Pb</th>
<th>Sn</th>
<th>Bi</th>
<th>Sb</th>
<th>Mo</th>
<th>W</th>
<th>Age (m.y.)</th>
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</thead>
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<td>Brisbane</td>
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<td>X</td>
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<td></td>
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<td></td>
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<td>Stanthorpe</td>
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<td></td>
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<td></td>
<td>X</td>
<td>X</td>
<td></td>
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</tr>
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<td>Monsildale</td>
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<td>X</td>
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<td>X</td>
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<tr>
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<td>Biggenden</td>
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<tr>
<td>Mount Perry</td>
<td>X</td>
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<td>X</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>220</td>
</tr>
<tr>
<td>Nanango</td>
<td></td>
<td>X</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>235</td>
</tr>
<tr>
<td>Eidsvold</td>
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<td>X</td>
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<td></td>
<td></td>
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<tr>
<td>Moonmera</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>235</td>
</tr>
</tbody>
</table>

* Denotes assumed age. For explanation, see text.
Epoch are associated. It can be seen that although copper and gold mineralisation are common to both the 235 m.y. and 220 m.y. periods of intrusion, the younger phase appears to contain in addition, ores of bismuth, molybdenum, antimony, tin and tungsten. The Table includes deposits from the Maryborough district which had been placed in the Maryborough Epoch by Jones (1947), but which, for reasons explained below, may well belong to the Triassic Epoch of mineralisation.

Where the mineralised areas are widespread and embrace more than one intrusive body, there may be some difficulty in designating the source of the mineralisation. This is the case in the Stanthorpe district, where a large area of the New England Batholith is mineralised. Relatively few age determinations have been made on this batholith and only two ages of granitic emplacement have been recognised (Evernden and Richards, 1962; Cooper et al., 1963; Binns and Richards, 1964). At least six distinct intrusions have been mapped in the northern area alone (Saint-Smith, 1914). GA 5282 (Table 20) is from the Sandy Granite of Saint-Smith, who showed it to be the youngest phase of intrusion. It is associated with the Sn, Mo, Bi and W mineralisation. Jones (1947), summarising the views of the earlier workers, stated that the Au, Ag and Pb mineralisation was also associated with late stages of the igneous activity, and this has been included in the 220 m.y. old group. Supporting evidence of the age of the Mo mineralisation is given by Hirt et al. (1963), who report a rhenium-osmium age of 225 ± 20 m.y. for a molybdenite from Carpenter's Gully, southwest of Stanthorpe.
Another age reported by these authors was determined on molybdenite from Wonbah, in the Mt Perry district. The age of $210 \pm 40$ m.y. agrees well with the age of 220 m.y. measured on the granite from the Wonbah Range (GA 5325). The Mt Perry Au-Cu lodes lie midway between two dated localities (GA 5295, 250 m.y. Table 17, and GA 5325, 220 m.y. Table 4), but Ellis (pers. comm.) believes that the ores are related to the younger granites (220 m.y.) to the east.

The isotopic dating of the Middle Triassic granites in the Maryborough - Gympie area (Webb and McDougall, 1967), while confirming the conclusions of Jones with respect to the Gympie Epoch of mineralisation, has thrown doubt on the existence of the ore mineralisation which he assigned to the Maryborough Epoch. The ore deposits in this area are frequently found at the contacts between the granites and folded rocks of Palaeozoic age, e.g. Neardie, Teebar and Culgoa (Rands, 1890; Denmead, 1960). There is no stratigraphic evidence to indicate that the granites must be younger than Triassic. The proximity of the granitic rocks at Teebar, Culgoa, Marodian and Yorkey's to the known Triassic granites near Biggenden and the Permian or Triassic granites at Kilkivan, and their similar geological environment, suggest that no distinction as to age should be drawn between these intrusions. If the antimony deposit at Neardie is associated with the Woondum Granite (GA 5311, Table 4) then it too is of Middle Triassic age, although Denmead (1943) related this deposit to volcanic activity. David (1950, vol ii) included the deposits of Biggenden and Monsildale in the Cretaceous mineralisation. These were placed in the Gympie Epoch by
Jones, and the present work supports this interpretation.

Cretaceous mineralisation, however, did occur in other areas of Queensland. Between Mt Flora and Bowen, numerous occurrences of small scale mineralisation are frequently associated with granitic rocks which have been shown to be of Lower Cretaceous age. These are described in Chapter 4. a (vii) and are shown in Figures 13 and 15. They include Mt Flora (Ball, 1910 a), Eungella - Mt Barker (Ball, 1910 b), the Don River basin south of Bowen, and the mineralised contact between the Hecate Granite and the Permian volcanics west of Proserpine. The Mt Flora intrusion (Bundarra Granodiorite) was not dated, and its age has been deduced by correlation with a small porphyry intrusion a few miles to the south west (GA 1243, 123 m.y. Table 21). These intrusions are similar in lithology and form, and dome the Permian sediments around them.

Although these Cretaceous deposits are small, and most of them ceased to be of commercial interest during the last century, nevertheless almost every mineral prospect in the area belongs to this group. The Palaeozoic granites of the Urannah Complex appear to be barren. Thus there is some justification in regarding the Lower Cretaceous mineralisation as belonging to a metallogenic epoch in the sense used by Jones (1947).

With few exceptions, Jones' classification has been upheld. These exceptions are mainly in areas where the stratigraphic control on the age of the deposits is poor. Generally, the isotopic dating has narrowed the necessarily wide limits Jones placed on the age of the
### TABLE 29

Summary of Correlations of Ore Mineralisation with Time

<table>
<thead>
<tr>
<th>Locality</th>
<th>Mineralisation</th>
<th>Epoch (Jones, 1947, 1953)</th>
<th>Epoch (This thesis)</th>
<th>Isotopic Age (m.y.)</th>
</tr>
</thead>
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<tr>
<td>Cairns Hinterland</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elizabeth Ck.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Herbert R.</td>
<td>Sn</td>
<td>Herberton</td>
<td>Herberton</td>
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<td>pre-Herberton</td>
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<th>Epoch (This thesis)</th>
<th>Isotopic Age (m.y.)</th>
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metallogenetic epochs. The Herberton Epoch is probably mainly of Upper Carboniferous age, and the Gympie Epoch granitic phase is Upper Permian to Middle Triassic. The most important departure from Jones’ scheme is the probable non-existence of the Maryborough Epoch, and the discovery of the Lower Cretaceous mineralisation in the Bowen-Mackay area. Thus some modifications to Jones’ classification and nomenclature are now possible. The granitic phases of the Gympie Epoch have been designated Gympie I and Gympie II, while a change in nomenclature for the Cretaceous mineralisation is proposed. In the early reports on these Cretaceous mineral fields, geologists of the Geological Survey of Queensland used the term Mackay hinterland; and because there seems to be no acceptable alternative, the name Mackay Epoch is suggested, even though there may be mineralisation of an older age included in the region. A comparison of Jones’ (1947) classification with that based on isotopic dating is given in Table 29.

One notable feature of the Palaeozoic granites is that, although similar in most respects, some are almost completely barren of ore minerals, while others introduced some of the richest deposits in the State. The least productive are the Upper Devonian Retreat Granite and the Upper Carboniferous granites of the Connors and Auburn Arches. The latter case is even more anomalous, when it is considered that granites of this age were responsible for the rich mineralisation of the Cairns hinterland, and the Kanimblan deposits of New South Wales (Browne, 1949).
CHAPTER 7

SUMMARY

(1) Dating of the igneous rocks of eastern Queensland has provided more precise information on the age of the Middle Triassic and Upper Permian, and supports previous estimates of the age of the Upper Carboniferous and Lower Permian. These dates are summarised as follows:

- Middle or post-Middle Triassic: 220 m.y.
- Middle to late Upper Permian: 240 m.y.
- Early Upper Permian: 250 m.y.
- Lower Permian: 270 m.y.
- Late Carboniferous: 285 m.y.

(2) Granite intrusion and volcanism occurred in two periods during the Upper Palaeozoic and Mesozoic. The most widespread and prolonged phase occupied all of the Upper Palaeozoic and most of the Triassic, during which time, granite emplacement occurred in pulses separated by an average interval of 20 million years. The focus of intrusion moved irregularly to and fro in a north-south sense, and generally eastward with time. Episodes of volcanism coincided in time with some of the intrusive phases.

The second period of granite intrusion and volcanism occurred during the Lower Cretaceous. The initial phase was one of granite emplacement; and after an interval of 10 million years, the second phase - one of acid volcanism and high level granite intrusion - occurred.
A period of non-orogenic basaltic volcanism occurred in the Oligocene and Miocene, and was accompanied by near surface trachytic and rhyolitic intrusives.

(3) In areas where heating has occurred subsequent to granite formation (the Connors Arch), the isotopic mineral ages have been lowered. This effect applies to both K-Ar and Rb-Sr ages, but to a greater extent with the K-Ar ages. Under conditions of predominantly burial metamorphism hornblende loses argon to an equal degree to biotite, the two minerals giving concordant ages and (in the absence of Rb-Sr dating) suggesting that the measured date is a meaningful one. Thus it is possible to have a large number of apparently concordant K-Ar ages of mineral pairs resulting in a serious misinterpretation of the history of the particular rocks. In such cases, therefore, total rock Rb-Sr dating is the quickest and most reliable method of dating, although a loss of precision occurs if (as with most of the granites in eastern Queensland) the Rb-Sr ratios of the rocks are low.

Where the granites have not been subjected to later thermal activity, the K-Ar method produces reliable mineral ages on a wide variety of rock types and is probably the easiest method of age determination, especially on Upper Palaeozoic and younger rocks with low Rb/Sr ratios. The Rb-Sr method, however, has the advantage of indicating an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, and hence, information on the genesis of the material.

(4) The close correspondence between K-Ar mineral ages and Rb-Sr total rock ages using $\lambda^{87}\text{Rb} = 1.47 \times 10^{-11} \text{yr}^{-1}$ suggests that this is the best value for the $^{87}\text{Rb}$ decay constant, if the $^{40}\text{K}$ decay constants and isotopic abundance used are correct.
The classification of the Palaeozoic ore deposits of eastern Queensland with time and periods of granite intrusion proposed by Jones (1947) has been largely upheld, although several refinements are now possible. The Cretaceous mineralisation proposed by Jones in the Maryborough Basin is probably non-existent, but a phase of mineralisation west of Mackay at this time has been discovered by the isotopic dating. The epochs of mineralisation in eastern Queensland can now be defined as follows:

A. Herberton Epoch - Carboniferous, and probably mainly Upper Carboniferous.

B. Gympie Epoch - two granitic phases - I Upper Permian
II Middle Triassic.

C. Mackay Epoch - Lower Cretaceous.

The granites are mainly massive and typically post-tectonic in appearance. While some can be related in time to the Tabberabberan, Kanimbla and Hunter-Bowen orogenies, others, very similar in appearance, were emplaced during prolonged periods of crustal stability.

The initial ⁸⁷Sr/⁸⁶Sr of the granites and volcanics in eastern Queensland lie between 0.7035 and 0.7055, and can be interpreted as indicating a predominantly sub-crustal origin of these rocks. The hypothesis that eastern Australia has grown laterally by accretion to the Precambrian shield is supported. The geologically young part of the continent is believed to be composed largely of material derived from the mantle. Throughout the Phanerozoic, the region has been slowly stabilised by the evolution of an upper and lower crust. During this
time, granitic magmas were formed either by partial fusion of the more sialic material in the lower crust, or by assimilation of this material in primary magmas.
ROCK TYPE AND SAMPLE LOCALITIES

The samples listed in this Appendix each have two numbers. The GA number is the official registration of the sample in the Department of Geophysics and Geochemistry, A.N.U., and is used in the Text, Tables and Figures. The other number is based on a National Grid (1° of latitude and 1° 30' of longitude): the first part of the number, e.g. F55/15, refers to a particular map sheet (Emerald) and the final number is the sample identification for that sheet.

GA 399
Granodiorite - Retreat Granite
Emerald 4-mile grid ref. 581200, 2113300.
Lat. 23° 09' S. Long. 147° 38' E.
K-Ar Table 7.

GA 400
Granodiorite - Retreat Granite
Emerald 4-mile grid ref. 581000, 2105500.
Lat. 23° 13' S. Long. 147° 37' E.
K-Ar Table 7.

GA 401
Quartz Diorite - Retreat Granite
Emerald 4-mile grid ref. 591200, 2065900.
Lat. 23° 33' S. Long. 147° 43' E.
K-Ar Table 7.

GA 402
Adamellite - Retreat Granite
Emerald 4-mile grid ref. 585500, 2097300.
Lat. 23° 17' S. Long. 147° 39' E.
K-Ar Table 7.
GA 472
Granodiorite
Bowen 4-mile grid ref. 661385.
Lat. 20° 51' S. Long. 148° 17' E.
K-Ar Table 11. Rb-Sr Table 12.

GA 473
Adamellite
Bowen 4-mile grid ref. 620445.
Lat. 20° 24' S. Long. 147° 56' E.
K-Ar Table 15A.

GA 474
Adamellite
Bowen 4-mile grid ref. 627455.
Lat. 20° 20' S. Long. 148° 00' E.
K-Ar Table 11.

GA 729
Adamellite
Bowen 4-mile grid ref. 569400, 2411200.
Lat. 20° 42' S. Long. 147° 29' E.
K-Ar Table 8, Rb-Sr Table 10.

GA 781
Tonalite – Mt. Barker Granodiorite
Mt. Coolon 4-mile grid ref. 670000, 2354100.
Lat. 21° 9' 45" S. Long. 148° 22' 30".
K-Ar Table 21.

GA 782
Granodiorite – Mt. Barker Granodiorite
Mt. Coolon 4-mile grid ref. 671300, 2355500.
Lat. 21° 5' 30" S. Long. 148° 24' 0" E.
K-Ar Table 21.

GA 792
Granodiorite
Mackay 4-mile grid ref. 116800, 2357000.
Lat. 21° 07' S. Long. 148° 30½' E.
K-Ar Table 21.
Adamellite - Urannah Complex
Bowen 4-mile grid ref. 647500, 2409300.
Lat. 20° 43' S. 143° 10' E.
K-Ar Table 11. Rb-Sr Table 12.

Granodiorite
Bowen 4-mile grid ref. 536500, 2415600.
Lat. 20° 40' S. Long. 147° 12' E.
K-Ar Table 8. Rb-Sr Table 10.

Adamellite
Bowen 4-mile grid ref. 552700, 2441800.
Lat. 20° 27' S. Long. 147° 19' E.
K-Ar Table 8. Rb-Sr Table 10.

Granodiorite
Mulgildie No. 1 Well, Core 14, 3992'4" - 3993'3"
Monte 4-mile
Lat. 24° 58' S. Long. 151° 08' E.
K-Ar Table 17.

Adamellite - Retreat Granite
Emerald 4-mile grid ref. 569600, 2079600.
Lat. 23° 27' S. Long. 147° 31' E.
K-Ar Table 7.

Granodiorite - Retreat Granite
Emerald 4-mile grid ref. 576000, 2129300.
Lat. 23° 02' S. Long. 147° 34' E.
K-Ar Table 7.

Adamellite - Retreat Granite
Emerald 4-mile grid ref. 556700, 2115000.
Lat. 23° 09' S. Long. 147° 24' E.
K-Ar Table 7.
GA 1027  
Diorite - Retreat Granite  
Emerald 4-mile grid ref. 562000, 2118000.  
Lat. 23° 07' S. Long. 147° 27' E.  
K-Ar Table 7.

GA 1028  
Granodiorite - Retreat Granite  
Emerald 4-mile grid ref. 573300, 2073000.  
Lat. 23° 29' S. Long. 147° 33' E.  
K-Ar Table 7.

GA 1029  
Adamellite  
Emerald 4-mile grid ref. 571000, 2070500.  
Lat. 23° 31' S. Long. 147° 32' E.  
K-Ar Table 8.

GA 1030  
Adamellite  
Emerald 4-mile grid ref. 570000, 2069400.  
Lat. 23° 31' S. Long. 147° 31' E.  
K-Ar Table 8.

GA 1037  
Trachyte  
Mt. Ramsay  
Baralaba 4-mile grid ref. 276900, 1980000.  
Lat. 24° 14' S. Long. 149° 53' E.  
K-Ar Table 21.

GA 1040  
Schist - Anakie Metamorphics  
Clermont 4-mile  
Lat. 22° 51' S. Long. 147° 28' E.  
K-Ar Table 7.

GA 1053  
Xenolithic Granodiorite - (A) Matrix (B) Xenolith  
St. Lawrence 4-mile grid ref. 273600, 2149500.  
Lat. 22° 51' S. Long. 149° 53' E.  
K-Ar Table 17.
GA 1054

Granodiorite
St. Lawrence 4-mile grid ref. 275500, 2167000.
Lat. 22° 43' S. Long. 149° 53' E.
K-Ar Table 17.

GA 1067

Granodiorite - Auburn Complex
Mundubbera 4-mile grid ref. 337400, 1863900.
Lat. 25° 13' S. Long. 150° 26' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 1068

Diorite
Duaringa 4-mile grid ref. 267700, 2077400.
Lat. 23° 27' S. Long. 149° 49' E.
K-Ar Table 17.

GA 1069

Adamellite
Duaringa 4-mile grid ref. 269300, 2075500.
Lat. 23° 29' S. Long. 149° 50' E.
K-Ar Table 17.

GA 1072

Granite - Urannah Complex
Bowen 4-mile grid ref. 662700, 2393300.
Lat. 20° 51' S. Long. 148° 18' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 1073

Adamellite
Mt. Coolon 4-mile grid ref. 581800, 2347800.
Lat. 21° 12' S. Long. 147° 35' E.
K-Ar Table 8.

GA 1136

Granodiorite - Urannah Complex
Mackay 4-mile grid ref. 241300, 2347600.
Lat. 21° 13' S. Long. 148° 42' E.
K-Ar Table 11.
GA 1137
Granodiorite - Urannah Complex
Mackay 4-mile grid ref. 138000, 2346600.
Lat. 21° 14' S. Long. 148° 41' E.
K-Ar Table 11.

GA 1138
Granodiorite - Urannah Complex
Mackay 4-mile grid ref. 136600, 2342000.
Lat. 21° 17' S. Long. 148° 39' E.
K-Ar Table 11.

GA 1142
Granite
Proserpine 4-mile grid ref. 171000, 2384400.
Lat. 20° 55' S. Long. 148° 59' E.
K-Ar Table 21.

GA 1154
Granite
Proserpine 4-mile grid ref. 171000, 2385300.
Lat. 20° 54' S. Long. 148° 59' E.
K-Ar Table 21.

GA 1155
Gabbro
St. Lawrence 4-mile grid ref. 193000, 2228000.
Lat. 22° 10' S. Long. 149° 17' E.
K-Ar Table 20.

GA 1160
Adamellite
Bowen 4-mile grid ref. 536900, 2387000.
Lat. 20° 53½' S. Long. 147° 12' E.
K-Ar Table 8, Rb-Sr Table 10.

GA 1161
Adamellite
Bowen 4-mile grid ref. 532800, 2387100.
Lat. 20° 54' S. Long. 147° 10' E.
K-Ar Table 8.
GA 1162

Diorite — Urannah Complex
Bowen 4-mile grid ref. 625000, 2423900.
Lat. 20° 51' S. Long. 148° 17' E.
K-Ar Table 11.

GA 1163

Diorite
St. Lawrence 4-mile grid ref. 275200, 2166100.
Lat. 22° 43' S. Long. 149° 53' E.
K-Ar Table 17.

GA 1164

Diorite
St. Lawrence 4-mile grid ref. 275500, 2167900.
Lat. 22° 42' S. Long. 149° 53' E.
K-Ar Table 17.

GA 1166

Granodiorite
Monto 4-mile grid ref. 372000, 1988800.
Lat. 24° 12' S. Long. 150° 45' E.
K-Ar Table 17.

GA 1167

Granodiorite
Monto 4-mile grid ref. 370300, 1995200.
Lat. 24° 08' S. Long. 150° 44' E.
K-Ar Table 17.

GA 1168

Granodiorite — Auburn Complex
Mundubbera 4-mile grid ref. 352500, 1849100.
Lat. 25° 20' S. Long. 150° 34' E.
K-Ar Table 17.

GA 1169

Adamellite — Auburn Complex
Mundubbera 4-mile grid ref. 350700, 1846700.
Lat. 25° 22' S. Long. 150° 33' E.
K-Ar Table 17.
GA 1170
Adamellite - Urannah Complex
Proserpine 4-mile grid ref. 121600, 2398000.
Lat. 20° 48' S. Long. 148° 33½' E.
K-Ar Table 21.

GA 1187
Gabbro
St. Lawrence 4-mile grid ref. 209500, 2222200.
Lat. 22° 15' S. Long. 149° 19' E.
K-Ar Table 20.

GA 1189
Granodiorite - Urannah Complex
St. Lawrence 4-mile grid ref. 218100, 2190200.
Lat. 22° 31' S. Long. 149° 23½' E.
K-Ar Table 11.

GA 1190
Adamellite - Auburn Complex
Mundubbera grid ref. 310300, 1874000.
Lat. 25° 02' S. Long. 150° 26' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 1217
Granodiorite - Neurum Tonalite
Gympie 4-mile grid ref. 588677.
K-Ar Table 4.

GA 1243
Granodiorite
Bowen 4-mile grid ref. 532500, 2430000.
Lat. 20° 32½' S. Long. 147° 10½' E.
K-Ar Table 8, Rb-Sr Table 10.

GA 1244
Microgranodiorite
Clermont 4-mile grid ref. 664500, 2243600.
Lat. 22° 04' S. Long. 148° 20½' E.
K-Ar Table 21.
GA 1245
Granodiorite
Monto 4-mile grid ref. 412500, 1978200.
Lat. 24° 17' S. Long. 151° 07' E.
K-Ar Table 20.

GA 1246
Granodiorite
Monto 4-mile grid ref. 431900, 1961100.
Lat. 24° 25' S. Long. 151° 17' E.
K-Ar Table 20.

GA 1247
Granodiorite
Monto 4-mile grid ref. 431900, 1942700.
Lat. 24° 34' S. Long. 151° 17' E.
K-Ar Table 20.

GA 1248
Granodiorite
Monto 4-mile grid ref. 428400, 1942700.
Lat. 24° 34' S. Long. 151° 15' E.
K-Ar Table 20.

GA 1249
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 369000, 1923400.
Lat. 24° 44' S. Long. 150° 43' E.
K-Ar Table 17.

GA 1250
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 380400, 1903600.
Lat. 24° 54' S. Long. 150° 49' E.
K-Ar Table 17.

GA 1251
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 341900, 1908400.
Lat. 24° 51' S. Long. 150° 28' E.
K-Ar Table 11.
GA 1369
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 383900, 1919000.
Lat. 24° 46' S. Long. 150° 51' E.
K-Ar Table 17.

GA 1370
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 355300, 1899400.
Lat. 24° 56' S. Long. 150° 36' E.
K-Ar Table 17.

GA 5192
Glaucophane Schist - Rocksberg Greenstones
Ipswich 4-mile
Caboolture 1-mile grid ref. 903412.
K-Ar Table 17.

GA 5198
Granodiorite
Bowen 4-mile grid ref. 574900, 2423500.
Lat. 20° 15½' S. Long. 147° 32' E.
K-Ar Table 8.

GA 5252
Adamellite - Thunderbolt Granite
Bowen 4-mile grid ref. 619700, 2457000.
K-Ar Table 15a, Rb-Sr Table 15b.

GA 5253
Granodiorite - Thunderbolt Granite
Bowen 4-mile grid ref. 614300, 2446800.
K-Ar Table 15.

GA 5256
Granodiorite
St. Lawrence grid ref. 274200, 2149000.
Lat. 22° 52' S. Long. 149° 54' E.
K-Ar Table 17.
GA 5257

Gabbro
St. Lawrence 4-mile grid ref. 273300, 2147800.
Lat. 22° 53' S. Long. 149° 53' E.
K-Ar Table 17.

GA 5258

Pegmatite dyke
Port Clinton 4-mile grid ref. 289400, 2156500.
Lat. 22° 49' S. Long. 150° 01' E.
K-Ar Table 20.

GA 5259

Gabbro
Port Clinton 4-mile grid ref. 289700, 2157900.
Lat. 22° 48' S. Long. 150° 01' E.
K-Ar Table 17.

GA 5261

Granodiorite
Port Clinton 4-mile grid ref. 290600, 2162100.
Lat. 22° 46' S. Long. 150° 02' E.
K-Ar Table 17.

GA 5263

Hornblende Gabbro
St. Lawrence 4-mile grid ref. 278900, 2168000.
Lat. 22° 42' S. Long. 149° 55' E.
K-Ar Table 17.

GA 5264

Diorite
St. Lawrence 4-mile grid ref. 275200, 2168000.
Lat. 22° 42' S. Long. 149° 53' E.
K-Ar Table 17.

GA 5265

Granodiorite
St. Lawrence 4-mile grid ref. 275500, 2166700.
Lat. 22° 43' S. Long. 149° 54' E.
K-Ar Table 17.
GA 5266
Diorite
St. Lawrence 4-mile grid ref. 275500, 2166400.
Lat. 22° 43½' S. Long. 149° 53½' E.
K-Ar Table 17.

GA 5267
Granodiorite - Urannah Complex
Mackay 4-mile grid ref. 147900, 2333500.
K-Ar Table 11.

GA 5269
Granodiorite
St. Lawrence 4-mile grid ref. 220500, 2162000.
Rb-Sr Table 12.

GA 5270
Granodiorite
St. Lawrence 4-mile grid ref. 219500, 2190500.
Rb-Sr Table 12.

GA 5272
Gabbro
Bowen 4-mile grid ref. 636700, 2373900.
K-Ar Table 21.

GA 5274
Granodiorite - Ravenswood Granodiorite
Townsville 4-mile grid ref. 473200, 2511400.
K-Ar Table 27.

GA 5282
Adamellite
Warwick 4-mile grid ref. 508453.
K-Ar Table 20.

GA 5283
Granodiorite - Ravenswood Granodiorite
Townsville 4-mile grid ref. 456500, 2524100.
K-Ar Table 27.
GA 5284
Granite - Oweenee Granite
Townsville 4-mile grid ref. 384700, 2584000.
K-Ar Table 27.

GA 5289
Granodiorite - Urannah Complex
St. Lawrence 4-mile grid ref. 207300, 2234000.
Lat. 22° 10' S. Long. 149° 18' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 5290
Granodiorite - Urannah Complex
St. Lawrence 4-mile grid ref. 217500, 2189600.
Lat. 22° 31½' S. Long. 149° 23½' E.
K-Ar Table 11.

GA 5291
Granodiorite - Urannah Complex
Mackay 4-mile grid ref. 207000, 2294100.
Lat. 21° 41' S. Long. 149° 18' E.
K-Ar Table 11.

GA 5292
Granodiorite
Bowen 4-mile grid ref. 528700, 2402900.
K-Ar Table 8.

GA 5293
Granodiorite - Urannah Complex
Mt. Coolon 4-mile grid ref. 683100, 2346300.
Lat. 21° 12' S. Long. 148° 30' E.
K-Ar Table 11.

GA 5294
Granodiorite - Auburn Complex
Munduberra 4-mile grid ref. 336300, 180600.
Lat. 25° 13½' S. Long. 150° 26' E.
K-Ar Table 11.
GA 5295
Granodiorite - Mt. Perry Granite
Maryborough 4-mile grid ref. 456856.
Lat. 25° 15' 39" S. Long. 151° 30' 44" E.
K-Ar Table 17, Rb-Sr Table 18.

GA 5296
Adamellite - Taromeo Tonalite
Gympie grid ref. 510682.
K-Ar Table 17.

GA 5297
Granodiorite - Mt. Samson Granodiorite
Ipswich 4-mile grid ref. 599609.
K-Ar Table 4.

GA 5298
Granodiorite - Eskdale Granite
Ipswich 4-mile grid ref. 537627.
K-Ar Table 17.

GA 5311
Granodiorite - Woondum Granite
Gympie 4-mile grid ref. 597742.
K-Ar Table 4.

GA 5312
Tonalite - Taromeo Tonalite
Gympie 4-mile grid ref. 512676.
K-Ar Table 17.

GA 5313
Porphyritic Granite
Gympie 4-mile grid ref. 460745.
K-Ar Table 17.

GA 5314
Granite
Maryborough 4-mile grid ref. 508827
K-Ar Table 4, Rb-Sr Table 5.
GA 5315
Hornblende Gabbro - Somerset Dam Gabbro
Ipswich 4-mile grid ref. 567000, 634000.
K-Ar Table 4.

GA 5317
Granodiorite
Gympie 4-mile grid ref. 563758.
K-Ar Table 4.

GA 5318
Granite - Musket Flat Granite
Maryborough 4-mile grid ref. 557821.
Lat. 25° 34' S. Long. 152° 25' E.
K-Ar Table 4, Rb-Sr Table 5.

GA 5320
Granite
Maryborough 4-mile grid ref. 513858
K-Ar Table 4, Rb-Sr Table 5.

GA 5321
Granite
Maryborough 4-mile grid ref. 511801.
K-Ar Table 4, Rb-Sr Table 5.

GA 5322
Rapakiwi Granite
Maryborough 4-mile grid ref. 455798.
K-Ar Table 17, Rb-Sr Table 18.

GA 5324
Hornblende Porphyrite - Brisbane Valley Porphyrites
Ipswich 4-mile grid ref. 552626.
K-Ar Table 4.

GA 5325
Granodiorite
Maryborough 4-mile grid ref. 474883.
K-Ar Table 4, Rb-Sr Table 5.
GA 5326

Adammite - Eskdale Granite
Perserverance Creek Dam
Ipswich 4-mile
K-Ar Table 17, Rb-Sr Table 18.

GA 5327

Diorite - Urannah Complex
Bowen 4-mile grid ref. 631150, 2443750.
K-Ar Table 11.

GA 5328

Diorite - Urannah Complex
Bowen 4-mile grid ref. 626800, 2446300.
K-Ar Table 11.

GA 5329

Microdiorite dyke
Bowen 4-mile grid ref. 654000, 2423100.
K-Ar Table 16 B.

GA 5330

Granodiorite
Bowen 4-mile grid ref. 669800, 2440950.
K-Ar Table 21.

GA 5331

Adammite
Bowen 4-mile grid ref. 665100, 2434500.
K-Ar Table 21.

GA 5332

Adammite
Bowen 4-mile grid ref. 615700, 2458100.
K-Ar Table 15 a, Rb-Sr Table 15 b.

GA 5333

Foliated Diorite - Urannah Complex
Bowen 4-mile grid ref. 622900, 2462200.
K-Ar Table 11.
GA 5334

Trachyte
Mt. Jim Crow
Rockhampton 4-mile grid ref. 358800, 2106400.
Lat. 23° 13'. Long. 150° 37'1 E.
K-Ar Table 21.

GA 5335

Granodiorite - Urannah Complex
Bowen 4-mile grid ref. 643000, 2410900.
Lat. 20° 414 S. Long. 148° 07' E.
K-Ar Table 11.

GA 5336

Foliated Diorite - Urannah Complex
Bowen 4-mile grid ref. 612700, 2458300.
K-Ar Table 11.

GA 5337

Granite
Mundubbera 4-mile grid ref. 413500, 1845600.
Lat. 25° 22' S. Long. 151° 07' E.
K-Ar Table 17.

GA 5338

Adamellite
Bowen 4-mile grid ref. 629290, 2437450.
K-Ar Table 15a.

GA 5339

Granodiorite - Mount Morgan Granite
Mount Morgan Mine
Rockhampton 4-mile grid ref. 330000, 2056400.
Lat. 23° 38' S. Long. 150° 22' E.
K-Ar Table 7.

GA 5340

Feldspar Porphyry Dyke cutting Mount Morgan Granite
Rockhampton 4-mile grid ref. 330300, 2055700.
Lat. 23° 38' S. Long. 150° 22' E.
K-Ar Table 17.
Granodiorite - Moonmera Granite
Rockhampton 4-mile grid ref. 332000, 2062600.
Lat. 23° 35' S. Long. 150° 23½' E.
K-Ar Table 17.

Amphibolite - Auburn Complex
Mundubbera 4-mile grid ref. 375400, 1843300.
Lat. 25° 23' S. Long. 150° 46' E.
K-Ar Table 17.

Banded Adamellite - Auburn Complex
Monto 4-mile grid ref. 354200, 1894700.
Lat. 24° 58' S. Long. 150° 35' E.
K-Ar Table 17.

Biotite Gneiss - Auburn Complex
Mundubbera 4-mile grid ref. 378800, 1841900.
Lat. 25° 24' S. Long. 150° 48½' E.
K-Ar Table 17.

Adamellite - Auburn Complex
Mundubbera 4-mile grid ref. 379000, 1841900.
Lat. 25° 24' S. Long. 150° 48½' E.
K-Ar Table 17.

Diorite - Urannah Complex
Bowen 4-mile grid ref. 683100, 2397300.
K-Ar Table 11.

Adamellite
Bowen 4-mile grid ref. 656100, 2424700.
K-Ar Table 11.
GA 5348

Granodiorite
Monto 4-mile grid ref. 397000, 1926000.
Lat. 24° 43' S. Long. 150° 59' E.
K-Ar Table 17.

GA 5350

Granodiorite - Auburn Complex
Munduberra 4-mile grid ref. 385400, 1840200.
Lat. 25° 25' S. Long. 150° 52' E.
K-Ar Table 17.

GA 5351

Diorite
Munduberra 4-mile grid ref. 410700, 1846000.
Lat. 25° 22' S. Long. 151° 06' E.
K-Ar Table 17.

GA 5352

Granodiorite - Auburn Complex
Munduberra 4-mile grid ref. 383300, 1874800.
Lat. 25° 07' S. Long. 150° 50' E.
K-Ar Table 17.

GA 5353

Granodiorite - Auburn Complex
Munduberra 4-mile grid ref. 384500, 1885700.
Lat. 25° 02' S. Long. 150° 51' E.
K-Ar Table 17.

GA 5354

Adammellite - Urannah Complex
Bowen 4-mile grid ref. 684500, 2408500.
Lat. 20° 42' S. Long. 148° 30' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 5355

Adammellite
Bowen 4-mile grid ref. 644350, 2458500.
K-Ar Table 21.
GA 5356
Adamellite
Bowen 4-mile grid ref. 648000, 2445500.
K-Ar Table 21.

GA 5357
Biotite Gneiss - Auburn Complex
Mundubbera 4-mile grid ref. 376600, 1842400.
Lat. 25° 23' S. Long. 150° 46' E.
K-Ar Table 17.

GA 5358
Adamellite
Bowen 4-mile grid ref. 624100, 2411700.
K-Ar Table 21.

GA 5359
Granodiorite
Port Clinton 4-mile grid ref. 359100, 2157300.
Lat. 22° 50' S. Long. 150° 39' E.
K-Ar Table 17.

GA 5360
Diorite - Gracemere Granite
Rockhampton 4-mile grid ref. 341000, 2087300.
Lat. 23° 28' S. Long. 150° 28' E.
K-Ar Table 17.

GA 5361
Granodiorite - Auburn Complex
Monto 4-mile grid ref. 340500, 1904600.
Lat. 24° 53' S. Long. 150° 28' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 5362
Adamellite - Auburn Complex
Mundubbera 4-mile grid ref. 390800, 1838600.
Lat. 25° 26' S. Long. 150° 55' E.
K-Ar Table 17.
Granodiorite – Auburn Complex
Mundubbera 4-mile grid ref. 396700, 1876700.
Lat. 25° 06’ S. Long. 150° 57½’ E.
K-Ar Table 17.

Adamellite
Bowen 4-mile grid ref. 662600, 2398700.
K-Ar Table 15A.

Diorite – Town Granite
Rockhampton 4-mile grid ref. 332400, 2057400.
Lat. 23° 37½’ S. Long. 150° 23½’ E.
K-Ar Table 7.

Diorite – Mount Morgan Granite
Rockhampton 4-mile grid ref. 328700, 2054600.
Lat. 23° 39½’ S. Long. 150° 21½’ E.
K-Ar Table 7.

Diorite – Mount Morgan Granite
Rockhampton 4-mile grid ref. 329700, 2053200.
Lat. 23° 39½’ S. Long. 150° 22½’ E.
K-Ar Table 7.

Diorite – Town Granite
Rockhampton 4-mile grid ref. 333100, 2053900.
Lat. 23° 39½’ S. Long. 150° 24’ E.
K-Ar Table 7.

Granodiorite
Bowen 4-mile grid ref. 630350, 2423600.
K-Ar Table 15A.

Gneissic Granite – Urannah Complex
Bowen 4-mile grid ref. 647800, 2413700.
K-Ar Table 11.
GA 5380

Adamellite
Bowen 4-mile grid ref. 630300, 2432800.
Lat. 20° 30' S. Long. 148° 02' E.
K-Ar Table 15A.

GA 5382

Granite
Gympie 4-mile grid ref. 485711
K-Ar Table 17, Rb-Sr Table 18.

GA 5384

Rapakiwi Granite
Gympie 4-mile grid ref. 475748
K-Ar Table 17, Rb-Sr Table 18.

GA 5385

Granite
Gympie 4-mile grid ref. 548705
K-Ar Table 4.

GA 5386

Granite
Gympie 4-mile grid ref. 547706
K-Ar Table 4.

GA 5387

Granite
Maryborough 4-mile grid ref. 463816.
Lat. 25° 37' S. Long. 151° 31' E.
K-Ar Table 17, Rb-Sr Table 18.

GA 5391

Adamellite
Bowen 4-mile grid ref. 546900, 2440500.
K-Ar Table 8, Rb-Sr Table 10.

GA 5392

Granodiorite - Urannah Complex
Bowen 4-mile grid ref. 681100, 2399000.
Lat. 20° 46' S. Long. 148° 28' E.
K-Ar Table 11, Rb-Sr Table 12.
GA 5393

Adamellite
Rockhampton 4-mile grid ref. 318000, 2064900.
Lat. 23° 33' S. Long. 150° 16' E.
K-Ar Table 17.

GA 5394

Porphyry
Pentecost Is.
Proserpine 4-mile grid ref. 175100, 2447100.
K-Ar Table 21.

GA 5396

Adamellite - Urannah Complex
Bowen 4-mile grid ref. 679800, 2401700.
Lat. 20° 46' S. Long. 148° 28' E.
K-Ar Table 11, Rb-Sr Table 12.

GA 5397

Adamellite - Urannah Complex
Mackay 4-mile grid ref. 116400, 2372900.
K-Ar Table 11.

GA 5398

Adamellite
Bowen 4-mile grid ref. 641250, 2444200.
K-Ar Table 21.

GA 5399

Granodiorite
Bowen 4-mile grid ref. 629100, 2466400.
K-Ar Table 21.

GA 5501

Granite - Childers Granite
Maryborough 4-mile grid ref. 538858.
Rb-Sr Table 5.

GA 5502

Porphyry
Mt. Coolon 4-mile grid ref. 674100, 2374000.
Rb-Sr Table 16A.
GA 5503
Porphyry
Mt. Coolon 4-mile grid ref. 674100, 2374000.
Rb-Sr Table 16A.

GA 5504
Porphyry
Mt. Coolon 4-mile grid ref. 674100, 2374000.
Rb-Sr Table 16A.

GA 5505
Porphyry
Mt. Coolon 4-mile grid ref. 674100, 2374000.
Rb-Sr Table 16A.

GA 5506
Porphyry
Mt. Coolon 4-mile grid ref. 674100, 2374000.
Rb-Sr Table 16A.

GA 5507
Acid Volcanic
Proserpine 4-mile grid ref. 139500, 2447800.
Rb-Sr Table 22.

GA 5508
Acid Volcanic
Proserpine 4-mile grid ref. 143800, 2447900.
Rb-Sr Table 22.

GA 5511
Acid Volcanic
Proserpine 4-mile grid ref. 138900, 2445100.
Rb-Sr Table 22.

GA 5512
Acid Volcanic
Proserpine 4-mile grid ref. 137800, 2445200.
Rb-Sr Table 22.

GA 5514
Bulgonunna Volcanics
Bowen 4-mile grid ref. 546950, 2438900.
Rb-Sr Table 9.
GA 5515

Bulgonunna Volcanics
Bowen 4-mile grid ref. 546950, 2438850.
Rb–Sr Table 9.

GA 5517

Bulgonunna Volcanics
Bowen 4-mile grid ref. 564000, 2408200.
Rb–Sr Table 9.

GA 5518

Bulgonunna Volcanics
Bowen 4-mile grid ref. 561700, 2407500.
Rb–Sr Table 9.

GA 5519

Acid dyke
Bowen 4-mile grid ref. 569300, 2436200.
Rb–Sr Table 19.

GA 5520

Acid Volcanic
Bowen 4-mile grid ref. 562050, 2475700.
Rb–Sr Table 19.

GA 5521

Acid Volcanic
Bowen 4-mile grid ref. 565100, 2448600.
Rb–Sr Table 19.

GA 5522

Acid Volcanic
Bowen 4-mile grid ref. 565100, 2448700.
Rb–Sr Table 19.

GA 5523

Acid Volcanic
Bowen 4-mile grid ref. 564800, 2448500.
Rb–Sr Table 19.
GA 5524

Acid Volcanic
Bowen 4-mile grid ref. 572700, 2455600.
Rb-Sr Table 19.

GA 5525

Acid Volcanic
Bowen 4-mile grid ref. 577200, 2443700.
Rb-Sr Table 19.

GA 5528

Granite
Bowen 4-mile grid ref. 567200, 2411300.
Rb-Sr Table 10.

GA 5531

Granite
Bowen 4-mile grid ref. 600600, 2480200.
K-Ar Table 21.

GA 5533

Pall Mall Adamellite
Townsville 4-mile grid ref. 418900, 2557700.
K-Ar Table 27.

GA 5534

Adamellite
Bowen 4-mile grid ref. 656100, 2475100.
K-Ar Table 11.

GA 5535

Adamellite
Townsville 4-mile grid ref. 429200, 2572000.
K-Ar Table 27.

GA 5539

Acid Volcanic
Proserpine 4-mile grid ref. 136600, 2444100.
Rb-Sr Table 22.
GA 5546

**Acid Volcanic**
Proserpine 4-mile grid ref. 137400, 2445500.
Rb-Sr Table 22.

GA 5547

**Acid Volcanic**
Proserpine 4-mile grid ref. 139200, 2445200.
Rb-Sr Table 22.

GA 5552

**Acid Volcanic**
Proserpine 4-mile grid ref. 136400, 2442200.
Rb-Sr Table 22.

GA 5553

**Dacite**
Carlisle Island
Proserpine 4-mile grid ref. 205800, 2399800.
K-Ar Table 21.

GA 5554

**Granodiorite - Auburn Complex**
Monto 4-mile grid ref. 328200, 1947200.
Lat. 24° 32' S. Long. 150° 20' E.
Rb-Sr Table 12.

GA 5555

**Granodiorite - Auburn Complex**
Monto 4-mile grid ref. 321000, 1898100.
Lat. 24° 56' S. Long. 150° 17' E.
Rb-Sr Table 12.

GA 5556

**Bulgonunna Volcanics**
Bowen 4-mile grid ref. 538700, 2394300.
Rb-Sr Table 9.

GA 5557

**Bulgonunna Volcanics**
Bowen 4-mile grid ref. 555900, 2389700.
Rb-Sr Table 9.
GA 5559  
Bulgonunna Volcanics  
Bowen 4-mile grid ref. 573400, 2429700.  
Rb-Sr Table 9.

GA 5560  
Adamellite  
Bowen 4-mile grid ref. 655900, 2427800.  
K-Ar Table 11.

GA 5561  
Porphyrite dyke  
Charters Towers  
Charters Towers 4-mile grid ref. 434000, 2485300.  
K-Ar Table 27.

GA 5562  
Biotite Tuff – Gyranda Formation  
Mundubbera 4-mile grid ref. 309860.  
K-Ar Table 4.

GA 5720  
Hornblende Porphyrite Dyke  
Charters Towers 4-mile grid ref. 434000, 2485300.  
K-Ar Table 27.

GA 5721  
Hornblende Porphyrite Dyke  
Charters Towers 4-mile  
K-Ar Table 27.
APPENDIX B

A Comparison of Mineral and Whole Rock Potassium - Argon
Ages of Tertiary Volcanics from Central Queensland
Abstract

Potassium-argon ages measured on whole-rock samples of basalts of middle Tertiary age, and on sanidines from trachytes cogenetic with the basalts, indicated that no detectable argon leakage had occurred from many of the basalts even though most samples were altered to some extent. In the few cases where argon leakage was noted, there was a general increase in argon loss with increasing alteration of the plagioclase and the cryptocrystalline or glassy groundmass.

In order to achieve quantitative release of radiogenic argon from the sanidine samples it was found that an extreme heating procedure must be followed. Only at temperatures above 1650°C did complete extraction of radiogenic argon occur.
Introduction

The Eastern Highlands of Australia are covered by large areas of extrusive volcanic rocks, which are commonly referred to by the general term of "Tertiary Volcanics". The Tertiary age of some of these rocks has been demonstrated by the presence of interbedded fossiliferous sediments e.g. near Ipswich, Queensland (1, 2) and by the determination of the palaeomagnetic pole positions at the time of extrusion of the lavas (3), but frequently, it has been inferred from physiographic evidence. The widening application of the K/Ar method of dating young igneous rocks (4, 5, 6) has indicated the possibility of making a more accurate estimate of the ages of the Tertiary Volcanics in eastern Australia. In this paper are reported the results of potassium-argon age determinations, principally upon whole-rock samples of basaltic rocks, from the Springsure district of Central Queensland.

McDougall (5) demonstrated that by the imposition of rigid criteria in the selection of material for dating, ages can be obtained from whole-rock samples of basalts which are consistent with the observed order of extrusion. Alteration, devitrification or recrystallisation of potassium bearing phases in the rock are believed to cause a serious loss of radiogenic argon. Dalrymple (7) reported large scale argon leakage from altered whole-rock basalt samples. Flows which are at least 23 million years old gave apparent whole-rock ages of 13 million years and less. Some degree of alteration has occurred in almost every sample collected from the Springsure district; but there is no
evidence of either burial or of metamorphism in this area during the Tertiary so these other factors which produce argon leakage may be disregarded.

At Springsure there is a close petrogenetic association between the lavas and sanidine-bearing trachytes, and thus this suite of rocks provides an opportunity to check whole rock ages of the basalts against mineral ages of the sanidine separated from the trachytes. Sanidine in volcanic rocks has been shown to be extremely retentive of radiogenic argon (8) and therefore is considered to be a reliable mineral for use in potassium-argon dating. If the sanidine is assumed to be completely retentive of argon, then comparison between the sanidine and whole-rock ages would give a qualitative measure of the effect which alteration of the rock has on its argon retentivity. If this effect proves to be negligible, or at least tolerable, then it becomes feasible to attempt to correlate the times of Tertiary volcanism in this area with volcanic activity elsewhere in eastern Australia.

Analytical Procedures

The methods and precision of argon and potassium determinations made in this laboratory have been reported elsewhere (6, 9). Potassium determinations were made on pulverised splits of the whole rock samples, and on unground splits from the mineral concentrates. The argon extraction techniques are based on the system described by Evernden and Curtis (4). In every case the atmospheric \(^{40}\)Ar contamination was sufficiently low
that its effect on the precision of the radiogenic $^{40}$Ar measurements was negligible. Duplicate determinations would be expected to agree to within $\pm 3$ per cent at the 95 per cent confidence level (see Table 3).

The Springsure-Emerald Area

The volcanics in this area have been described by Richards (10), Reid and Morton (11) and Veevers et al. (12). Reid and Morton (11) reported plant fragments of probable Tertiary age in sediments interbedded near the base of the volcanics.

A sheet of olivine basalt, rarely thicker than 200 feet and probably containing a number of flows, extends from Emerald to the south of Springsure, a distance of over 45 miles. Much of the area is characterised by basalt rubble in a deep black soil, and outcrop is restricted to the edge of the basalt sheet and to creek banks. At Springsure and for a few miles to the north, a thickness of up to 800 feet of lavas and pyroclastics overlies the basal sheet of olivine basalts. This thick pile of sub-horizontal flows is intruded by plugs, domes, and dykes of trachyte and rhyolite which frequently contain large and abundant phenocrysts of sanidine which exceed 1-2 mm in size. Richards (10) examined the sequence near Springsure and distinguished a basaltic-trachytic-basaltic succession. Veevers et al. (12) have found that repetitions of the sequence basalt-trachybasalt-trachyandesite occur above the level of the basal olivine basalt sheet. They also report occurrences of trachytic
agglomerate, formed by shattering of a solidified trachyte plug, overlain by another basaltic-trachytic sequence of flows. Thus the acid intrusions may not all be younger than the youngest flows. However, the close petrogenetic association of the basic and acidic volcanics suggests that these rocks should be closely associated in time.

The pile of volcanics is now too deeply eroded to allow correlations to be made from one mesa to the next. Samples were collected up the sides of these hills so that the relative ages of a number of samples from each mesa would be known. Samples were collected, also, from the olivine basalts of the basal sheet, and from the porphyritic trachyte intrusions.

Discussion of results

A. Sanidine ages

The measured ages of sanidines separated from the trachyte samples are listed in Table 1. GA 686 was collected from a dome-like intrusion into Permian sediments. The other samples are from plugs and dykes in the basalts. The most striking feature of the results is the very poor reproducibility of the argon measurements, which seems to be related to the grain size of the concentrate used (Table 2). Not only does the reproducibility appear to improve, but the measured quantity of argon per gram of sample is frequently higher when the mineral is crushed to a finer grain size.

The spread in measured argon content is thought not to be due to inhomogeneities in the samples. The good reproducibility of the potassium determinations (except for the very coarse
<table>
<thead>
<tr>
<th>GA No.</th>
<th>% K</th>
<th>$^{40}\text{Ar}/^{40}\text{K}(x10^{-2})$</th>
<th>$^{40}\text{Ar}_{\text{atm}}$</th>
<th>Age (x10^6 yrs)</th>
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<td>686 A</td>
<td>5.416</td>
<td>5.429</td>
<td>0.1585</td>
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<td>39.0</td>
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<td>5.391</td>
<td>5.407</td>
<td>0.1651</td>
<td>22.2</td>
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<td></td>
<td>0.1632</td>
<td>19.0</td>
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<tr>
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<td>5.729</td>
<td>5.777</td>
<td>0.1635</td>
<td>15.4</td>
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<td>0.1570</td>
<td>12.3</td>
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<tr>
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<td>5.850</td>
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<td>0.1581</td>
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<td>0.1481</td>
<td>14.1</td>
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fraction), which were made on 0.15 gram splits, suggests that the samples were homogeneous with respect to potassium. A much larger sample weight (0.6 gram) was used for each argon extraction. Petrographic examination of thin sections of the rocks and of the mineral concentrates did not indicate any mineralogical inhomogeneities. The sanidine in every case was fresh, had a low 2V, and X-ray diffractometer measurements on GA 686 and 1150 showed that these minerals were monoclinic with no sign of unmixing. The mineral concentrates had a grain purity of greater than 98 per cent, the only contaminant being quartz. The higher argon content measured on the finer grain sizes also can not be explained by appealing to an inhomogeneous sample.

The analyses of GA 686 are presented in Table 2, and illustrate the effect both of different grain sizes and different fusion procedures. Fraction B was prepared by crushing A. Fraction C was a fresh separation from the original sample. Fractions D and E were prepared from a fresh sample, E being prepared from D by crushing. The results indicate:

1) Samples heated to 1500°C and held at that temperature for 15 minutes will retain some of their radiogenic argon. Even with fractions finer than 100 B.S. mesh there is no certainty that complete extraction will be achieved.

2) The high recovery from Fraction B and one run on Fraction C suggests that incomplete release of argon occurred in the other runs, even when samples were heated to above
Table 2

Apparent ages of GA 686 (Sanidine) for different grain sizes and heating procedures

<table>
<thead>
<tr>
<th></th>
<th>FRACTION A -60+100 BS</th>
<th>FRACTION B -100+150 BS</th>
<th>FRACTION C -100+150 BS</th>
<th>FRACTION D -22+44 BS</th>
<th>FRACTION E -100+150 BS</th>
</tr>
</thead>
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<td>NORMAL FUSION</td>
<td></td>
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<tr>
<td>15 minutes at ~ 1500°C</td>
<td>26.9 m.y.</td>
<td>28.1 m.y.</td>
<td></td>
<td>20.5 m.y.</td>
<td>26.9 m.y.</td>
</tr>
<tr>
<td></td>
<td>24.0 m.y.</td>
<td>27.7 m.y.</td>
<td></td>
<td>18.3 m.y.</td>
<td>24.0 m.y.</td>
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<td></td>
<td></td>
<td></td>
<td>20.4 m.y.</td>
<td>26.1 m.y.</td>
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<td></td>
</tr>
<tr>
<td>HIGH TEMPERATURE FUSION</td>
<td></td>
<td></td>
<td>27.8 m.y.</td>
<td></td>
<td></td>
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<tr>
<td>15-20 minutes at</td>
<td></td>
<td></td>
<td>26.1 m.y.</td>
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<tr>
<td>1600°-1650°C (estimated)</td>
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<td>26.6 m.y.</td>
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<tr>
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<td>26.4 m.y.</td>
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</tr>
<tr>
<td>HIGH TEMPERATURE FUSION</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>30 minutes at</td>
<td></td>
<td></td>
<td>26.1 m.y.</td>
<td>27.0 m.y.</td>
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<tr>
<td>~ 1650°C</td>
<td></td>
<td></td>
<td>26.7 m.y.</td>
<td>26.8 m.y.</td>
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<tr>
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<td></td>
<td></td>
<td>*</td>
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</table>

* Temperatures measured with optical pyrometer
1650°C. However, the difference between this and the high temperature runs of Fractions D and E is only just outside experimental error, and it is concluded that heating at 1650°C or greater for 20 to 30 minutes will cause an essentially quantitative release of radiogenic argon. These conclusions are supported by the data on the two fractions of GA 1150, (Table 1) where the higher ages of Fraction B are due to a finer grain size and a more intense heating.

Evernden and Curtis (4) considered this possibility of incomplete release of radiogenic argon during heating, and concluded that for samples of small bulk, heating for 20 to 30 minutes at 1550°C quantitatively released the argon. They also found no difference in the amount of argon recovered from samples which had fused to a clear glass (1650°C) and that recovered from melts which remained vesicular (low temperature). Their conclusion is not supported by the present investigation. The samples which were heated to only 1500°C were all highly vesicular, and many of them retained significant amounts of argon.

Dalrymple (7) discussed discordant dates on mineral pairs (sanidine-biotite and sanidine-plagioclase) from volcanic rocks. The sanidine dates were frequently lower than those of either the biotite or the plagioclase but because of the possibility of contamination of the biotite and plagioclase by older material, Dalrymple placed more credence on the sanidine ages.
In the present study, the spread in measured argon content of the sanidines probably is the result of a combination of several factors. The short period of time during which the temperature is raised to the fusion point of the mineral (about 15 minutes) does not allow complete diffusion to occur from the solid. This effect is expected to be more marked for the coarser grain sizes. Once fusion has occurred the viscosity of the melt will be the only factor inhibiting the release of argon, and this is independent of the initial grain size. The high viscosity of dry alkali feldspar melts was noted by Schairer (13). It appears that the difference in the percentage of argon retained in the two size fractions before fusion may be maintained for a short time after melting because of the high viscosity. The incongruent melting of K-rich feldspar to form leucite, which has a much higher melting point (13), may be another reason why difficulties were experienced in removing all the radiogenic argon. However, the argon extraction procedure is carried out under non-equilibrium conditions and the compositions of the sanidines used in the present study lie only just on the K-feldspar side of the lowest melting point of the dry NaAlSi$_3$O$_8$ - KAlSi$_3$O$_8$ system (13).

By comparison, the samples used by Evernden and Curtis (4) lie on the Na-feldspar side of the lowest melting point on the alkali feldspar liquidus curve, where complete fusion is reached at relatively low temperatures, and where there is no possibility of incongruent melting to form leucite.
The sanidine results suggest that the best minimum age for the trachytes is approximately $27.0 \pm 0.5$ million years, and this can be taken as a younger limit to the age of the basalts.

B. Whole rock ages

The whole rock ages determined on the flows are listed in Table 3, and the relevant petrographic details are given in Appendix 1. In general, the measured ages agree with the relative positions of the samples in the sequence. The basal olivine basalts may be as old as 33 m.y. (Middle Oligocene), while the thick sequence near Springsure was extruded in a period of about 1.5 million years, between 28 m.y. and 26.5 m.y. ago (Upper Oligocene) (14).

The spread of apparent ages in the older group of flows requires examination. The three samples are altered to a far greater degree than are those in the younger sequence. Consequently, all three results must be regarded as minimum ages. They could be interpreted as indicating several phases of extrusion, but most probably reflect varying degrees of argon leakage from flows which are all at least 33 million years old.

In the younger sequence of flows near Springsure, GA 1034 overlies GA 1033 near St. Peter, and GA 1035 overlies GA 1036 at Mt. Boorambool. The K/Ar ages are within experimental error, and the apparent agreement between age and stratigraphic position may be fortuitous. However, the age of 28.0 m.y. to 26.5 m.y. for this sequence agrees closely with the age of 27.0
<table>
<thead>
<tr>
<th>GA No.</th>
<th>%K</th>
<th>$^{40}\text{Ar}/^{40}\text{K}$ (x10$^{-2}$)</th>
<th>$^{40}\text{Ar}_{\text{atm.}}$</th>
<th>Age (x10$^6$ yrs)</th>
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<td><strong>Lower Flows</strong></td>
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<td>0.1574</td>
<td>73.5</td>
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± 0.5 m.y. measured on the sanidines. GA 1031 cannot be related to any of the other samples, but its measured age falls within this range. GA 1032, another isolated sample, appears to have lost radiogenic argon by comparison with GA 5158, which was subsequently collected from the same outcrop. The average of three determinations on GA 5158 (26.0 m.y.) falls just below the range of the other samples, and is significantly higher than the result for GA 1032, even though the degree of alteration was similar in both samples.

A possible cause of anomalous K/Ar ages, the presence of excess argon, must be considered. Lovering and Richards (15) have reported the occurrence of excess $^{40}$Ar in basic inclusions in basaltic pipes which were not completely outgassed by the enclosing hot lava at the time of extrusion. In the Anakie area, about 50 miles north west of Springsure, there is a group of basalt plugs of Tertiary age (unpublished data) which contain abundant inclusions of pyroxenite, peridotite, and anorthosite, as well as large xenocrysts of spinel, corundum, pyroxene and plagioclase. Inclusions of this type may carry $^{40}$Ar in excess of that produced by the radioactive decay of their $^{40}$K. However, the samples dated in this work were all dense, non-porphyritic, and homogeneous when viewed both in hand specimen and in thin section, and the possibility that they contain incompletely outgassed inclusions is remote. Consequently, it is unlikely that any possible argon loss by diffusion has been balanced by the presence of inherited
Conclusions

If the assumption that the trachytes and the younger basalts are closely related in time is valid, then the comparison between the mineral and the whole-rock ages indicates that there has been no appreciable leakage of radiogenic argon from most of these whole-rock samples. However, considerable argon loss has occurred in at least one of the older basalts (GA 5152), and this rock shows quite strong alteration of the plagioclase and the interstitial feldspathic material. The alteration of the basalts is presumed to be deuteric, and hence contemporaneous with the time of consolidation of the lavas. Thus, the alteration products, in most cases, must have retained radiogenic argon almost quantitatively over this time, despite their fine grain size.

Recent work on whole rock and mineral separates from the basic lavas and intrusives of Brazil (16, 17, 18) and measurements made on late Cainozoic basalts from Victoria (19) have also indicated that a certain degree of alteration may be tolerated before detectable argon leakage occurs.

However, the selection of samples for whole rock dating remains highly empirical, and although altered samples may on occasions give meaningful ages, they should be avoided wherever possible. If unaltered material is not available, several related samples should be analysed so that at least the
criterion of internal consistency may be applied in the evaluation of the results.

Acknowledgements

The writers acknowledge the critical reading of the manuscript by Dr J.R. Richards. R.G. Mollan collected several of the samples and two of the potassium determinations were made by J.A. Cooper. J.M. Rhodes made the X-ray diffractometer measurements. One of the authors (A.W.W.) has received permission to publish from the Director, Bureau of Mineral Resources, Canberra.
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(18) I. McDOUGALL and N.R. RUEGG

(19) I. McDOUGALL, H.L. ALLSOPP and F.H. CHAMALAUN
APPENDIX B-1
Sample descriptions

GA 686  Trachyte, Crystal Hill. 23°58' S., 148°08' E.

GA 777  Olivine basalt. Olivine titaniferous augite and plagioclase are fresh. 5-10% intersertal cryptocrystalline material which is slightly altered. 23°50' S., 148°02' E.

GA 1031  Olivine basalt. Holocrystalline, fresh except for very slight alteration of plagioclase along the cleavage. 24°08' S., 147°56' E.

GA 1032  Olivine basalt. Plagioclase and most of pyroxene is fresh. Interstitial pyroxene and fine grained ground mass with exsolved Fe oxide is altered. 24°08' S., 147°55' E.

GA 1033  Olivine basalt. Olivine strongly altered but plagioclase and pyroxene show little sign of alteration. A few percent of green chloritic material between plagioclase laths. 24°01'S., 148°03' E.

GA 1034  Olivine basalt. Very fine grained, olivine mainly altered, pyroxene occurs as tiny fresh granules between plagioclase laths, patchy alteration of interstitial material. 24°01'S., 148°03' E. Overlies GA 1033.


GA 1036  Basalt. About 10% intersertal glass and cryptocrystalline material, plagioclase slightly altered. Mt. Boorambool. 24°06' S., 148°04' E.

GA 1043  Trachyte. Minerva Hills. 23°59' S., 148°05' E.

GA 1143  Olivine basalt. Strong alteration of olivine and interstitial material which comprises 5-10% of the rock. Plagioclase also altered along cleavage planes. 23°42' S., 148°05' E.
GA 1149  Rhyolite dyke. Red Hill 24°02' S., 148°06' E.

GA 1150  Rhyolite dyke. Red Hill 24°02' S., 148°06' E.

GA 5152  Olivine basalt. Large amounts (10-20%) of intersertal glass and cryptocrystalline material which is partly altered or devitrified. 23°52' S., 148°08' E.

GA 5158  Olivine basalt. Similar to GA 1032, but amount of groundmass is less and alteration not as strong. Same locality as GA 1032.
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Isotopic Age Determinations on Tertiary Volcanic Rocks and Intrusives of South-Eastern Queensland

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ISOTOPIC AGE DETERMINATIONS ON TERTIARY VOLCANIC ROCKS AND INTRUSIVES OF SOUTH-EASTERN QUEENSLAND

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SYNOPSIS

Potassium-argon ages of whole-rock and mineral samples from the extrusives and near surface intrusives of the Moreton District are reported. Minor volcanic activity occurred during the early Eocene and late Oligocene, but the most widespread phase occurred in the early Miocene, between 25 and 22 million years ago. During this interval, the lavas of the Main Range and the Mt Warning Shield were extruded, and the rhyolite and trachyte intrusions of the Glass Houses and south-west Moreton District were emplaced.

The laterites which formed on the basalts at Toowoomba and Tamborine are of post-early Miocene age, while there are inconclusive indications of an older period of lateritization in the area north of Toowoomba.

INTRODUCTION

In many parts of eastern Australia, especially along the main divide and adjacent tablelands, volcanic rocks, largely basalts, rest on Palaeozoic and Mesozoic rocks. Excepting those which are obviously very young (emanating from more or less intact craters or filling recent valleys), these volcanic rocks are usually assigned to the Tertiary Period. There are also numerous post-Mesozoic sills, dykes, plugs and laccoliths which have been intruded during the same (lengthy) period. More definite dating based on fossils is, in most places, impossible or dubious, due to the lack of marine strata. Accurately known ages of the volcanic rocks are necessary for correlation of separate volcanic provinces, determining relations between intrusives and extrusives and dating (within narrower limits) the events in the geomorphological history of an area, e.g. the formation of laterite.

In recent years, a revival of interest in the Tertiary volcanic rocks of eastern Queensland and New England has led to the use of isotopic dating methods to determine the ages of the volcanics. So far, the only published isotopic dates (Cooper, Richards and Webb, 1963; Dulhunty and McDougall, 1966) have been on rocks from northern New South Wales, where ages of 34 million years (Oligocene) and 14 million years (Upper Miocene) were obtained.

GENERAL GEOLOGY

The Tertiary volcanic rocks of south-east Queensland occur as almost horizontal flows, unconformably overlying Mesozoic sedimentary rocks, the youngest of which are the Jurassic Walloon Coal Measures.
Two major groups of volcanic rocks are recognized (Text-figure 1): the Main Range Volcanics (west and south-west of Brisbane) and the Lamington Group of the Mt Warning Shield (south of Brisbane). A third group of Tertiary volcanics of uncertain affinities is interbedded with (?) Oligocene freshwater sediments in small basins between Ipswich and Brisbane.

Most of the post-Jurassic intrusives are concentrated in the belt of Coal Measures east of the Main Range and south of Ipswich. A prominent group of plugs, the Glass Houses, is separate from the main belt, to the north of Brisbane (Text-figure 1).

EXTRUSIVE ROCKS

The Main Range Volcanics (Stevens, 1965) form the southern part of an extensive belt of volcanic rocks which make up the Great Dividing Range from the New South Wales border at Wilson’s Peak north to Cunningham’s Gap, Toowoomba and the Bunya Mountains.

They are an alkali olivine basalt–trachyte suite typical of continental non-orogenic regions. Basalt is the most abundant rock type, but the volcanics show much variation, ranging from olivine basalts through to hawaiites (olivine-andesine basalts) and mugearites, and these grade into melanocratic pyroxene trachytes and trachyandesites. Leuco-trachytes and trachyte breccias are common in the lower half of the formation along the eastern escarpment (Russell, 1965), and two flows of trachyte and comendite are found over a wide area to the west, interbedded with the basalts. The upper half of the formation consists largely of regularly stratified olivine basalts. Very few occurrences of interbedded sediments have been found in the volcanic sequence. The maximum thickness of the Main Range Volcanics is about 3000 feet.

The Lamington Group, predominantly of basalts with some interbedded rhyolites, rhyolitic pyroclastics and sediments, is associated with the Mt Warning volcanic centre west of Murwillumbah in northern New South Wales. The volcanic rocks have a maximum thickness of about 3400 feet and form a shield volcano, the lavas extending in all directions for up to 34 miles (Solomon, 1964). Several subsidiary centres have supplied lavas and pyroclastic rocks to the volcanic pile.

According to McTaggart (1962), the generalized sequence of formations is as follows:

1. Numinbah Valley Formation (shales) 100 feet
2. Albert Basalt 800 feet
3. Chinghee Conglomerate and Hillview Rhyolite 100 feet, 200 feet
4. Beechmont Basalt 900 feet
5. Binna Burra (=Mt Lindesay) Rhyolite 1000 feet, 800 feet
6. Hobwee Basalt 1960 feet

Except for the Albert Basalt, the lavas are notably less alkaline than those of the Main Range; there are no trachytes or comendites and the suite seems to be transitional between alkaline and tholeiitic (Bryan and Green, in press).

In the Ipswich District, basalts are interbedded with lacustrine sediments of the Silkstone Formation, considered to be of Oligocene age (Cribb, McTaggart and Staines, 1960). The basalts make up a total thickness of 300 to 500 feet, in flows about 50 feet thick. Although the basalts have been correlated with similar types in the lower part of the Lamington Group (Bryan, 1959), they are far removed from the nearest representatives (at Mt Tamborine), and are closer to outliers of the Main Range Volcanics (at Mt Walker).
INTRUSIVE MASSES

The main vent for the emission of lavas of the Lamington Group appears to be represented now by the Mt Warning Intrusive Complex (Solomon, 1959). It forms a mountain mass, largely of gabbro and syenite, and is separated from the lavas of the shield by an erosion caldera floored by Mesozoic and Palaeozoic sedimentary rocks. Ring-dykes of trachyte, alkali granite and syenite have been recognized in the gabbro and at its margin.

The Mt Barney Central Complex (Stephenson, 1959), situated close to the State border between the two major lava areas, forms the mountain mass of Mt Barney and Mt Ballow. Mt Barney itself is a boss of granophyre, intruded into Middle Carboniferous sedimentary rocks and subsequently brought to the surface by upthrow of a block bounded by a closed ring-fault. Boulders of granophyre thought to have been derived from Mt Barney have been found in the Chinghee Conglomerate of the Lamington Group. East of Mt Barney, rhyolitic pyroclastics at Mt Gillies are associated with the Central Complex.

The Mt Alford Ring-Complex (Stevens, 1959, 1962) is 15 miles northwest of Mt Barney. The central boss is partly surrounded by a zone of
Intrusive Masses

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The Mt Alford Ring-Complex (Stevens, 1959, 1962) is 15 miles north-west of Mt Barney. The central boss is partly surrounded by a zone of
steeply dipping Mesozoic sandstones with steeply dipping ring-dykes of rhyolite and trachyte. Later transverse dykes of rhyolite, trachyte, comendite etc. have intruded the central boss and the zone of ring-dykes. A comendite ring-dyke forms Minto Craggs, to the south-east, and a similar comendite (a plug or tholoid) forms Mt Greville, west of Mt Alford.

Mt Edwards, to the north of Mt Greville, is a large intrusive mass of pyroxene trachyte grading into microsyenite. A notable feature of this mountain is the deep gorge cut through it by Reynolds Creek, cited as an example of a superimposed stream (Marks, 1933).

Mt French is composed of rhyolite; its step-like profile and vertical columnar jointing suggest a multiple sill or two thick flows. There is no sign of any overlying strata.

In the district to the north, between Kalbar and Ipswich, there are numerous intermediate to basic intrusives, mainly microsyenites and dolerites, poorly exposed (Stevens, 1960). One of these, the Flinders Teschenite, is considered to be intrusive into dolomitic limestone (Cochrane, 1960) similar to that of the Silkstone Formation.

Further east, several plugs intrude Mesozoic sandstones. The most prominent of these forms Flinders Peak, a complex mass of leuco-trachyte, trachyte breccia, melanocratic aegirine trachyte and some pitchstone.

North of Brisbane, another group of plugs, the Glass Houses, intrudes the Lower Jurassic Landsborough Sandstone. Most of the plugs are composed of alkali rhyolite (comendite); some (e.g. Mt Beerburrum) are melanocratic trachytes, porphyritic in anorthoclase. Similar comendites are found further north, forming Mt Coolum, Mt Cooroora and Mt Cooran.

CHEMICAL COMPARISONS OF INTRUSIVES AND EXTRUSIVES

Chemical analyses of the lavas of the Lamington Group and Main Range, when plotted on an alkali-silica diagram (Text-figure 2), fall, for the most part, on two distinct curves. The Main Range Volcanics are the more alkaline, and the Lamington Group, while not tholeiitic by generally accepted standards (Tilley, 1950), is closer to that suite at least in the lower silica region of the curve. An anomaly is the position of the Fingal basalt which falls on the Main Range curve, rather than on the curve for the Lamington Group lavas with which it appears to be associated.

The diagram also shows the alkaline trend of the rocks from the Glass Houses and Flinders Peak, and the close parallelism of the Mt Alford rocks and the Mt Barney-Mt Ballow granophyres with the Lamington Group lavas.

PREVIOUS VIEWS ON THE AGE OF THE VOLCANIC ACTIVITY

Before Richards' pioneer work on "The Volcanic Rocks of South-Eastern Queensland" (1916) opinion was divided between Tertiary and Trias-Jura for the age of these rocks. Jensen (1909) had stated that on the Darling Downs, basalts overlie Cretaceous sediments, and proposed an early Tertiary age, both for these basalts and for the "trachytic outpourings" east of the Dividing Range. Richards established that they were of post-Walloon age and postulated a threefold partition of the extrusive rocks into Lower, Middle and Upper Divisions. He suggested that they, and the associated near-surface alkali intrusives, were Tertiary, ranging from (?) Lower Cainozoic for the Lower Division of basaltic rocks to (?) Upper Cainozoic for the Upper Basalts. The Middle Division of acid and sub-acid rocks, which included the rhyolites of the McPherson Range, the trachyte of Spicer's Gap (in the Main Range) and the alkaline intrusives of the Glass
Text-figure 2.—Silica-total alkali curves for Lamington Group volcanic rocks, Main Range Volcanics, intrusive rocks of the Flinders Peak, Glass Houses and Mt Alford Groups and granophyres (G) of the Mt Barney-Mt Ballow complex. MC = Minto Crags comendite, which is probably similar to the Mt Greville rock. C = Mt Coolum comendite, 28 = basalt from Fingal Point.

Data from Richards (1916, pp. 181-183, Lamington, Glass Houses, Flinders Peak, 1-33); Stevens (1965, Main Range I—X and 1, 2 and 3); Stevens (1962, 1A—4A and MC), Stephenson (1956, G) and Jensen (1906, C).
Houses, Flinders Peak and Mt Greville, was assigned to the (?) Middle Cainozoic.

Richards apparently included the basalt at Bundamba, near Ipswich (and presumably other basalts in the same district) with his Upper Basalts. Since that time it has been found that the formation containing these basalts (the Silkstone Formation) rests conformably on fossiliferous sediments which are considered to be Oligocene or Eocene on evidence from fossil fish (Hills, 1934). Bryan (1959) suggested a correlation between the basalts of the Silkstone Formation and those of Richards' Lower Division, and favoured a range from Eocene to Upper Oligocene for the volcanic rocks. This was a slight modification of W. R. Browne's conclusions that, excepting the Silkstone Formation basalts, which were placed in the Eocene, the volcanic rocks were of Oligocene age (David, 1950).

Palaeomagnetic studies (Green and Irving, 1958; Robertson, 1966) have indicated an Upper Tertiary age for the volcanics. Robertson also placed the intrusive rocks in the Upper Tertiary, but he concluded that the intrusives and the volcanic rocks did not form simultaneously. Solomon (1964) favoured a Late Tertiary age for the volcanic rocks of the Mt Warning Shield, on geomorphological evidence.

ANALYTICAL INFORMATION

The methods of argon and potassium analysis used in this study have been described previously (McDougall, 1966; Cooper, 1963; Cooper, Martin and Vernon, 1966). McDougall claims an overall precision, at the 95 per cent confidence level, of ± 3 per cent for individual age determinations where the atmospheric argon contamination is less than 85 per cent. In the present work, the atmospheric argon contamination was sufficiently low in all analyses that its effect on the precision of the radiogenic argon measurements was negligible.

Most of the determinations were made on whole rock samples, and therefore should be treated with caution. The alteration, recrystallization, or devitrification of any potassium-bearing phase in the rock will result in a loss of radiogenic argon and a measured age which is too low. There appears to be no quantitative relationship between degree of alteration and argon leakage, but McDougall (1964) and Evernden and Curtis (1965) have shown that by the rejection of all altered material, internally consistent K/Ar ages can be measured routinely on whole-rock samples. K/Ar dating of the Tertiary volcanics at Springsure (Webb, in prep.) indicates that where the alteration of the rock is only slight, acceptable minimum ages may frequently be obtained.

Of the samples from south-east Queensland, those from the Lamington Group were altered beyond the desirable limits, but fresher material was not available. In addition, GA 5 302 (Toowoomba), GA 5 299 (Mt Walker Creek) and GA 1 413 (Mt Greville) are moderately altered. These results can only be regarded as minimum ages.

Argon was extracted from the sanidines at a temperature of 1 650°C, and it is assumed that complete extraction of argon occurred. The high result on GA 5 301 (run 2) is thought to be due to a different analytical procedure used for that run, rather than indicating that incomplete release of argon occurred in the other three runs on that sample.

DISCUSSION OF RESULTS

The Lavas

The ages determined on the flows are listed in Table 1. The Main Range
Volcanics are represented by six samples; four come from a vertical succession at Mt Mitchell, and two unrelated samples come from the Toowoomba area. The results on the Mt Mitchell sequence are internally consistent and show a decrease in age from 24 million years for the basal flow, to 22 million years for a flow 2,000 feet above this level. GA 5 302, from the Toowoomba Municipal Quarry, has a lower apparent age, but this sample was somewhat altered. The age of the sixth sample (GA 5 540) is probably reliable, and falls within the range of the Mt Mitchell sequence. These flows are early Miocene on the time scale of Funnell (1964).

The apparent ages of the flows from the Lamington Group range from 22 to 20 million years. In this case, there is no internal agreement between the K/Ar age and the stratigraphic position, and these discrepancies are probably due to the altered nature of the samples. The most reliable date is that of GA 5 542. These dates are all younger than the biotite age of 22.5 to 23 million years from the Mt Warning gabbro (GA 1 408). Unpublished data of one of us (I.McD.) indicates an age of 22.5 to 23 million years for basalts from Burleigh Heads and Fingal, so all four of the Lamington Group lavas dated in this study may have lost radiogenic argon.

The unreliability of the dates measured on the Lamington Group makes the correlation between this area and the Main Range difficult. The present evidence does not justify the conclusion that the volcanism in the Main Range began before that in the Mt Warning Shield. The results suggest that alkali olivine basalt magma and sub-alkaline magma were being extruded during the same interval of time from centres only 50 miles apart.

The basalts at Mt Walker Creek (GA 5 299) and Kumbia, west of Nanango (GA 5 314) are not continuous with either the Main Range or Lamington basalts. The apparent age of the Mt Walker Creek basalt (~60 million years) is considerably older than any other ages determined on Tertiary lavas and intrusions in south-east Queensland. This age corresponds to the early Eocene (Funnell, 1964), but is a minimum age only, due to the alteration of the sample. The Kumbia basalt age (22 million years) is similar to the other Main Range basalt ages, and supports the interpretation that the Bunya Mountains lavas are a northern extension of the Main Range Volcanics.

The Intrusions

On the basis of their K/Ar ages (Table 1) most of the intrusive volcanic rocks of south-east Queensland form two fairly distinct groups, which coincide on a broad scale with petrographic groups. Only one sample (GA 1 407, dolerite, Flinders Teschenite) falls outside the limits of these groups, the plagioclase age of approximately 29 million years (Upper Oligocene) indicating that it is distinctly older than the other intrusions. The age of the dolerite is in agreement with the tentative field correlations which suggest an Oligocene age for the sediments which it intrudes (Cochrane, 1960).

The remaining intrusions may be divided into groups with ages of 24-25 million years and 22.5-23.5 million years. The older group includes the alkali rhyolites of the Glass Houses and Mt Coolum and the alkali trachytes from Mt Edwards and Flinders Peak. The younger group contains the rhyolites from Mt Alford, Mt French and Mt Gillies, the gabbro from Mt Warning and the Mt Barney granophyre. The measured age of the Mt Greville comendite (22.6 m.y.) falls within the range of the younger group, but this sample may have lost argon from the altered feldspathic groundmass. The division of rock type with time is not a sharp one; the difference between the mean ages of the two groups is barely outside experimental error, and the relationship in the field between dykes of alkaline and tholeiitic affinities
**Table 1.**—K/Ar Ages of Whole-rock and Mineral Samples

<table>
<thead>
<tr>
<th>GA No.</th>
<th>Sample</th>
<th>%K</th>
<th>$^{40}\text{Ar}*/^{40}\text{K}$ ((\times 10^{-6}))</th>
<th>$^{40}\text{Ar}$ atm. ((\times 10^{6} \text{ yrs}))</th>
<th>Age ((10^{6} \text{ yrs}))</th>
<th>Locality/Stratigraphic position</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Extrusions</td>
<td></td>
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<tr>
<td>1 400</td>
<td>Whole Rock</td>
<td>1.856 1.85</td>
<td>(1) 0.1294</td>
<td>2.9</td>
<td>22.0</td>
<td>Mt Mitchell 3’745’</td>
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<tr>
<td></td>
<td></td>
<td>1.850 1.32</td>
<td>(2) 0.1303</td>
<td>6.0</td>
<td>22.1</td>
<td>Mt Mitchell 3’330’</td>
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<tr>
<td>1 401</td>
<td>Whole Rock</td>
<td>1.317 2.31</td>
<td>0.1309</td>
<td>12.9</td>
<td>22.3</td>
<td>Mt Mitchell 2’280’</td>
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<tr>
<td>1 403</td>
<td>Whole Rock</td>
<td>2.314 2.31</td>
<td>0.1392</td>
<td>60.9</td>
<td>23.7</td>
<td>Mt Mitchell 1’750’</td>
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<tr>
<td>1 404</td>
<td>Whole Rock</td>
<td>2.337 2.34</td>
<td>(1) 0.1399</td>
<td>46.2</td>
<td>23.8</td>
<td>Mt Mitchell 3’745’</td>
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<tr>
<td></td>
<td></td>
<td>2.337 2.34</td>
<td>(2) 0.1403</td>
<td>51.5</td>
<td>23.9</td>
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<tr>
<td>5 302</td>
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<td>1.813 1.81</td>
<td>0.1138</td>
<td>11.8</td>
<td>19.4 (M)</td>
<td>Toowoomba</td>
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<td>5 540</td>
<td>Whole Rock</td>
<td>1.807 1.33</td>
<td>0.1366</td>
<td>35.0</td>
<td>23.2</td>
<td>Cooby Creek</td>
</tr>
<tr>
<td>5 541</td>
<td>Whole Rock</td>
<td>1.957 1.96</td>
<td>0.1176</td>
<td>9.1</td>
<td>20.0 (M)</td>
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</tr>
<tr>
<td>5 542</td>
<td>Whole Rock</td>
<td>1.353 1.35</td>
<td>0.1282</td>
<td>25.3</td>
<td>21.8</td>
<td>Beechmont Basalt 1 mile west of Canungra</td>
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<tr>
<td>5 543</td>
<td>Whole Rock</td>
<td>1.349 1.73</td>
<td>0.1240</td>
<td>59.9</td>
<td>21.1 (M)</td>
<td>Beechmont Basalt Beechmont</td>
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<tr>
<td>5 544</td>
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<td>1.739 1.28</td>
<td>0.1252</td>
<td>28.9</td>
<td>21.3 (M)</td>
<td>Top of Beechmont Basalt Binna Burra</td>
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<tr>
<td>5 299</td>
<td>Whole Rock</td>
<td>0.2694 0.269</td>
<td>(1) 0.3757</td>
<td>52.2</td>
<td>63.2 (M)</td>
<td>Mt Walker Creek</td>
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<td></td>
<td></td>
<td>0.2688 0.269</td>
<td>(2) 0.3505</td>
<td>52.3</td>
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<td>Mt Walker Creek</td>
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<tr>
<td>5 316</td>
<td>Whole Rock</td>
<td>2.284 2.28</td>
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<td>9.5</td>
<td>22.1</td>
<td>Kumbia</td>
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<td>GA No.</td>
<td>Sample</td>
<td>%K</td>
<td>$^{40}\text{Ar}^* / ^{40}\text{K}$ $(\times 10^{-3})$</td>
<td>$^{40}\text{Ar}^\text{atm.}$ $(\times 10^4$ yrs)</td>
<td>Age $(\times 10^4$ yrs)</td>
<td>Locality/Stratigraphic Position</td>
</tr>
<tr>
<td>--------</td>
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<tr>
<td><strong>Intrusions</strong></td>
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<tr>
<td>1 410</td>
<td>Whole Rock</td>
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<td>0.1453</td>
<td>8.0</td>
<td>24.7</td>
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<td>Whole Rock</td>
<td>3.486</td>
<td>3.70</td>
<td>0.1463</td>
<td>13.9</td>
<td>24.9</td>
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<td>1 412</td>
<td>Whole Rock</td>
<td>3.717</td>
<td>3.72</td>
<td>0.1454</td>
<td>1.3</td>
<td>24.7</td>
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<td>1 413</td>
<td>Whole Rock</td>
<td>3.475</td>
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<td>0.1327</td>
<td>19.4</td>
<td>22.6 (M)</td>
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<td>5 300</td>
<td>Whole Rock</td>
<td>3.902</td>
<td>3.90</td>
<td>0.1414</td>
<td>8.7</td>
<td>24.0</td>
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<td>5.522</td>
<td>6.52</td>
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<td>6.1</td>
<td>22.6</td>
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<td>Whole Rock</td>
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<td>4.49</td>
<td>0.1420</td>
<td>18.0</td>
<td>24.1</td>
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<td>6.44</td>
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<td>Whole Rock</td>
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<td>3.96</td>
<td>0.1360</td>
<td>31.5</td>
<td>23.1</td>
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<td>4.34</td>
<td>0.1378</td>
<td>8.7</td>
<td>23.4</td>
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<td>1 408</td>
<td>Biotite</td>
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<td>6.93</td>
<td>(1) 0.1362</td>
<td>21.7</td>
<td>23.1</td>
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<tr>
<td>1 407</td>
<td>Plagioclase</td>
<td>0.2158</td>
<td>0.216</td>
<td>(1) 0.1712</td>
<td>62.4</td>
<td>29.1 $\pm$ 1.5</td>
</tr>
</tbody>
</table>

(M) Minimum age due to alteration of sample. See Sample Descriptions and Localities.

$^{40}\text{Ar}^*:$— Radiogenic argon.

K Decay Constants:— $\lambda_\beta = 4.72 \times 10^{-19}$yr$^{-1}$, $\lambda_K = 0.584 \times 10^{-18}$yr$^{-1}$. $^{40}\text{K} = 1.22 \times 10^{-4}$g/g K.
indicates that some overlapping has occurred (see under *General Geology, Intrusive Masses*). The general tendency for the alkaline intrusions to be older than the sub-alkaline ones is similar to the time/chemical composition relationship of the lavas of the Lamington Group.

The presence of boulders of the Mt Barney granophyre interbedded with the flows of the Lamington Group has been considered as evidence that the granophyre must be much older than the lavas (Stephenson, 1959), but the K/Ar ages imply that this is not so. If the date of 23.4 m.y. for the Mt Barney intrusion is correct, and this mass is the source of the granophyre boulders in the Chinghee Conglomerate, then the measured age of the Beechmont Basalt (GA 5 542, 21.8 m.y.), which overlies the conglomerate, indicates that the upfaulting of the Mt Barney mass must have occurred soon after its emplacement, allowing a period of 1.5 million years for erosion to remove the covering strata and expose the granophyre. This also suggests that there has been no serious loss of radiogenic argon from GA 5 542.

**The Age of the Laterites**

Many of the opinions about the age of the Tertiary laterites have been summarized by Connah and Hubble (1960). Although this project was not directed primarily toward dating the period(s) of laterite formation, our results place certain time limits on these processes. The laterites which formed on the basalts at Tamborine and Toowoomba must be younger than the whole-rock basalt ages of 22 million years and at least 20 million years respectively. However, it is difficult to find unequivocal cases where the volcanic rocks are younger than the laterites. The Kumbia basalt (GA 5 314) is at a higher level than the present laterite surface (Tweedale, pers comm.), while the trachyte (GA 5 540) appears to overlie laterite north west of Toowoomba. Both samples give dates older than the basalt at Toowoomba. This may indicate an earlier, pre-Miocene, period of laterite formation, but the evidence for this from these two samples is not strong. In the case of the Kumbia basalt, an overlying laterite, which formed on an uneven surface, may have been stripped from the higher levels by erosion. Langford-Smith, Dury and McDougall (1966) report a minimum age of 23 million years for a dolerite which cuts the duricrust to the north of Roma, indicating a pre-Miocene period of duricrust formation.

**CONCLUSIONS**

(1) Cainozoic volcanism began in south-east Queensland in the early Eocene but probably was not extensive at that time.

(2) A minor phase of intrusive activity (Limestone Ridges) occurred in the late Oligocene.

(3) The main volume of the volcanic rocks (both flows and intrusions) was produced in the early Miocene, over a period of about 3 million years. Volcanism in the two major extrusive provinces was approximately synchronous, while intrusive activity began slightly earlier and continued simultaneously with the extrusions. No determinations have been made on any extrusive rocks that may have been related to the early intrusive activity.

(4) There appears to be some correlation between time of emplacement and chemical composition of the intrusions. The earliest intrusions were the comendites, which were followed by the sub-alkaline rhyolites. This relationship between age and chemical composition is similar to that found in the lavas of the Lamington Group.

(5) One period of laterite formation was post-early Miocene, but no
ISOTOPIC AGE DETERMINATIONS ON TERTIARY VOLCANIC ROCKS

younger limit can be placed upon its age. There is also the possibility of an older, pre-Miocene lateritization.

(6) No evidence has been found in this study for the late Tertiary volcanism suggested by Green and Irving (1958) and Robertson (1966).

(7) There is no correlation between the times of Tertiary volcanic activity in south eastern Queensland and those so far reported from northern New South Wales by Cooper et al. (1963) and Dulhunty and McDougall (1966).

ACKNOWLEDGEMENTS

The analytical work was carried out by A. W. Webb in the Department of Geophysics and Geochemistry, A.N.U. under the supervision of I. McDougall. The samples were collected with the assistance of research funds from the University of Queensland. We wish to thank Dr J. R. Richards for critically reading the manuscript. A. W. Webb has received permission to publish from the Director, Bureau of Mineral Resources, Canberra.

SAMPLE DESCRIPTIONS AND LOCALITIES

GA 1400 Whole-rock, Main Range Volcanics.
Mt Mitchell, 3 745' elevation. Warwick 1-mile 495 193.
Andesine basalt. Plagioclase (? andesine) is fresh and interstitial glass is unde-vitrified.

GA 1401 Whole-rock, Main Range Volcanics.
Mt Mitchell, 3 330' elevation. Warwick 1-mile 492 191.
Olivine basalt. Plagioclase is fresh, slight alteration or devitrification of intersertal glass which comprises about 10% of rock.

GA 1403 Whole-rock, Main Range Volcanics.
Mt Mitchell, 2 280' elevation. Warwick 1-mile 505 197.
(?Oligoclase basalt. A few percent of cryptocrystalline material, and slight alteration around some of the pyroxene granules.

GA 1404 Whole-rock, Main Range Volcanics.
Mt Mitchell (Clayton Gully), 1 750' elevation. Warwick 1-mile 522 192.
Pyroxene trachyte. Slight alteration around some of the pyroxene grains. Up to 5% of interstitial cryptocrystalline material.

GA 1407 Plagioclase from analcite dolerite.
Flinders Teschenite (Limestone Ridges). Flinders 1-mile 842 488.

GA 1408 Biotite from gabbro.
Mt Warning. Murwillumbah 1-mile 468 773.

GA 1410 Whole-rock.
Mt Ngun Ngun. Glass House 1-mile 106 593.
Comendite. Few phenocrysts. Groundmass of quartz, feldspar and Na-amphibole is unaltered.

GA 1411 Whole-rock.
Trachyte Range. Glass House 1-mile 129 527.
Comendite. Slight clouding of some of the feldspars.

GA 1412 Whole-rock.
Mt Coolum. Maroochydore 1-mile 275 995.
Comendite. No alteration.

GA 1413 Whole-rock.
Mt Greville. Dugandan 1-mile 627 160.
Comendite. Slight to moderate clouding of the feldspars.
GA 5 299 Whole-rock.  
Mt Walker Creek, Cunningham Highway. Ipswich 1-mile 788 586.  
Olivine basalt. About 20% of Fe-rich glass, partly devitrified. Plagioclase is fresh.

GA 5 300 Whole-rock.  
Mt Edwards, Moogerah Dam. Dugandan 1-mile 671 227.  
Analcite microsyenite. Both feldspar and analcite are fresh. About 10% of calcite present.

GA 5 301 K-feldspar from quartz-feldspar porphyry.  
A vertical dyke in the Mt Alford Ring Complex. Dugandan 1-mile 648 166.

GA 5 302 Whole-rock.  
Toowoomba Municipal Quarry. Toowoomba 1-mile 064 810.  
Olivine basalt. Slight alteration of plagioclase laths and the interstitial feldspathic matrix.

GA 5 304 Whole-rock.  
Mt Flinders, northern foothills. Flinders 1-mile 942 497.  
Fine grained pyroxene trachyte. Feldspathic matrix unaltered. Slight alteration of sodic pyroxene.

GA 5 316 Whole-rock.  
West of Nanango. Kumbia 1-mile 746 803.  
Fine grained vesicular basalt. Very high percentage of pinkish-brown glass, mainly undevitrified. Plagioclase and pyroxene are fresh.

GA 5 367 K-feldspar from porphyritic pitchstone.  
1 mile south of Mt Gillies. Mt. Lindsay 1-mile 892 903.

GA 5 368 Whole-rock.  
Mt French. Dugandan 1-mile 733 263.  
Rhyolite. Feldspar in phenocrysts and groundmass is fresh. The few grains of Na-amphibole present are unaltered.

GA 5 540 Whole-rock.  
3.5 miles N.N.E. of Cooby Creek Dam. Jondaryan 1-mile 027 072.  
Fine grained pyroxene trachyte. Mainly unaltered but some patchy alteration around some of the pyroxene.

GA 5 541 Whole-rock, Albert Basalt.  
Olivine basalt. Slight alteration of plagioclase laths. Interstitial feldspathic material strongly altered.

GA 5 542 Whole-rock, Beechmont Basalt.  
Mt Misery, west of Canungra. Springbrook 1-mile 305 235.  
Basalt. Almost no alteration of plagioclase and pyroxene.

GA 5 543 Whole-rock, Beechmont Basalt.  
Northern end of Beechmont plateau, Canungra-Beechmont road. Springbrook 1-mile 363 152.  
Olivine basalt. Olivine phenocrysts strongly altered. Plagioclase is fresh. High percentage of glass, largely devitrified.

GA 5 544 Whole-rock, top of Beechmont Basalt.  
0.5 mile N.W. of Binna Burra. Springbrook 1-mile 346 019.  
Olivine basalt. Plagioclase and pyroxene are fresh. About 10% of intersertal glass, partly devitrified.

GA 5 545 Whole-rock.  
Margin of Mt Barney mass, Rocky Creek. Mt. Lindsay 1-mile 834 926.  
Granophyre. Feldspar is fresh.
REFERENCES


